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ORIGINAL ARTICLE

# $N_2O$ and $CO_2$ emissions from South German arable soil after amendment of manures and composts

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**Abstract** Organic residues can be a major source of nutrients and are valuable fertilizers. But their benefits with regard to soil quality are undisputed. However, only few studies have focused on emissions of greenhouse gases from soil enriched with organic residues. A microcosom approach was employed to investigate the influence of the origin and composition of various organic residues on mineralization and $N_2O$ and $CO_2$ emissions in an arable soil. In total, we set up six treatments: control, poultry manure, bio-waste compost, sheep and wheat straw compost, cow manure (CM) and for further comparison, the mineral fertilizer calcium ammonium nitrate. 500 g of sieved and homogenized soil was mixed with the amendments and packed into microcosms. After a pre-incubation period of 10 days, gas concentrations were measured periodically from the headspace of the microcosm by means of an airtight surgical syringe. The measurement period continued for 32 days. Soil amended with CM showed a significantly ($\alpha = 0.05$) higher cumulative $CO_2$ emission (914 mg $kg^{-1}$) followed by bio-waste compost than poultry manure, sheep waste compost, control and calcium ammonium nitrate. Amending soil with cow manure and poultry manure led to the highest $N_2O$-N emissions (110 µg $kg^{-1}$). However, poultry manure and calcium ammonium nitrate significantly enhanced mineralization and net nitrification. Amendment of sheep and wheat straw compost and cow manure led to C sequestration and reduced $N_2O$ emission. Soil pH greatly decreased with poultry manure, sheep and wheat straw compost and bio-waste compost. Summing up, the application of organic residues to soil has some disadvantageous environmental effects calling for further research.

**Keywords** Organic residues · $N_2O$ · $CO_2$ · Arable soil

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## Introduction

Climatic perturbations have increased due to greenhouse gas emissions from anthropogenic sources during the last decades. The agricultural sector is generally known to release about 50 % of the climate-relevant gas emissions (IPCC 2007). Soils are the major source of $CO_2$, $N_2O$ and $CH_4$ emissions (Rastogi et al. 2002). The aerobic decomposition of organic compounds is the main biological process responsible for the release of $CO_2$ from soil to the atmosphere (Alexander 1977). The incorporation of organic residues has caught worldwide attention because it improves the physical and chemical properties of soils. The application of organic residues can enhance $N_2O$ and $CO_2$ emissions (Flessa and Beese 1995). Specific practices, such as organic residue management (Pattey et al. 2005) can reduce greenhouse gas emissions from the agricultural sector.

$N_2O$ is produced naturally in soils through the microbial processes of nitrification and denitrification. In agricultural soils, these processes depend on environmental factors, heterogeneity of soil conditions and management practices (Philippot et al. 2009), organic C (Boeckx et al. 2011), soil pH (Mørkved et al. 2007), temperature (Saad and Conrad 1993), and water content (Bergsma et al. 2002).

Application of organic fertilizer is not an immediate source of N but the provision of organic C in the form of organic fertilizer enhances denitrifiers' activity and the denitrification process. Mineral-N fertilizers also activate microbial activity by providing inorganic nitrogen (N) needed for growth (Khan et al. 2007).

Animal wastes are added to the soils as N source and, besides this, for storing organic C in soil (Flessa and Beese 1995). Cow manure contains about 4.5–18.1 kg of N per ton, most of it being in organic form. About half of this N is converted to available N to the plants during the first growing season. Organic matter, N and P contents in soils significantly increased over the control when the soil was amended with poultry manure and cow manure (Rahman 2010). Excess application of manure accumulates N in the soil, resulting in the accumulation of $NO_3^-$ in crops and ground water pollution (Harada 1992). Composting is a reasonable solution to re-cycle the animal manure for agricultural purposes (Bernal et al. 2009).

In Germany, the application of bio-waste is regulated by "application and introduction of materials onto or into the soil" (BioAbfV 1998). Organic residues can be a significant source of nutrients and a sound alternative to chemical fertilizers if properly managed. The amount of N converted to $N_2O$ depends on the bio-chemical composition of residues, in particular on their C/N ratios (Baggs et al. 2000) and physicochemical properties (Danga et al. 2010). Cumulative emissions of $N_2O$ and $CO_2$ were found to be negatively correlated with C/N ratios of the organic residues (Huang et al. 2004).

Applications of manure, compost and bio-solids are the recommended nutrient management practices to enhance C sequestration. Recent findings (Mondini et al. 2010) suggest that the addition of organic wastes can reduce $CO_2$ evolution; however, this increases $N_2O$ emissions because organic residues serve as an energy source for the microbes enhancing nitrification and denitrification processes. The organic material is enriched with carbohydrates (e.g. cellulose), lipids, fiber and lignin. These compounds will decompose slowly (Tuomela et al. 2000). The pre-dominant kind of proteins in the residues affects C mineralization (Mondini et al. 2010). It is a promising option to produce compost with different degradability and consequently, different N mineralization (Pal et al. 2010). The magnitude of greenhouse gas reduction affiliated with compost might be a few times higher than that of mineral fertilizers (Enzo and Schleiss 2009).

An incubation experiment was performed with soil amended with two different animal manures (poultry and cow manure) and two composts of different organic composition (sheep and wheat straw and kitchen garbage composts) and studied their biochemical properties in relation to nitrogen concentration and total organic carbon enhancing $N_2O$ and $CO_2$ emissions from soil. The study was based on the hypothesis that composts and animal manures similar in composition amended to the soil alter C and N cycling differently.

## Materials and methods

### Soil sampling and manure collection

The soil was taken from plots at the "Heidfeldhof" research station of Hohenheim University, Stuttgart, Germany, which had been recently harvested for wheat. Samples were taken from 0 to 15 cm depth. Sampled soil was immediately transported to the laboratory, well homogeneized, sieved to 4 mm (soil properties are given in "Physico-chemical properties of soil" section).

Soil organic amendments used were fresh poultry manure (PM), fresh cow manure (CM), sheep and wheat straw compost (SWC) and bio-waste compost (BWC). Fresh poultry and cow manures were provided by the research stations of Farm Animal Ethology and Poultry Production and of Husbandry and Organic Farming affiliated with Hohenheim University. The research station of Husbandry and Organic Farming prepared sheep and wheat straw compost using 15 % chopped wheat straw and pure sheep excreta. Institute of Plant Nutrition, Hohenheim University, prepared bio-waste compost that included bio-degradable fraction (Andersen 2010) of kitchen and garden waste (European Commission 2010).

Both composts under investigation were prepared by Indian Bangalore method (FAO 1980). This method does not require a particular structure. Consequently, recommended dimensions for a heap are 5 feet wide by 3 feet high (Illinois 2013). The chemical properties are mentioned in Table 1. The major advantages of this method are: frequent turning that provides aeration, reduces composting period and higher temperatures are produced as a result of turning (32.2–60° F) which will kill major pathogens and weed seeds (Illinois 2013). This method has also some disadvantages (FAO 2003), which are direct exposure to weather conditions, nutrient losses due to high wind, frequent turnings, time and labor consumptions.

For comparison we applied commercial mineral-N fertilizer calcium ammonium nitrate (CAN; 27 % total N).

### Experimental setup

Organic residues were oven dried at 60 °C, mashed in a shredder and passed through a 1 mm stainless steel sieve. The experimental setup included six treatments: control, soil + PM, soil + SWC, soil + BWC, soil + CM, and soil + CAN with ten replicate each. In total, 60 microcosms were prepared. 500 g soil (gravimetric water content: 28 %, on dry basis) was filled into each microcosm (0.82 l). Amendments were mixed homogenously into the soil. All amendments were applied as 50 mg N $kg^{-1}$ soil comparable to the field applications. Likewise we added C

**Table 1** Biochemical properties of the organic fertilizers included in the study

| Amendment | Total N (%) | pH | C/N ratio | C/N ratio | Total Sugar (%) | ADF (%) | ADL (%) | Cellulose (%) |
|---|---|---|---|---|---|---|---|---|
| Cow manure (CM) | 6 | 8.1 | 4.6 | 35.4 | <0.50 | 38 | 11 | 27 |
| Poultry manure (PM) | 3 | 7.8 | 12 | 16.1 | 0.88 | 18.1 | 3.1 | 15 |
| Bio waste compost (BWC) | 3 | 7.3 | 8.3 | 14.2 | <0.50 | 61.1 | 20.4 | 40.7 |
| Sheep and wheat straw compost (SWC) | 3 | 7.3 | 13 | 17.9 | <0.50 | 56.7 | 29.8 | 26.9 |

All percentages are given on dry weight basis

The cellulose percentage has been calculated from ADF and ADL

*ADF* acid detergent fiber, *ADL* acid detergent lignin

as 600, 666, 416.5 and 116.64 as mg/kg through PM, SWC, BWC and CM to each treatment.

Microcosms were pre-equilibrated for 10 days at room temperature (23 °C) in the dark. Temperature was recorded with two probes in the room. The water content of the cores was regularly controlled by weighting. Evaporation losses were compensated by adding deionized water to achieve the target gravimetric water content of 28 %. Except for the addition of water, no changes were made during the entire period of incubation, that is, there was no further mixing and no extra addition of fertilizer.

Prior to incubation, soil and manures were analyzed for their properties. Mineral-N ($NH_4^+$ and $NO_3^-$) and pH were measured before amendment as well as on the 8th, 16th, 24th, and 32nd day (termination of experiment). Total organic carbon % (TOC) was measured at the beginning and at the termination of experiment.

## $N_2O$ and $CO_2$ flows measurement

The whole system was airproof with rubber seals and butyl rubber septa in plastic lids of the microcosms allowing for the sampling of headspace gas. The plastic lids were fitted with a two way Luer-Lock valve. Samples were taken at 0, 30 and 60 min by connecting the headspace with a vacutainer (25 ml) through a mounted septum using a 100 $cm^3$ multi sample syringe (Smith et al. 1995). To ensure the prior absence of $N_2O$, all vacutainers were evacuated and rinsed with $N_2$ thrice, shortly before sampling. $N_2O$ and $CO_2$ concentrations were analyzed by gas chromatography (AutoSystem XL Perkin Elmer) equipped with an $N^{63}$ electron capture detector (ECD) and a flame ionization detector (FID), respectively, coupled to an auto sampler. The instrumental conditions were as follows: oven temperature 65 °C, ECD operation temperature 100–350 °C, carrier gas for ECD and FID $CH_4$/Ar (10 %/90) and He (95 %), respectively. Calibration was done with three external standards of 700, 900 and 1500 ppb for $N_2O$ and 400, 1500 and 3000 ppm for $CO_2$. Gas flow rates were calculated from the change of concentration in the headspace of the microcosm using linear regression (Livingston and Hutchinson 1995). Cumulative emission was calculated by linear interpolation thereafter.

## Analytical methods used for organic fertilizers

The dry matter content of the organic fertilizers was determined by drying samples to constant weight at 60° C. Total N and total organic carbon (C) contents were analyzed using an automatic elemental micro-analyser (NA 1500 Carlo Erba). Remaining analyses were performed at the State Institute of Agricultural Chemistry (LA Chemie), Stuttgart. Crude protein, total sugar, acid detergent fiber (ADF), acid detergent lignin (ADL) and cellulose were determined according to EU and VDLUFA guidelines [VO (EG) Nr.152/2009 III C, VO (EG) Nr.152/2009 III M, VO (EG) Nr.152/2009 III J, see http://eur-lex.europa.eu; VDLUFA MB III 6.5.2, VDLUFA MB III 6.5.3, see http://www.vdlufa.de/Methodenbuch/]. The cellulose content was determined by subtracting ADF (cellulose+lignin) from ADL.

## Soil analysis

TOC % was detected by a LECO 2000 CN analyzer. The particle size distribution was determined by the Pipette method (Gee and Bauder 1986). Soil pH was measured in 1:2.5 (soil/0.01 M $CaCl_2$) using glass electrode pH meter. Soil mineral-N ($NH_4^+$ and $NO_3^-$) was extracted in a 1 mol $L^{-1}$ KCl solution (soil/liquid ratio 1:5 w/w) as referred by Keeney and Nelson (1982). The filtrates were then analyzed on an automated flow injection analysis (Brann en Luebbe TrAAcs 800 Auto analyzer).

Net nitrogen nitrification (NNN) was calculated as final concentration of $NO_3^-$ minus initial concentration of $NO_3^-$. Likewise, net nitrogen mineralization (NNM) was assumed as final concentration of $NO_3^-$ plus $NH_4^+$, minus initial concentration of $NO_3^-$ plus $NH_4^+$.

## Physico-chemical properties of soil

The soil was classified as Haplic Luvisol (FAO-UNESCO 1997). Soil pH was nearly neutral (pH 6.8). Bulk density was 1.23 g/cm$^3$. Particle size distribution was 19 % sand, 52 % silt and 29 % clay (silty loam). TOC was 1.2 % by mass. $NO_3^-$ and $NH_4^+$ contents of the soil before incubation and addition of amendments were 10.8 and 5.6 mg kg$^{-1}$, respectively.

### Statistical analysis

Measured data were statistically evaluated by one way analyses of variances (ANOVA) using the software IBM SPSS Statistics Version 19. The least significant difference (LSD) test ($\alpha = 0.05$) was used to identify significant differences between treatments. Correlation was calculated as Pearson's correlation coefficient using Sigma plot 12.

## Results

### Chemical and bio-chemical properties of organic fertilizer added

Bio-waste and sheep and wheat straw composts had pH values of 7.3 (Table 1). Animal manures were somewhat more alkaline. All amendments had low C/N ratios (Table 1). CM contained high crude protein. Total sugar of PM was slightly higher than 1 %, but higher than that of the other organic fertilizers. In contrast, BWC had the highest cellulose content followed by CM, SWC and PM. ADF and ADL were pre-dominantly higher in BWC and SWC compared to the other organic fertilizers tested (Table 1). The only inorganic fertilizer used was CAN, which is a compound fertilizer ($NH_4NO_3 + CaCO_3$) with neutral pH (pH 7.0). Ca and N contents of CAN were 8 and 27 % by mass, respectively.

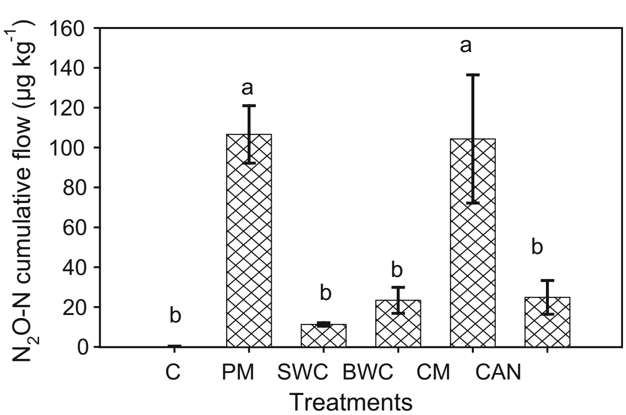


**Fig. 1** Cumulative $N_2O$-N flows (µg kg$^{-1}$) of different treatments. *Bars* denote the means of three replicates, *error bars* standard errors. *Different lower case letters* indicate significant difference at $\alpha = 0.05$

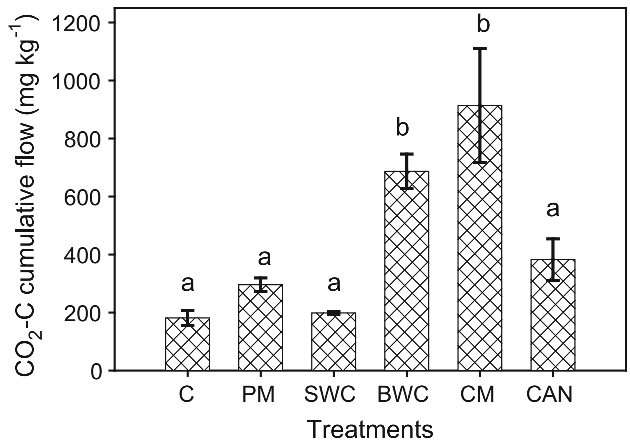


**Fig. 2** cumulative $CO_2$-C flows (mg kg$^{-1}$) of different treatments. *Bars* denote the means of three replicates, *error bars* standard errors. *Different lower case letters* indicate significant difference at $\alpha = 0.05$

### Cumulative $N_2O$ flow

Figure 3 shows the release of $N_2O$ of the different treatments, measured over a period of 32 days. The amendment with animal manures resulted in significantly ($\alpha = 0.05$) higher $N_2O$ emissions compared to the other amendments (Fig. 1). $N_2O$ flows decreased in the following sequence: PM < CM < CAN < BWC < SWC < control.

### Cumulative $CO_2$ flow

Soils amended with CM and BWC showed a significantly higher release of $CO_2$ than the other soils (Fig. 2). $CO_2$ emission decreased in the following order CM < BWC < CAN < PM < SWC < control. The cumulative flows of PM, CAN and SWC were similar to that of the control.

### Course of $N_2O$ flow from soil

The highest flow of $N_2O$ was observed during the first 3 days after the addition of CM (Fig. 3). With PM, the $N_2O$ flow was low in the first week of incubation, but started to rise between the 10th and the 15th day. SWC treatment showed continuously low $N_2O$ flows from the beginning to the end of experiment (<2 µg kg$^{-1}$ h$^{-1}$). BWC and CAN also emitted low flows (<4 µg kg$^{-1}$ h$^{-1}$).

### Dynamics of $CO_2$ evolution from soil

Soil respiration (Fig. 4) showed the largest reaction to CM and BWC amendment, where it sharply increased at the early stages of the experiment, while it declined after a few days. CAN showed a similar increase, which, however, remained smaller. $CO_2$ emissions of PM, SWC and also the control fluctuated at relatively low levels.

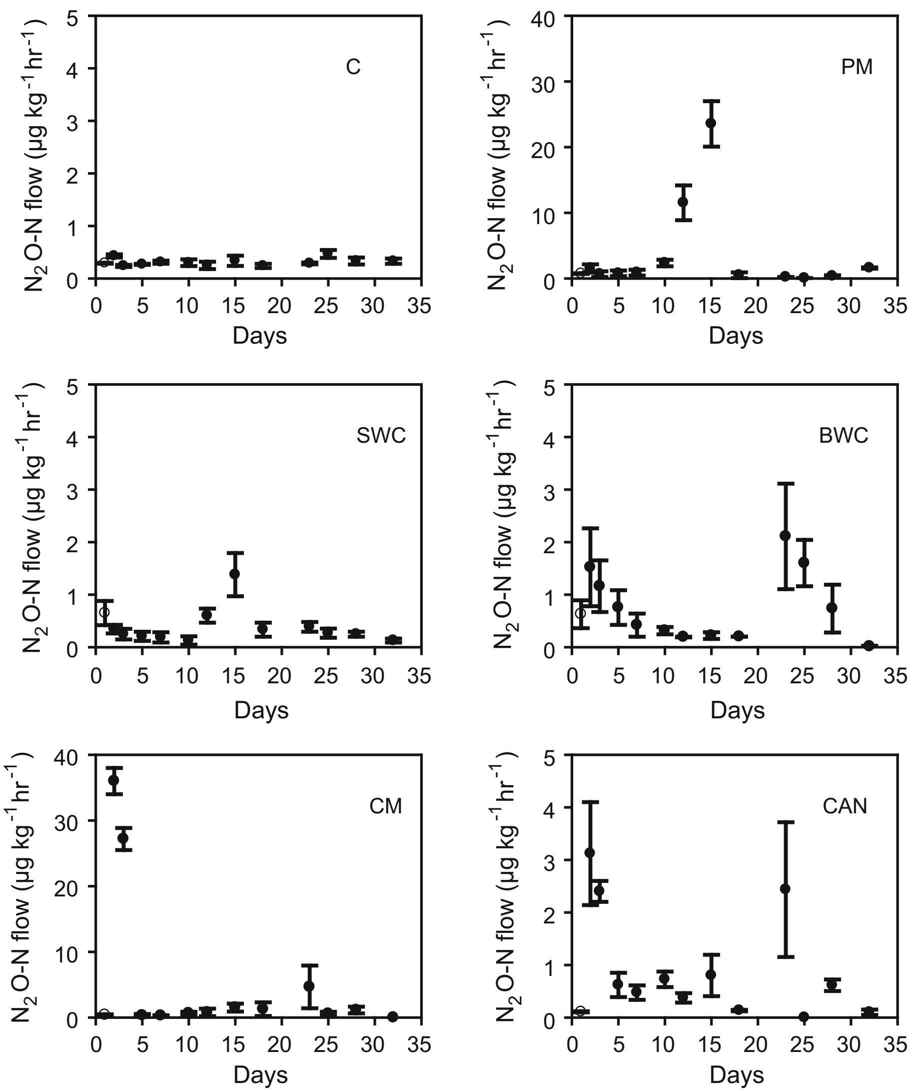


**Fig. 3** Temporal dynamics of $N_2O$-N flows (µg kg $^{-1}$ h $^{-1}$) after amendment. *Filled circles* denote the means of three replicates with standard error bars

### Total organic carbon

Only the amendment of SWC significantly increased the TOC over the time of incubation (Fig. 5). It was significantly higher than the other treatments.

The application of PM and CAN led to a significant increase of N concentration after 32 days (Fig. 6). In the PM treatment, concentration of $NH_4^+$ shot up to 110 mg kg$^{-1}$. From the fifth day on, nitrification started and $NH_4^+$ decreased. Soil amended with CAN reached 50 mg kg$^{-1}$ $NH_4^+$ and then, like PM, dropped down from the fifth day on. In the other treatments, the $NH_4^+$ concentration increased slightly and remained more or less constant at values of around 20 mg kg$^{-1}$ for most of the incubation period until it declined towards the end. The $NO_3^-$ concentration was higher during the experiment. Throughout the experiment, the net mineralization and net nitrification of PM were 52.8 62.0 mg kg$^{-1}$, while those of CAN 57.7 and 56.4 mg kg$^{-1}$, respectively. These values were significantly higher than the respective values of SWC, BWC and the control. The net nitrification of CM and SWC was only 5.6 and 6.7 mg kg$^{-1}$ and in case of BWC even less 2.53 mg kg$^{-1}$ (Fig. 6).

### Soil pH

The soil pH data are presented in Fig. 7. During the incubation soil pH of the SWC, BWC and PM amended treatments decreased by about one unit. After addition of CAN soil pH slightly increased, while after CM amendment it slightly decreased.

### Correlation

No other factors were correlated with each other. Only $NO_3^-$ concentration was negatively correlated ($r = -0.61$) with $NH_4^+$ in PM amended soil.

## Discussion

### $CO_2$ flows and C sequestration

The soils amended with organic fertilizers (composts, manures) behaved quite differently in the first 10 days of incubation (Fig. 4). BWC and CM showed $CO_2$ emission peaks while PM and SWC did not. The peaks may be attributed to the low C/N ratios of BWC and CM rather than to other factors (Table 1). The stability of SWC (cf. Fig. 5), the compost with the higher C/N ratio, may be attributed to the fact that SWC is made up to 15 % of wheat straw, which contains a high fraction of lignin (Table 1). It is, therefore, quite resistant to mineralization due to strong chemical bonds (McCrady 1991). Addition of such high lignocellulosic material to a compost leads to slower decomposition, so that less $CO_2$ is emitted. Comparing sheep and wheat straw compost to cow and wheat straw compost, Jianming et al. (2008) pointed out that sheep and wheat straw compost is more resistant to rapid degradation, so that its nutrients are released rather according to the changing demand of the growing crop (melon). Fabrizio et al. (2009) found a linear response of C sequestration to the application dose of sheep and wheat straw compost. Roberson et al. (2008) suggested that no tillage is an effective way to mitigate $CO_2$ emission from soil amended with PM.

The respiration peak of BWC indicates that, even after 3 months of storage, BWC still contains a considerable fraction of easily degradable material. CM shows a similar $CO_2$ emission pattern as BWC (Fig. 4), but showed the different trend for $N_2O$ (Fig. 3) the $N_2O$ flows were lower in BWC treatment, probably because the easily minerlizable N containing substances have already been mineralized during the composting process. This is also indicated by the C/N ratios of these amendments (Table 1).

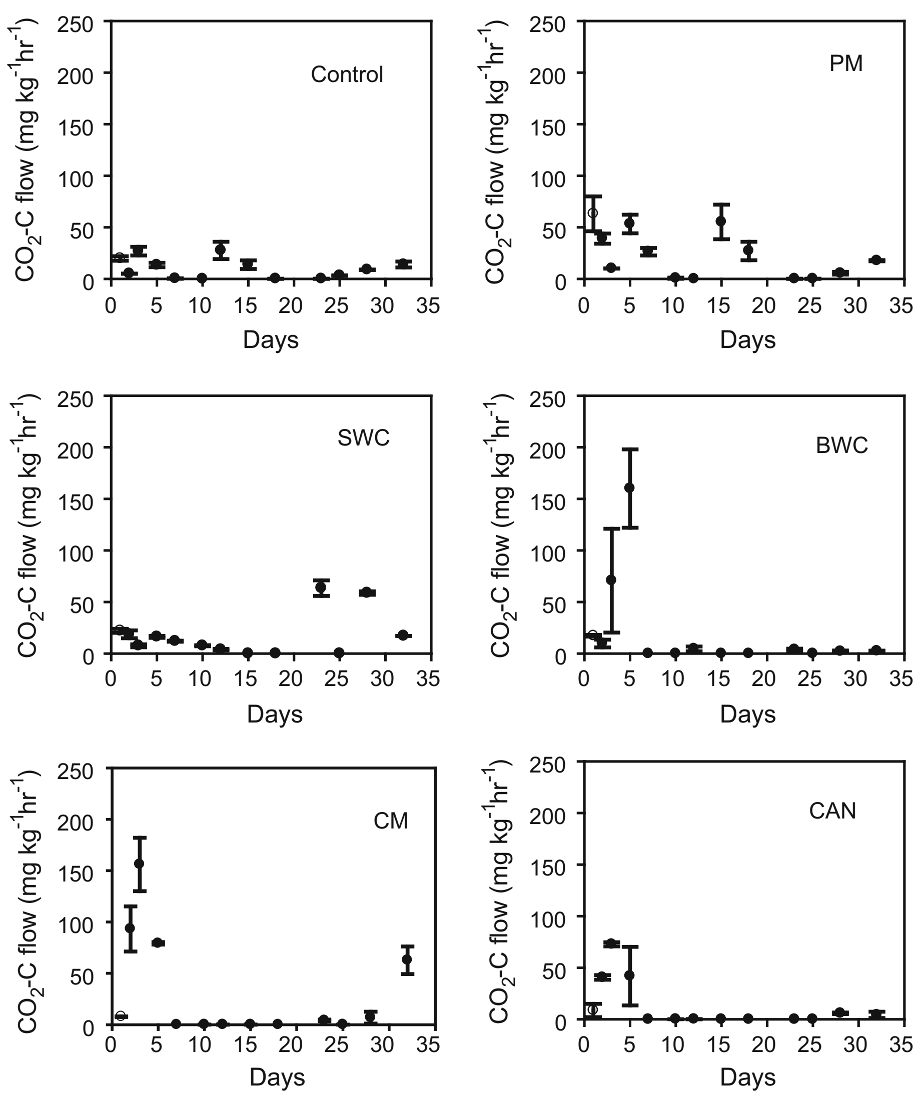


**Fig. 4** Temporal dynamics of $CO_2$-C flow (mg kg$^{-1}$ h$^{-1}$) after amendment. *Filled circles* denote the means of three replicates with standard error bars

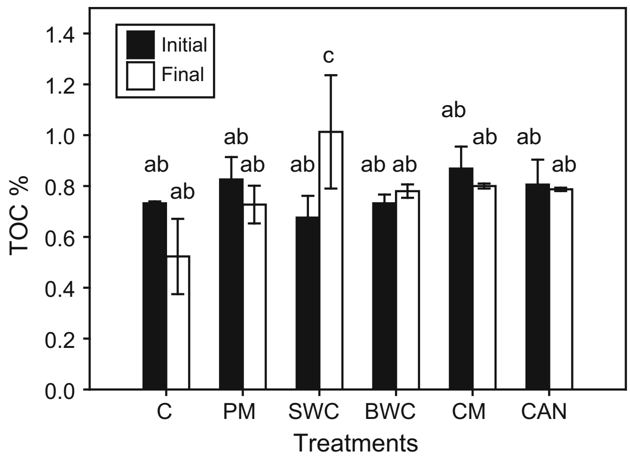


**Fig. 5** TOC % contents of soil after amendment. *Different lower case letters* indicate significant difference at $\alpha = 0.05$

However, CAN produced a priming effect, it enhanced soil respiration by providing N to accelerate the decomposition of indigenous organic matter by soil microorganisms. The stimulation of soil respiration by the addition of mineral-N fertilizer has already been reported many times (e.g. Khan et al. 2007; Wang et al. 2010).

With SWC amended soil, the maximum emission of $CO_2$ (Fig. 4) was observed in the second phase of the experiment. It was accompanied by a decline in $NH_4^+$-N content (Fig. 6). The coincidence mirrors the interconnections of microbial utilization of C compounds as energy source and of mineral-N for their cellular synthesis (Deenik 2006). Over all, bio-waste compost amended soil respired 80 % of the C added within first 5 days. Approximetly 46 % of added C respired till third day, added as cow manure. Conversely, poultry manure and sheep and wheat straw compost amendment only emitted 19 and 2.5 % of C added (Fig. 4).

## $N_2O$ flow and N concentration

$N_2O$ emission from soil amended with manures is well documented in the literature (Baggs et al. 2003; Huang et al. 2004; Millar and Baggs 2004; Millar et al. 2004). In case of the CM amendment, the main $N_2O$ emission occurred within the first 5 days and it was accompanied by a $CO_2$ peak, reflecting rapid mineralization. It seems that the mineral-N released in the course of mineralization is readily denitrified and released as an $N_2O$ peak. Despite a similarly high mineralization, BWC showed no such peak. However, because of the low sampling resolution (7 days) a mineral-N peak may have remained undetected. The late appearance of the $N_2O$ peak after the PM amendment (compared to CM amendment) is a consequence of the higher C/N ratio and the higher crude protein content (Table 1). Because of the slower mineralization, nitrification of PM amended soil started later than that of CM amended soil (Fig. 6). Dutta and Stehouwer (2010) reported immediate heterotrophic activity after the application of organic amendment, but low levels of $NO_3$.

To ensure homogeneity, all manures were finely ground and sieved before mixing with soil. This may have resulted $NO_3^-$ content and $N_2O$ emission. Cabrera et al. (1994) noticed higher $N_2O$ emissions when PM was applied as a powder rather than as pellets.

CAN amendment generated a moderate $N_2O$ peak shortly after the beginning of incubation, which was considerably lower than the $N_2O$ peak of the soil amended with animal manures. Upendra et al. (2010) reported that $N_2O$ emission after PM amendment was higher than after the application of mineral fertilizer. They explained their finding with the enhancement of C and N cycling by the addition of extra C. In contrast, Cayuela et al. (2010) and Velthof et al. (2005) observed similar $N_2O$ emissions after the application of CM and CAN, respectively.

$NH_4^+$ and $NO_3^-$ contents of soil after CAN application were similar in the first half of the experiment, reflecting the equal proportion of $NH_4^+$ and $NO_3^-$ in CAN. The solubility of a mineral fertilizer depends on its type (Millar et al. 2010). CAN is one of the readily soluble N fertilizers. $NH_4^+$ stimulates the activity of nitrifiers in soils (Khan et al. 2007). Nitrifiers are obligate chemolithoautotrophs as they use $NH_4^+$ as an energy source instead of organic material. The divergence of the $NH_4^+$ and $NO_3^-$ contents in the second half of the experiment indicates the onset and ongoing of nitrification.

The amendment of composts, be it SWC or BWC, resulted in considerably lower $N_2O$ flows due to the slow release of N from composts. This finding is in an agreement with the data of Dennis and Burke (2001). It is mainly due to high contents of cellulose and fiber (Pal et al. 2010), as well as of lignin (Tuomela et al. 2000) (Table 1). Organic N mineralization of SWC stopped at the 15th day of incubation. N concentration in SWC amended soil is low and with low $N_2O$ emission. Mixing of straw is an effective strategy to avoid excess $NO_3^-$ and to reduce greenhouse gas emission (Shaojun et al. 2009) and nitrate leaching (Eghball et al. 1997).

Because of the small proportion of readily mineralizable N in composted manures, organic N is less likely to be released quickly. The developing microorganisms require more N than the substrate provides. In compost amended soil, the mineral-N pool was constant until the end of the incubation, reflecting the gradual mineralization and utilization of mineral-N by microbes (Deenik 2006).

The TOC contents of the CAN amended soil (0.81 %) were similar to that of the manure amended soil in the beginning. CAN application has an impact on the activity

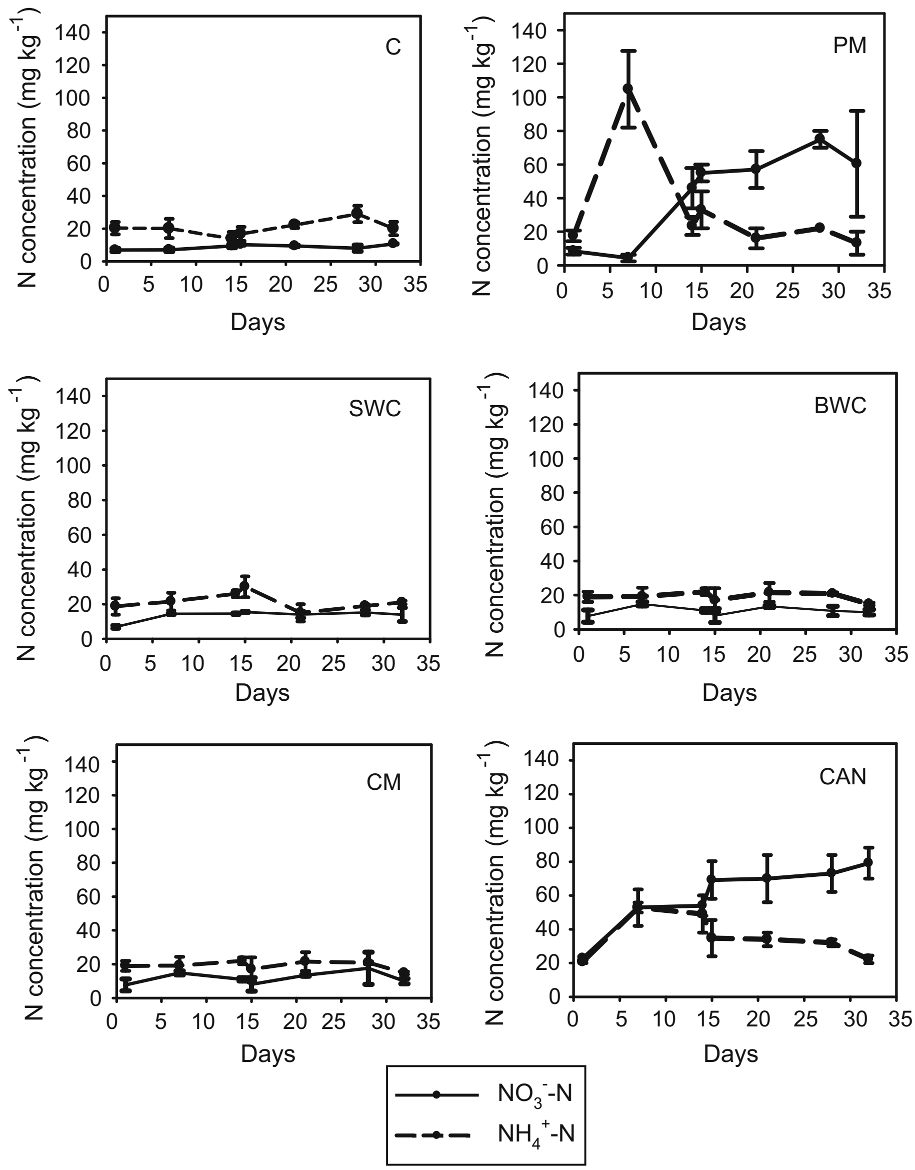


**Fig. 6** Temporal dynamics of mineral N (mg kg$^{-1}$) after amendment. *Filled circles* denote the means of three replicates with standard error bars

of nitrifying bacteria and subsequent N transformations (Watson et al. 1995). The course of mineralization of PM amended soil resembled that of the CAN amended soil, but that of CM did not.

## Nitrogen content of manures

Nitrogen content of poultry manure was found to be lower than that of cow manure (Table 1). It is a general finding (Kaur et al. 2005) that the total N content of poultry manure is higher than that of cow manure. The poultry manure used in this study was collected from layer poultry cages. Layer poultry manure contains lower N content than that from broilers and turkeys (Menzi et al. 1998). The cow manure was collected directly in cow houses. Within the dairy cow group, calves, heifers, lactating cows, dry cows and veal calves will show variations with regard to their N content of manure. The nutrient content of manures varies with type of animal, bedding material, storage, and processing (Rosen and Bierman 2005).

There are still some gaps in the scientific understanding of the factors controlling nutrient composition (especially N), handling of manure and its long term efficiency in northern and central Europe (Menzi et al. 1998). The C/N ratio of the cow manure was much lower (Table 1) than previously calculated by Rynk (1992) and Hills (1979), i.e. 19 and 8. It was lower than the C/N ratio of the decomposers. Soil microorganisms have a C/N ratio of approximately 8. They must acquire enough C and N from the environment in which they live to maintain the C/N of their bodies (USDA 2011). A high C/N ratio means that N will be exhausted before the C is digested by the bacteria as an energy source. Conversely, a low C/N ratio results in high $NH_4^+$ concentrations which may become toxic to the anaerobic bacteria (Homan et al. 2013).

### Soil pH as an influencing factor of denitrification

The application of compost leads to a decrease of soil pH. Ano and Ubochi (2007) found a significant decrease of soil pH (by one unit) after compost application because of the release of fulvic and humic acids (Tuomela et al. 2000). The decrease of pH with PM was similar (Fig. 7). In CM, it declined negligibly due to uric acid (Nahm 2003). This effect of cow manure is known to be due to its buffering agents, such as carbonates and organic matter. Risse et al. (2006) found that soil pH of plots receiving mineral fertilizer increased by half a unit (5.2–5.6). This supports the results of the current study, which showed a similar increase of pH in the CAN treatment. $N_2O$ emission from CAN treated soils decreased regardless of the increase in pH insinuates that the decrease in soil pH in the treatments with organic amendments was not the limiting factor of $N_2O$ emission. Denitrification is not only positively correlated with soil pH, but several other factors exert an influence, such as abundance and kind of denitrifiers (Lakha et al. 2009). The ultimate low $N_2O$ emission rate can be credited to the decline or declined activity of the denitrifier population with the passage of time (Nemeth 2012). Although the trends of pH are different, PM and CAN amendment leads to a comparable reaction regarding the process of nitrification and the course of $NO_3^-$ concentrations. Tarre et al. (2004) also observed a high nitrification rate despite a low pH.

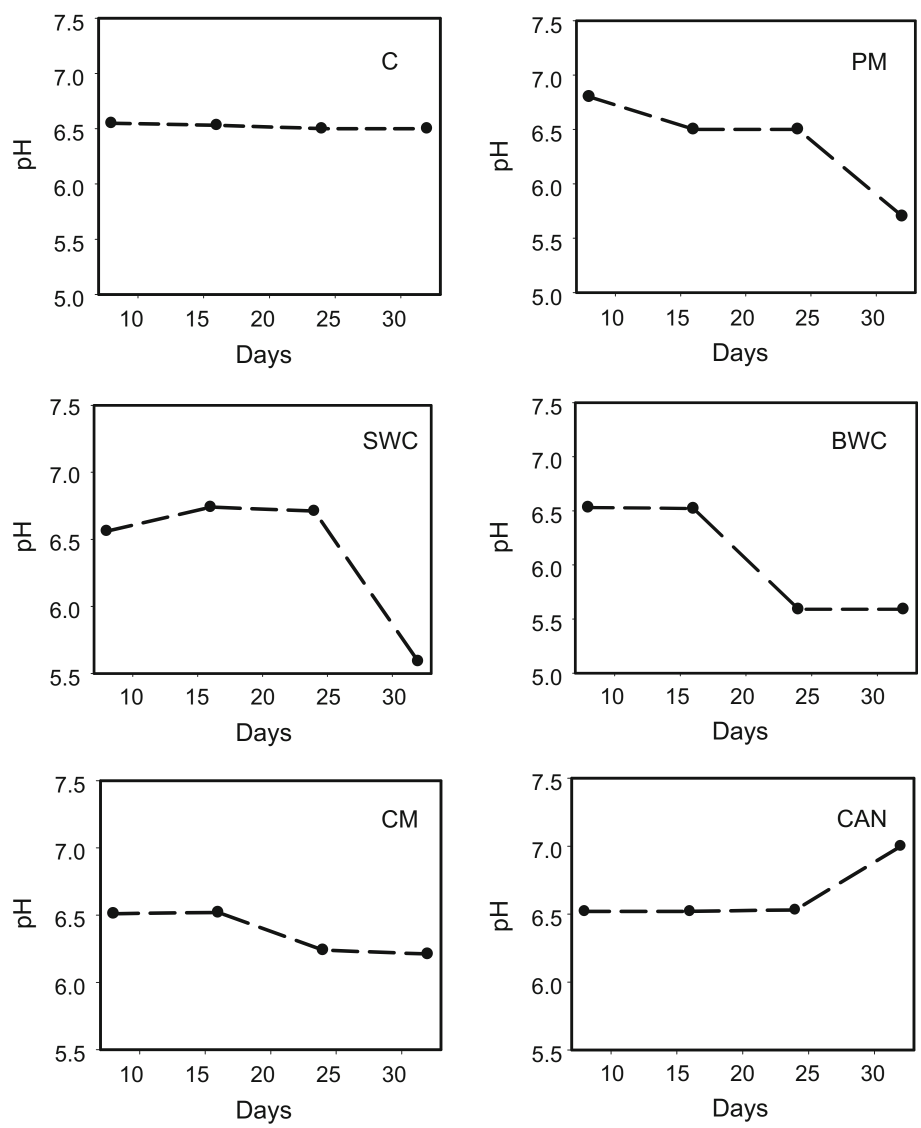


**Fig. 7** Soil pH (0.01 M $CaCl_2$) after amendment. *Filled circle* denotes the individual value

### Efficiency of manures and composts in sequestering C

The slow degradability of sheep and wheat straw compost is the result of high lignin content (Table 1) which becomes even higher in the composting process (Leifeld et al. 2002). Co-composting with wheat straw, which is a relatively slow releasing material has been suggested as a mitigation practice for $N_2O$ (Kariyapperuma et al. 2012). Organic residues, either as manures (green or animal) or composts are added to the soil as a source of organic matter (Bot and Benites 2005). Organic matter with low C/N ratio provides larger amount of readily mineralizable N substrate for microbial $N_2O$ production (Kawabata et al. 2010). In the end of the experiment, only sheep manure and wheat straw compost had sequestered C significantly. It can be concluded that the bio-degradable portion of organic C of the mentioned compost was not high enough. An other explanation is in the maturity of compost (Biala 2011). The sheep and wheat straw compost was more mature (1 year) than the bio-waste compost (3 months). On the other hand, the application of sheep manure alone has also been reported to increase organic matter and cation exchange capacity of soil (Dong and Shu 2004). The sheep manure exchanges $NH_4^+$ with other cations and retains nutrients in soil. For soil C sequestration strategies to be effective in the long-term, it is likely to increase the slow and passive pools of soil organic matter (Franzluebbers and Stuedemann 2002). Further research is recommended to compare sheep manure application with composted sheep manure regarding CEC efficiency and reduction of $CO_2$ and $N_2O$ emissions.

The results obtained were in line with the hypothesis suggesting that manures contain different easily soluble C and N fractions. The small proportion of readily mineralizable N in some manures suggests that the organic N in these manures may be more strongly bound and is less likely to be released quickly. In our investigation, all organic residues had C/N ratios less than 20. The higher net $NH_4^+$ mineralization of the poultry manure treatments might be explained by a higher specific mineralization rate, probably related to a higher decomposability and low C/N ratio of poultry manure. Organic residues are applied to the soil as a source of N and require a reasonable understanding to predict the mineralization of organic N compounds.

## Conclusion

The use of composts has decelerated not only N mineralization and $N_2O$ flow, but it also decreased soil pH, which could slow down nitrification. The practice of applying composts with such low C/N ratios could be advantageous for soils with moderate to high pH, but it is not recommended for soils with pH below 7. Application of PM has emitted significantly more $N_2O$, but still less than 1 % of applied N. PM showed fast mineralization, but it considerably reduces soil pH which again is not suitable for acidic or neutral soils. CM and BWC emitted significantly more $CO_2$ indicating higher mineralization, which, in principle, could enhance denitrification.

Not only composts but also poultry manure reduced soil pH; this will slow down the nitrification process and can reduce rapid $NO_3^-$ losses through leaching. Cow manure stabilized soil pH. Whalen et al. (2000) reported that application of cow manure increased pH of acid soils. Soils with low organic matter and N content and high pH can be improved by cow manure application lowering soil pH and increasing N content to fulfill crop requirement. Cow manure application to soil as a fertiliser and organic matter source is the most adopted agricultural technology by developing countries.

Animal manure applications are anticipated to supplement soil organic matter and augment total N content, which was not evident in our study (Fig. 5). Total C increased after amendment with SWC, but not BWC. There is little specific research on $N_2O$ and $CO_2$ flows after compost application in farming systems. Further studies with a wide variety of C/N ratios are required to evaluate composts and their application rates under laboratory and field conditions.

## Recommendations

- It is recommended to avoid direct application of animal manure to the soil.
- Co-composting of cow and poultry manures with wheat straw or rice-husk (with high lignin) are advantageous to reduce N losses from soil.
- Co-composting of bio-waste with wheat straw reduces $N_2O$ and $CO_2$ losses.
- Residual effects of manures and composts (Ginting et al. 2003) should be evaluated under laboratory and field conditions.
- Applying composts with low C/N ratios to the field is more effective than applying manures with low C/N ratios.

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