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The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali

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Abstract

The yield and flux of nitrous oxide (N_2O) emitted from continuous cereals (with and without urea), legumes/cereal in rotation and cereal/legume in rotation all with or without organic manure was monitored from January 2004 to February 2005. All treatments except continuous cereals had phosphate added. The cereal grown July–October in 2003 and 2004 was pearl millet (*Pennisetum glaucum)* and the legume was a bean (*Phaseolus vulgaris*). The 10 m × 10 m plots were established in a semi-arid climate in Mali. The addition of organic manure and both inorganic fertilizers increased yield and N_2O emissions. Continuous cereals treated with both organic manure and urea emitted significantly less N_2O (882 g N/ha per year) than plots receiving no organic manure(1535 g N/ha per year). Growing N-fixing crops in rotation did not significantly increase N_2O emissions. This study supports the new practice of growing cereal and legumes in rotation as an environmentally sustainable system in semi-arid Mali.

Keywords: Crop yield, nitrous oxide, semi-arid soils, Africa, manure, tillage, on farm experiment

Introduction

The emission of greenhouse gases, and their implications for global warming, are important in the desert margins of Africa where climatic variability is particularly critical for livelihoods (Sanchez, 2000). Since 1988, the Intergovernmental Panel on Climate Change (IPCC) has reviewed scientific research and provided governments with summaries and advice on climate problems. This Panel has consistently called for additional information, especially from developing countries, in order to make more accurate predictions (IPCC, 2001; Ringius, 2002). Data are necessary to formulate sensible mitigation and adaptation policies, and to allow Africa to take advantage of the international funds established to support such policies (Beg *et al*., 2002; Bouwnam *et al*., 2002; Niles *et al*., 2002; Ringius, 2002; Dessai & Schipper, 2003).

There are a few reported studies of greenhouse gas emissions from soil in Africa. but most studies have either measured emission rates in the laboratory from soil collected in African countries (Dick *et al*., 2001, 2006) or measured emissions in the field for short periods (Leroux *et al*., 1995; Cofer *et al*., 1996; Levine *et al*., 1996; Zepp *et al*., 1996; Scholes *et al*., 1997; Serca *et al*., 1998; Otter *et al*., 1999; Andersson *et al*., 2002).

The prediction that the African agricultural sector will become more intensive through the use of biological nitrogen-fixing crops either in agroforestry systems, improved fallows or by the use of leguminous crops in rotation has led to the suggestion that the continent may become a larger emitter of nitrous oxide (N_2O) (Bagayoko *et al*., 2000; Alvey *et al*., 2001; Sanginga, 2003). Short-term laboratory studies have suggested that while the use of nitrogen-fixing trees in African plantations does increase N_2O emissions by up to four times (Dick *et al*., 2001), the same is not true for nitrogen-fixing crops (Dick *et al*., 2006). Long-term greenhouse gas monitoring studies of the new agricultural rotations *in situ* have not been reported.

The aim of this study was to determine the difference in N_2O emissions from field plots of continuous cereals, the most common land use in the parklands of Mali, and plots of the cereal/legume rotations recommended by regional researchers (Bationo *et al*., 1998; Bagayoko *et al*., 2000). The effects of adding organic manure and urea applied at

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commonly recommended rates were also monitored because they are known to increase N_2O emissions (Skiba *et al.*, 1998; Martin-Olmedo & Rees, 1999; Vallejo *et al.*, 2005).

Materials and methods

Study area

The site selected was close to the village of Siribougou, 35 km from the town of Ségou and about 250 km northeast of the Mali capital, Bamako. At the site the Tropical Soil Biology and Fertility Programme has sponsored a long-term experiment investigating improved water and nutrient management technology to sustain food production and reduce degradation in Sub-Saharan Africa. Three cropping systems were selected for this study (continuous cereals, legume/cereal and cereal/legume in rotation) and the effects of both organic manure (8000 kg dry matter/ha) urea (50 kg/ha) and 20 kg phosphate/ha) were monitored. Three farm fields were selected within a 500 m^2 area. The soils were typical alfisols with a sandy texture derived from polycycled and preweathered Continental Terminal sandstone bedrocks The organic matter content in the upper horizon (0–20 cm) is typically less than 0.5%. Each field was subdivided into 10 m × 10 m plots and one treatment randomly assigned to each plot. The legume/cereal rotation treatment commenced with the legume crop planted in July 2003 and the cereal planted the following July 2004, while the plots allocated to the cereal/legume rotation treatment were planted with the cereal in 2003 and the legume crop in 2004. The land was extensively grazed by cows, sheep and goats during the dry seasons of both years (May–September). N_2O emissions were monitored from January 2004 to February 2005.

The cereal grown in both years was pearl millet (*Pennisetum glaucum)* and the legume haricot beans (*Phaseolus vulgaris*). The pearl millet sown was a local variety improved at the Cinzana research station (Mali) named 'Totoniou'. It is adapted for low rainfall (400–800 mm) and has a growth cycle of 100–110 days. The yield potential is 2000 kg/ha. The haricot beans selected was an improved variety (IT89KD-245) from IITA, Nigeria locally called 'Sangaraka'. It is adapted to low rainfall (400–800 mm) with a growth cycle of 75–85 days. This variety has a yield potential of 1500–2000 kg/ha and a residue fodder yield potential of 2000 kg/ha. Crops were harvested and grain weights determined by ICRAF.

Dry organic and inorganic fertilizer was spread by hand between 8 and 12 July 2004. Organic fertilizer (cow dung and goat/sheep droppings, collected during the dry season) was spread at a rate of 8000 kg dry matter/ha and mineral fertilizer was spread at a rate of 50 kg urea/ha and 20 kg phosphate/ha. All plots were ploughed by oxen following manure application (10–14 July 2004) and the crop was sown by hand immediately after cultivation Throughout this paper continuous cereals cropping is denoted by Cer and the rotation treatments are denoted by the order of the rotation, i.e. CerLeg denotes the plots were sown with cereal in 2003 and leguminous crop in 2004. The additions of organic fertilizer, urea and phosphate are denoted by M, N and P respectively.

Nitrous oxide emissions

The measurement of emissions was established in two phases. Sixteen circular chambers (2 farms × 8 treatments) constructed of stainless steel (40 cm depth and 40 cm diameter) with a 3 cm flange were dug into the ground in January 2004 each enclosing an area of 0.126 m^2. A third field was included in February 2004 giving a total of 24 chambers (3 replicates × 8 treatments). The chambers remained in place throughout the measurement period except when the land was cultivated. They were replaced following cultivation and as near to the original position as possible. A secure fitting lid (43 cm diameter with 35 mm self adhesive draught) was held by four to six bulldog clips creating an airtight seal during measuring events.

Air samples (12 mL) were extracted from the headspace of the chamber (25.4 ± 0.5 L) via a 2 cm hole in the lid fitted with a grommet and a three-way air tight tap. Duplicate samples were collected monthly (after 1 h closure) during the dry season and more frequently during the wet season in evacuated glass vials (839/WGL; Labco Exetainer, Buckinghamshire, UK). Ambient air samples (2 per farm) were collected when sealing the chambers. Air temperature inside the chambers was recorded before closing and after opening.

The samples were analysed at CEH Edinburgh within 5–10 days of collection. N_2O concentration was determined using electron capture gas chromatography (Crompack CP9000A, London, UK). The N_2O flux was calculated as the product of the increase in N_2O concentration above ambient air and the volume of the headspace divided by the time the chamber was sealed and the soil surface area. The annual emissions were calculated from the arithmetic mean flux of the first 15 measurements (between January 2004 and January 2005) and converted to g N/ha per year.

Soil respiration

Carbon dioxide emission from the soil was measured once in January 2004 within 1–2 m of the chambers (2 per chamber), using the PP System EGM2 Soil Respiration probe – 8.

Soil analysis

Five soil samples (0–10 cm) were taken from around each of the 24 chamber sites in January 2004 (middle of dry season). The samples were air dried and bulked before analysis at CEH Edinburgh, by standard methods for soil NH_4^+ and NO_3^- extracted in 1 M KCl (Crooke & Simpson, 1971;

Henriksen & Slemar-Olsen, 1970). Loss on ignition (LOI) was used to determine soil carbon (C) (Rowell, 1994).

Statistical analysis

As the experiment was not balanced, a one-way ANOVA with a block effect (Field) and a treatment effect with levels to model the eight individual treatment combinations allows the use of contrasts (linear combinations of the treatment factor levels). These estimate individual effects and provide tests of statistical significance (Genstat 8, VSN International Ltd, Hemel Hempstead, UK). The contrasts use all the information available, e.g. for cereal, the cereal-only data are combined with data from the cereal in rotation plots. When necessary, data were log-transformed to meet assumptions of normal distribution and homogeneity of variance.

Results

Grain yield

The yields for each treatment and year are shown in Figure 1. The plots planted with haricot beans and receiving manure (LegCer + M + P-N) were the highest yielding in 2003 (1210 kg ha^{-1}), and continuous cereals plots receiving manure, urea and phosphate (Cer + M + P + N) were the highest yielding (830 kg ha^{-1}) in 2004 (Figure 1). Statistical analysis (Table 1) showed that there were significant differences in grain yield (cereal and bean) between the treatments both in the year prior to our gas flux measurements (2003) and the year we monitored them (2004). The addition of manure significantly increased yield by an average of 122 kg ha^{-1} in

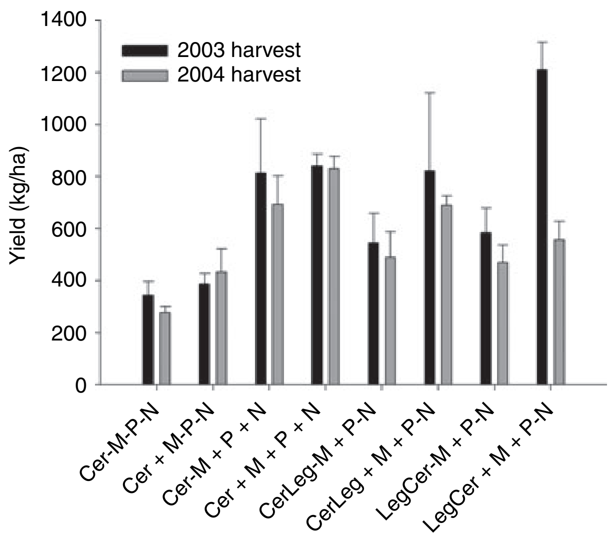

Figure 1 Average yield in four cropping regimes with or without added organic manure in each of 2 years (± SE). For key to treatments, see Table 1.

Table 1 Results of an ANOVA of grain yield (kg/ha) and estimated mean and standard error for each comparison (*F* probability values greater than 0.05 in bold; individual effects estimated using contrasts)

	Grain yield 2003			Grain yield 2004		
	F probability	Mean	SE	*F* probability	Mean	SE
Effect of manure (M)	**0.037**	122	52.7	**0.019**	72	27.3
Effect of phosphate (P)	**0.009**	195	64.5	**< 0.001**	141	33.5
Effect of urea (U)	0.358	71	74.5	**0.006**	124	38.7
Effect of cereal (Cer)	**0.043**	−136	60.8	0.472	−23	31.6
M × U	0.415	−63	74.5	0.751	12	38.7
M × P	0.681	27	64.5	0.742	−11	33.5
M × Cer	0.054	−128	60.8	0.571	−18	31.6

2003 and 72 kg ha^{-1} in 2004 (Table 1). The addition of phosphate similarly increased yield in both years (average increase of 195 and 141 kg/ha in 2003 and 2004 respectively). Urea gave no significant increase in yield in 2003 but increased yield in 2004 by an average of 124 kg/ha. The beans yielded significantly more than cereal crops in 2003 with an average increase of 136 kg/ha (Table 1). There were no statistically significant differences between crop yields in 2004.

Environmental variables

The ambient air temperature ranged between 22.2 °C in January 2004 to a maximum of 34.9 °C on 31 May 2004, just prior to the onset of the rains, and after the rains slowly climbed again during the following dry season to a maximum of 37.1 °C in November 2004 (Figure 2). The air temperature inside the chamber rose by an average of 2.4 ± 0.1 °C during the hour when the chamber was closed. The rainy period started on 29 May (Julian day 150) and stopped on 13 September (day 257). A total of 586 mm rainfall fell over the 136 day period but there was rain on only 36 days during this period (Figure 2). The maximum rainfall in any one day was 58 mm.

Soil-available NH_4^+ and NO_3^- and organic C content January 2004

Ammonium concentrations ranged from 0.9 to 5.6 μg N/g dry soil (Table 2). The addition of urea significantly (P = 0.035) increased the concentration of NH_4^+ by an average of 1.2 μg N/g (Table 3). Applications of manure to the plots in the previous October did not significantly increase NH_4^+ concentrations (Table 3). There was, however, a significant interaction (P = 0.027) between man-

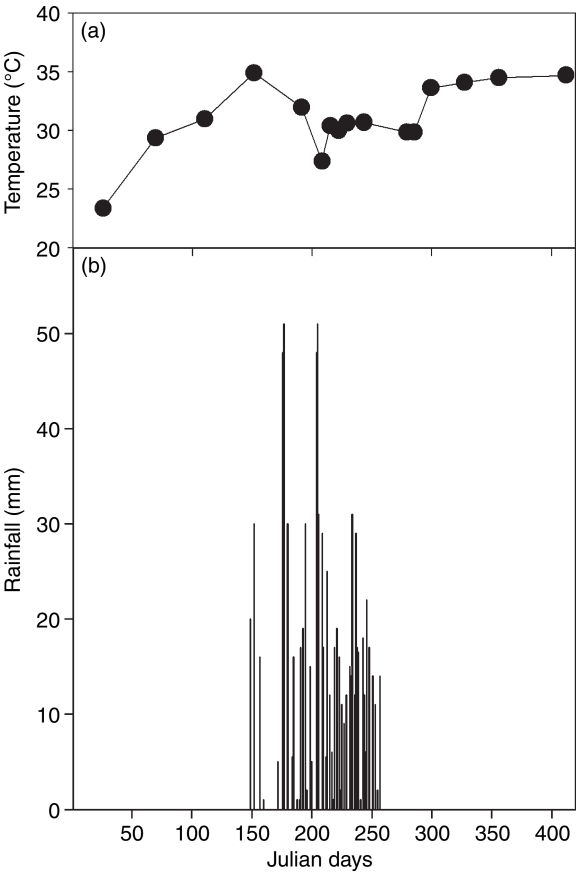

Figure 2 Air temperature at each of the 16 sampling periods and the daily rainfall pattern in 2004.

Table 2 Mean and standard error of ammonium and nitrate concentrations and carbon content of soil samples (0–10 cm) taken in January 2004 around each of the 24 nitrous oxide flux monitoring chambers

		NH_4^+ (µg N/g dry soil)		NO_3^- (µg N/g dry soil)		LOI (%)	
Manure	Treatment code	Mean	SE	Mean	SE	Mean	SE
No manure	Cer-M-P-N	1.09	0.27	1.26	0.40	0.16	0.013
	Cer-M + P + N	5.62	2.56	3.47	1.47	0.18	0.017
	CerLeg-M + P-N	0.86	0.41	0.51	1.72	0.14	0.021
	LegCer-M + P-N	1.96	0.22	2.20	0.16	0.18	0.008
Organic manure	Cer + M-P-N	2.42	0.05	2.33	0.07	0.19	0.017
	Cer + M + P + N	1.14	0.21	0.71	0.08	0.16	0.013
	CerLeg + M + P-N	1.28	0.46	0.52	0.25	0.16	0.015
	LegCer + M + P-N	1.98	0.20	1.82	0.29	0.20	0.023

LOI, loss on ignition. For key to treatments, see Table 1.

ure and urea application. The plots receiving both manure and urea had a lower (−1.2 µg N/g dry soil) than expected NH_4^+ concentration. A similar trend in NO_3^- concentrations was observed but was not statistically significant (Table 3). Nitrate concentrations ranged from 0.51 to 3.47 µg N/g dry soil (Table 2). There was no significant treatment effect on soil C. Organic carbon as measured by LOI, was low in all soils (0.16–0.20% C).

Table 3 Results of an ANOVA on NH_4^+ and NO_3^- concentrations in soil estimated mean and standard error for each comparison (*F* probability values greater than 0.05 in bold; individual effects estimated using contrasts)

	NH_4^+			NO_3^-		
	F probability	Mean	SE	*F* probability	Mean	SE
Effect of manure (M)	0.269	−0.40	0.35	0.475	−0.21	0.28
Effect of phosphate (P)	0.595	0.23	0.43	0.489	−0.25	0.35
Effect of urea (U)	**0.035**	1.16	0.49	0.072	0.79	0.40
Effect of cereal (Cer)	0.671	0.17	0.40	0.28	−0.37	0.33
M × U	**0.027**	−1.23	0.49	0.108	−0.69	0.40
M × P	0.071	−0.84	0.43	0.103	−0.61	0.35
M × Cer	0.796	−0.11	0.40	0.674	−0.14	0.33

Soil respiration and nitrous oxide emissions January 2004

There was a direct relationship ($P = 0.007$) between soil respiration and N_2O flux during the dry season in January 2004 (Figure 3). The plots treated with urea and phosphate (Cer-M + P + N) produced the highest flux of both N_2O and CO_2. There was a significant residual effect of the urea applied in July 2003 on both N_2O and CO_2 emissions (Table 4). On average, the addition of urea increased N_2O and CO_2 emissions by 4.0 µg N_2O-N m^2/h and 0.012 g CO_2 m^2/h respectively. There was also a significant interaction ($P = 0.05$) between the plots which had received urea and organic manure with the addition of manure significantly depressing soil respiration (Table 4). N_2O flux was also lower but the interaction term was only significant at the 0.1% probability level.

There was a significant linear relationship between mineral N and C content of soil and the flux of both CO_2 and N_2O (Figure 4). The relationship between N_2O flux and soil N and C was strongly influenced by the cereal plus urea treatment (Cer-M + P + N). In January 2004, a high emission of both CO_2 and N_2O was associated with large total nitrogen and C content in the soil.

Nitrous oxide flux measurements

All treatments had broadly similar patterns of N_2O emissions during the year (Figure 5). There were increases (45–80%) in

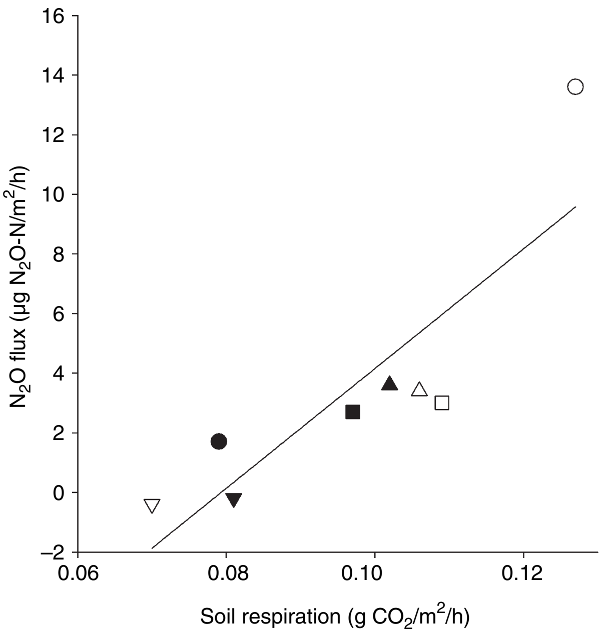

Figure 3 Linear regression between soil respiration and N_2O flux measured in January 2004 ($r^2 = 0.73$). Data are averages for (i) continuous cereals (square) (ii) cereals + 50 kg/ha urea (circle) (iii) cereal/legume rotation (down triangle) and (iv) legume/cereal rotation (up triangle). Closed black symbols denotes treatments with manure, open symbols represent treatments without manure.

Table 4 Results of an ANOVA on soil respiration and N_2O flux and estimated mean and standard error for each comparison (*F* probability values greater than 0.05 in bold; individual effects estimated using contrasts)

	Soil respiration ($g\ CO_2\ m^2/h$)			N_2O flux ($\mu g\ N_2O$-$N\ m^2/h$)		
	F probability	Mean	SE	*F* probability	Mean	SE
Effect of manure (M)	0.114	−0.0076	0.004	0.217	−1.5	1.1
Effect of phosphate (P)	0.087	−0.0103	0.005	0.770	0.4	1.3
Effect of urea (U)	**0.014**	0.0199	0.006	**0.036**	4.0	1.5
Effect of cereal (Cer)	0.217	−0.0066	0.005	0.982	0.0	1.3
M × U	**0.050**	−0.0143	0.006	0.092	−3.0	1.5
M × P	0.068	−0.0112	0.005	0.332	−1.4	1.3
M × Cer	0.947	0.0003	0.005	0.430	−1.1	1.3

For key to treatments, see Table 1.

emissions just before the onset of measurable rain (Julian day 150) in seven of the eight treatments. The exception to this pattern was an average 25% reduction from Cer-M + P + N, (not statistically significant – Table 5). The reduction in this treatment was caused by the single plot on Field 1, which had a very high emission rate (93 μg N_2O-N m^2/h) in the previous sampling period followed by a considerably lower emission (30 μg N_2O-N m^2/h) at the onset of the rainy period. At the onset of the rainy period the largest emission peak of 52.0 μg N_2O-N m^2/h was from the Cer + M-P-N treatment. The peak associated with the first rain had diminished by the next sampling period (40 days later). At the onset of the rainy period manure increased N_2O emissions by an average of 2.9 μg N_2O-N m^2/h and phosphate reduced emissions by an average of 6.85 μg N_2O-N m^2/h (Table 5). The application of urea did not significantly influence emissions. However, the interaction between urea and manure was significant ($P = 0.012$) depressing N_2O emissions by an average of 4.2 μg N_2O-N m^2/h. The millet crops produced significantly more emissions (average 4.3 μg N_2O-N m^2/h) than the bean crops at the onset of the rain (Table 5).

There was a similar increase in N_2O emissions (34–86%) following ploughing (Julian days 191). Ploughing was followed by a more intensive measurement period during which emissions from the CerLeg + M + P-N peaked at 59.4 N_2O-N m^2/h (Figure 5). The millet crops again emitted significantly more N_2O (average 3.1 N_2O-N m^2/h) than the leguminous crops (Table 5). The manure also significantly increased emissions by an average of 2.36 μg N_2O-N m^2/h (Table 5). There was a significant positive interaction between the addition of organic manure and urea ($P = 0.023$) and between organic manure and cereal crops ($P = 0.014$).

Discussion

Grain yield

The yield of pearl millet and beans reported in this study is similar to the values reported in other studies in the region. For example, Snapp *et al.* (1998) compared the yield of five varieties of bean on a farmer's field in central Mali. They applied 20 kg/ha urea plus or minus 30 kg/ha triple superphosphate and reported an average for all five varieties of 650 and 430 kg/ha for the two study years without additional P and 1020 and 760 kg/ha when P was added. Similarly, the pearl millet yields in this study ranged from 300 to 800 kg/ha and are typical of on farm studies in the Sahel (de Rouw & Rajot, 2004). However, these yields are considerably lower than the 2000 kg/ha reported by IITA, Nigeria or Cinzana Agronomic Research Station, Mali, for the same varieties grown. Similarly, Kouyate *et al.* (2000) reported harvests of between 750 and 1150 kg/ha continual pearl millet production for a 6-year period at the Cinzana Agronomic Research Station, Mali. The increased productivity of research stations, which usually have higher soil fertility, is recognized in the region (de Rouw & Rajot, 2004).

The rotation of millet and haricot beans increased millet yield compared with continuous millet, although only in the

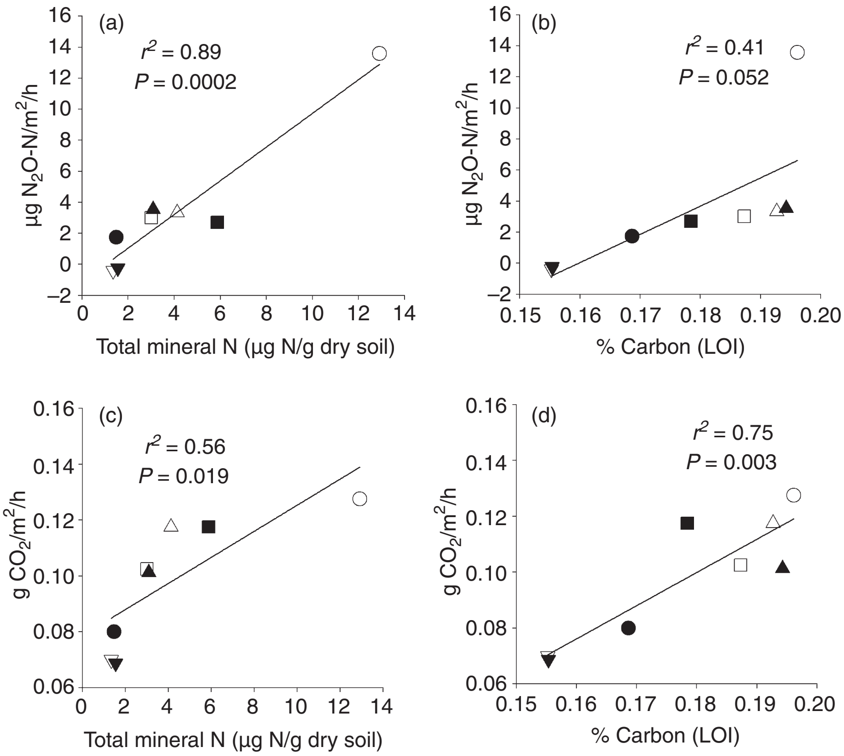

Figure 4 Linear regressions between mineral nitrogen and carbon content of soil and N_2O (a, b) and CO_2 flux measured in January 2004 (c, d). Data are averages for (i) continuous cereals (square) (ii) cereal + 50 kg/ha urea (circle) (iii) cereal/legume rotation (down triangle) and (iv) legume/cereal rotation (up triangle). Closed black symbols represent treatments with manure, open symbols represent treatments without manure.

first year was the increase statistically significant. This increase accords with that reported in Mali over an 8-year period (Kouyate *et al.*, 2000). As in our study the authors found annual variation resulting in cereal grain yield increases ranging from −2% to 92% depending on growing conditions. Similarly, manure and N and P has been found to significantly increase yields of both pearl millet and haricot beans in semi-arid parts of the region (Snapp *et al.*, 1998; de Rouw & Rajot, 2004).

Field trace gas fluxes

Nitrous oxide production is controlled by many factors which either directly or indirectly influence nitrifying and denitrifying bacteria (Potter *et al.*, 1996; Freney, 1997). In our study, rainfall, manure, urea, phosphate and tillage affected N_2O emission. It is well known that manure and inorganic fertilizers increase N_2O emissions (Skiba *et al.*, 1997; Pinto *et al.*, 2004; Vinther *et al.*, 2004). In this study manure increased both grain yield (42% in 2003 and 30% in 2004) and N_2O emissions (15% in 2004). The increase in yields and N_2O emissions was associated with increased total N content of the soils (Davidson, 1991; Skiba *et al.*, 1998; Diez *et al.*, 2004).

Although the main factors influencing N_2O production were as expected, an interaction between manure and inorganic fertilizers was not expected. The statistical analysis indicates that the application of urea, phosphate and manure together significantly reduced the emissions of N_2O, soil respiration rates and soil-available NH_4^+ in the dry season following application. This finding is counterintuitive and at variance with other studies which have combined manure and inorganic fertilizers (Dittert *et al.*, 2005). The mechanism responsible for this effect is not clear. One study conducted on a low organic C agricultural soil (0.8%) in Spain also reported that the application of a range of organic fertilizers resulted in lower emissions of N_2O and NO, compared to emissions from adjacent soils only treated with urea (Vallejo *et al.*, 2005). The authors suggested that the addition of easily decomposable C compounds favours complete denitrification to N_2 and therefore reduced the emissions of N_2O and NO. Another possible explanation is that the simultaneous addition of easily available C and N to a soil deficient in C and N was more efficiently immobilized by the existing microbial biomass than when N alone was applied. This mechanism is supported by the decrease in soil respiration rate measured in the same treatment. Further work would be needed to decide between these two hypotheses. It should be borne in mind that as the organic matter was collected during the dry season little loss of C or N would have occurred prior to spreading.

The rates of soil respiration measured in January 2004 were typically low and similar to those reported by Hall *et al.* (2006) for the same time of year in a continuous cropped plot in Mali. A recent review of CO_2 efflux from soils distinguished five important biogenic sources: root respiration, rhizo-microbial, decomposition of plant residues, the priming effect induced by root exudation and basal

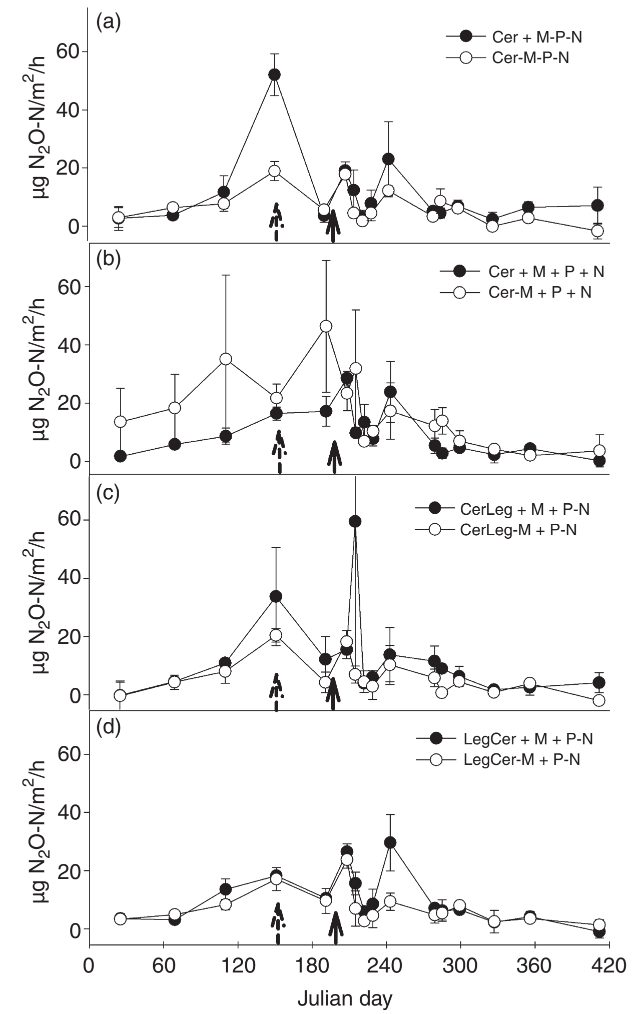

Figure 5 Emission of N_2O from four cropping treatments (for key to treatments see Table 1), with and without manure application (open and closed symbol respectively). Onset of measurable rains denoted by broken arrow and the solid arrows denote when the fields were ploughed (tilled).

respiration produced by microbial decomposition of soil organic matter (Kuzyakov, 2006). In our study the latter source is considered the most important as there was extremely sparse vegetation cover at the end of the dry season.

Pulsing effect

Biogeochemical cycles in arid and semi-arid ecosystems depend upon the ability of soil microbes to respond to the sudden availability of resources. Brief periods of high activity generally occur after precipitation that provides access to nutrients for soil organisms. Such a stimulation of N_2O emissions, known as the 'Birch effect' (Birch, 1958) or 'pulsing', is caused by the reactivation of water-stressed bacteria following a dry period which readily decomposes and mineralizes the labile organic matter fraction in the soil. There was an increase (45–80%) in N_2O emission at the onset of the rains. Such an increase in emissions following wetting and drying cycles in African soils has been measured in many studies both in the laboratory and in the field with natural rainfall events and artificial irrigation (Scholes *et al*., 1997; Dick *et al*., 2001, 2006; Andersson *et al*., 2002; Breuer *et al*., 2002).

Table 5 Results of an ANOVA on N_2O flux (μg N_2O-N m^2/h) at the onset of the rains (Julian day 150) and immediately following ploughing (Julian day 191) and manure application – estimated mean and standard error for each comparison (*F* probability values greater than 0.005 in bold; individual effects estimated using contrasts)

	Rainfall			Tillage/manure		
	F probability	Mean	SE	*F* probability	Mean	SE
Effect of manure (M)	**0.014**	2.9	0.8	**0.033**	2.4	0.9
Effect of phosphate (P)	**< 0.0001**	−6.8	0.9	0.260	1.4	1.2
Effect of urea (U)	0.589	0.6	1.1	0.100	−2.4	1.3
Effect of cereal (Cer)	**0.005**	4.3	0.9	**0.019**	3.1	1.1
M × U	**0.012**	−4.2	1.1	**0.023**	3.6	1.3
M × P	**0.001**	−6.3	0.9	0.232	1.5	1.2
M × Cer	0.787	0.3	0.9	**0.014**	3.3	1.1

For key to treatments, see Table 1.

The magnitude of emission prior to the pulse was similar to that measured by Andersson *et al*. (2002) in Ghana during the dry season in January (0–1.56 μg N_2O-N m^2/h) compared with −0.2 to 3.4 μg N_2O-N m^2/h for most of the treatments in this study. As for all nitrogen-cycling processes, the spatial heterogeneity of nitrogen flux from terrestrial ecosystems is large (Smith *et al*., 1994; Leroux *et al*., 1995; Christensen *et al*., 1996; Lafolie *et al*., 2005).

Tillage effect

Similar to the effect of rainfall, N_2O emissions increased by 34–86% following soil tillage. The release of N_2O following ploughing has been observed in several studies (Skiba *et al*., 1992, 2002; Estavillo *et al*., 2002; Vellinga *et al*., 2004). It is believed that when soil is disturbed by tillage, organically bound C and N are released, providing substrates for nitrifying and denitrifying micro-organisms (Skiba *et al*., 2002; Pinto *et al*., 2004).

Annual emissions

Compared to continuous millet with no additional fertilizer (595 g N_2O-N/ha per year) we found a 158% increase in annual N_2O emission (Table 6) from continuous cereals with added urea (1535 g N_2O-N/ha per year) and a 63% increase

Table 6 Estimated average annual emissions of N_2O from eight treatments, (estimated from the average flux of 15 measurements between January 2004 and January 2005

Manure	Treatment code	Estimate of annual emission of N_2O (g N ha per year)
No manure	Cer-M-P-N	595
	Cer-M + P + N	1535
	CerLeg-M + P-N	556
	LegCer-M + P-N	635
Animal manure	Cer + M-P-N	972
	Cer + M + P + N	882
	CerLeg + M + P-N	1149
	LegCer + M + P-N	917

For key to treatments, see Table 1.

with added manure (972 g N_2O-N/ha per year). While the addition of manure did increase N_2O emissions, our results support Seneviratne (2001), who after reviewing a range of mitigation strategies for tropical agriculture concluded that the recycling of organic materials, rather than the use of inorganic fertilizer, was the most feasible, realistic and immediately applicable option both for mitigating N_2O emission and boosting food production.

The UNFCCC database reports that for the year 1995 the total N_2O emission from arable soils in Mali was 1.65 Gg. We estimate that the average annual emission for continuous cereals without addition of organic manure – the most common agricultural practice in Mali – is 595 g N/ha per year. Assuming 3 37 9000 ha of arable land in Mali in 1995 (FAO statistic: http://faostat.fao.org) the annual emission of N_2O from our calculations would be 3.16 Gg N_2O. Given the inaccuracies in these calculations we consider that these two estimates do not differ to a significant extent.

Contrary to IPCC-recommended Tier I methodology (Freney, 1997) for estimating national emissions, we did not find that growing leguminous crops in the C and N-poor soils of Mali increased soil emissions of N_2O significantly compared with continuous cereals cropping. This supports earlier laboratory experiments, using agricultural soils from Senegal, which found no significant increase in N_2O emissions associated with leguminous crops (Dick *et al.*, 2006). Growing cereal and legumes in rotation is recommended as a new technology in many semi-arid regions of West Africa (Bationo *et al.*, 1998; Bagayoko *et al.*, 2000; Alvey *et al.*, 2001). Our results would suggest that this practice does not increase the emission of N_2O to the atmosphere.

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