

# Combining organic and inorganic nitrogen fertilisation reduces N<sub>2</sub>O emissions from cereal crops: a comparative analysis of China and Zimbabwe

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**Abstract** Agriculture is one of the major sources of nitrous oxide (N<sub>2</sub>O), a potent greenhouse gas (GHG) whose atmospheric concentrations are estimated to increase with efforts to increase food production through increasing nitrogen (N) inputs. The objective of this study was to quantify N<sub>2</sub>O emissions from maize (*Zea mays L.*) and winter wheat (*Triticum aestivum L.*) fields amended with inorganic, organic N and a combination of both sources (integrated management), in tropical (Zimbabwe) and temperate (China) climatic conditions. In Zimbabwe N<sub>2</sub>O emissions were measured from maize plots, while in China emissions were measured from maize and winter wheat plots. In Zimbabwe the treatments were; (i) Control, (ii) 60 kg N ha<sup>-1</sup> ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>), (iii) 120 kg N ha<sup>-1</sup> NH<sub>4</sub>NO<sub>3</sub>, (iv) 60 kg ha<sup>-1</sup> cattle (*Bos primigenius*) manure-N, plus 60 kg N ha<sup>-1</sup> NH<sub>4</sub>NO<sub>3</sub>, (v) 60 kg N ha<sup>-1</sup> cattle

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manure-N, and (vi) 120 kg N ha<sup>-1</sup> cattle manure-N. In China, treatments were; (i) Control, (ii) 300 kg N ha<sup>-1</sup> Urea, (iii) 92 kg N ha<sup>-1</sup> Urea plus 65 kg ha<sup>-1</sup> chicken (*Gallus domesticus*) manure-N, (iv) 100 kg N ha<sup>-1</sup> Urea and (v) 100 kg N ha<sup>-1</sup> control release Urea. Our results showed that under both temperate and tropical conditions, integrated nutrient management resulted in lower N<sub>2</sub>O emissions compared to inorganic fertilizers which had higher total and yield-scale N<sub>2</sub>O emissions. We conclude that by combining organic and inorganic N sources, smallholder farmers in both China and Zimbabwe, and other countries with similar climatic conditions, can mitigate agricultural emissions without compromising productivity.

**Keywords** Mitigation · Nitrous oxide · Organic and Inorganic N · Smallholder farming systems

## 1 Introduction

Nitrous oxide, an intermediate product of microbial processes such as nitrification and denitrification, is a potent greenhouse gas (GHG) that has a global warming potential 298 times higher than carbon dioxide over a 100 year period (IPCC 2007). Globally, agriculture is the main contributor of anthropogenic N<sub>2</sub>O emissions (~60 %), mainly from N inputs in mineral fertilisers, manures and crop residues to crop and soil systems (Smith et al. 2007; Snyder et al. 2009). In arable soils, the magnitude of soil N<sub>2</sub>O emissions depends on several factors including N fertilization rates and type (Mosier et al. 1998) and soil properties such as soil aeration, temperature and carbon availability (Novoa and Tejeda 2006; Ruser et al. 2006; Chirinda et al. 2010). Inefficiencies in N utilization increase susceptibility of N to loss as N<sub>2</sub>O, and constitute a loss of money for the farmer. Managing agricultural systems to maximize N efficiency is therefore a promising strategy for mitigation of greenhouse gas emissions from agriculture (Smith et al. 2007).

Fertility management as a greenhouse gas mitigation strategy will differ according to crop, climate, and current agricultural practices and policies. In the current study we investigated the potential of combining organic and inorganic fertilizers on N<sub>2</sub>O emissions in two locations, Zimbabwe and China. These two sites typify opposite ends of the spectrum in terms of current nitrogen management practices. In Zimbabwe, crop production is conducted within a context of seasonally dry tropical conditions and low fertilizer inputs (as low as 15 kg N ha<sup>-1</sup>), because fertilizer purchase prices make them unaffordable to most smallholder farmers (Nyamangara and Nyagumbo 2010). Both the typically dry conditions and low fertilizer application rates constrain soil N<sub>2</sub>O emissions from arable soils in Zimbabwe (Wuta 2003; Mapanda et al. 2010). Low soil N contents may in fact lead to soils becoming net sinks of N<sub>2</sub>O (Glatzel and Stahr 2001; Chapuis-Lardy et al. 2007). Current yields of maize (*Zea mays L.*), the staple crop in Zimbabwe, are also low: 1 Mg ha<sup>-1</sup> on average (FAO 2006), due largely to low soil fertility, low nitrogen inputs (Nyamangara and Nyagumbo 2010) and occasional droughts. The challenge in Zimbabwe is to increase soil fertility and crop yields in a way that does not substantially increase N<sub>2</sub>O emissions and further contribute to climate change. In contrast, smallholder farmers in the North China Plain (NCP) typically apply large amounts of N fertilizer (i.e., 550–600 kg N ha<sup>-1</sup> yr<sup>-1</sup>) (Ju et al. 2009), which far exceeds crop demand and potentially enhances the N<sub>2</sub>O source strength of arable soils in China (Li et al. 2001). In China crop production is carried out under warm and wet conditions in summer, cold and dry in winters. Yields are quite high (6 Mg ha<sup>-1</sup>) compared to Zimbabwe's smallholder farming area where yields are 1 Mg ha<sup>-1</sup> for maize on average (FAO 2006). The challenge in the NCP is to maintain these yields while reducing N<sub>2</sub>O emissions.

A potential mitigation strategy for both sites is to apply inorganic fertilisers in combination with manures or other organic nutrient sources. In areas such as Zimbabwe where soils have

low organic matter content and fertilizer use has historically been low, combining organic and inorganic nutrient sources could lead to improved nutrient and water retention and exchange capacity. This is expected to enhance resource (N and water) use efficiencies, reduce soil N concentration due the slow release of mineral N by cattle (*Bos primigenius*) manure and, consequently, reduce soil N<sub>2</sub>O emissions and also contribute towards high crop growth and productivity (Pan et al. 2009; Shi et al. 2013). In addition organic amendments will reduce nutrient leaching and release nutrient slowly, factors which all contribute towards increased crop productivity. In China, where N fertilization rates are already too high, a combination of organic and inorganic fertilizer sources could ensure controlled nutrient release during the growing seasons, ensure nutrient availability, thus improving crop N utilization and reducing the susceptibility of soil nitrogen to leaching and loss as N<sub>2</sub>O.

Unlike in China, there are very few studies that have explored N<sub>2</sub>O emissions from arable soils in Zimbabwe (Nyamadzawo et al. 2012). Moreover, there are few studies that have compared soil N<sub>2</sub>O emissions from different management practices and also explored the role of integrated nutrient management on soil N<sub>2</sub>O emissions across different climatic regions. The objective of our study was to quantify soil N<sub>2</sub>O emissions from maize and winter wheat (*Triticum aestivum* L.) fields amended with inorganic or organic nutrient sources as well as a combination of both organic and inorganic nutrient sources (integrated management), from smallholder farming systems under tropical (Zimbabwe) and temperate (China) climatic conditions.

## 2 Materials and methods

### 2.1 Study sites

Field measurements were conducted at one site in Zimbabwe and another in China. Descriptions of the study sites are given below.

### 2.2 Zimbabwe

At Domboshawa Training Centre, in Zimbabwe, a study of soil N<sub>2</sub>O emissions from maize fields was conducted during 2008/2009 growing season. The site is located 30 km north-east of Harare (17°42' S, 31°00' E) with a subtropical climate characterised by wet summers and dry winters. Mean annual temperature is 18.6°C and the mean annual rainfall is 750 mm. The soil at Domboshawa is sandy loam classified as Haplic lixisol (FAO 2006) (Table 1).

**Table 1** Soil physical properties at the study sites in China and Zimbabwe

	China	Zimbabwe
Clay (g kg <sup>-1</sup> )	140	40
Silt (g kg <sup>-1</sup> )	125	130
Sand (g kg <sup>-1</sup> )	735	830
SOC (g kg <sup>-1</sup> )	6.3	6.0
Total (g N kg <sup>-1</sup> )	0.41	0.8
pH	7.7	5.4
Bulk density (g cm <sup>-3</sup> )	1.5	1.7

N nitrogen, g grams, kg kilograms

### 2.2.1 Experimental design and soil sampling

The study at Domboshawa evaluated the effects of different inorganic and organic fertilizer treatments on N<sub>2</sub>O emissions from soils under maize (Mapanda et al. 2011). Prior to this study, the maize fields had been fallowed for at least 10 years. The fields were subjected to conventional tillage using an ox-drawn plough which disturbed the top 0–20 cm depth. After tillage, experimental plots (5 m×6 m) were laid out with six treatments arranged in a randomized complete block design with four replicates. The treatments were: (i) No amendments (control), (ii) Low inorganic N (NH<sub>4</sub>NO<sub>3</sub> applied at 60 kg N ha<sup>-1</sup>), (iii) High inorganic N (NH<sub>4</sub>NO<sub>3</sub> applied at 120 kg N ha<sup>-1</sup>), (iv) Integrated management, (cattle manure-N applied at 60 kg N ha<sup>-1</sup> and mixed with 60 kg N ha<sup>-1</sup> inorganic fertiliser in the form of NH<sub>4</sub>NO<sub>3</sub>), (v) Low manure (cattle manure-N applied at 60 kg N ha<sup>-1</sup>), (vi) high manure (Cattle (*Bos primigenius*) manure-N, applied at 120 kg manure-N ha<sup>-1</sup>) as shown in Table 3. Ammonium-nitrate fertilizer was applied at each sowing position at 60 and 120 kg N ha<sup>-1</sup> with 50 % at sowing and the remaining 50 % 6 weeks after sowing. Manure was applied in a strip at 5 cm from each planting row at planting at rates of 60 and 120 kg N ha<sup>-1</sup>. In all plots additional annual basal dressings of both P (as single super phosphate) and K (as muriate of potash) were each applied at rates of 30 kg ha<sup>-1</sup>. Prior to setting up the experiment, soil samples were collected from the 0–0.1 m depth using a Dutch auger and characterized for soil physical and chemical properties. At harvest maize yields were collected from 3×3 m net plots. Total maize grain yields were measured and adjusted to 12.5 % moisture content.

### 2.2.2 Soil analysis

Soils were characterized for texture, organic carbon and total N content. Specifically, soil organic carbon was determined using the modified Walkley-Black procedure (Nelson and Sommers 1992), texture was determined using the hydrometer or Bouyoucos method (Bouyoucos 1962), bulk density was measured using the clod method described by Blake and Hartge (1986), and total N was determined using the Kjeldahl method (Anderson and Ingram 1993).

## 2.3 China

A field trial was established in October 2008 at Agro-ecosystem Experiment Station of China Agricultural University, located in Huantai County, Shandong Province, North China Plain (NCP), (36°58' B, 117°59' E). The experiment was set up to evaluate the effects of different management regimes on soil N<sub>2</sub>O emissions in a winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.). The area has a temperate monsoon climate (warm and wet conditions in summer, cold and dry in winter). The annual air temperature is approximately 12.5 °C, and average annual precipitation is 543 mm. The soil of the experimental field (0–20 cm depth) is a sandy loam derived from alluvial sediments of the Yellow River and was classified as aquic inceptisol (Table 1).

### 2.3.1 Experimental design

The five crop management treatments were conventional (CON), three recommended regimes (REC-1, REC-2 and REC-3), and a control without fertilizer application (CK). Each treatment had four replicated blocks, and each block was 18 m wide by 25 m long. All plots were arranged in a randomized complete block design with four replicates. A detailed description of the treatments is given in Table 2. Triple super phosphate was applied in wheat in all treatments at sowing at a rate of 52 kg P ha<sup>-1</sup>. Potassium sulfate and zinc sulfate were also applied in

**Table 2** Tillage treatments in wheat and maize plots at the study site in China

Tillage	CON Conventional tillage	REC-1 Deep ploughing	REC-2 No tillage	REC-3 No tillage	Control (CK) Conventional tillage
Irrigation	Flooding	Reduced	Reduced	Reduced	Flooding
Residue management	Burning	Retained	Retained	Retained	Burning
Fertilizer rate and type	300 kg N ha <sup>-1</sup> Urea	92 kg N ha <sup>-1</sup> Urea	100 kg N ha <sup>-1</sup> Urea	100 kg N ha <sup>-1</sup> Control release Urea	None
Organic manures	None	65 kg N ha <sup>-1</sup> as Chicken (Gallus domesticus) manure (1.7 % N)	None	None	None

*N* nitrogen, *N* nitrogen, *g* grams, *kg* kilograms. *CON* conventional, (*REC-1* recommended regimes 1, *REC-2* recommended regimes 2 and *REC-3* recommended regimes 3, and *CK* a control without fertilizer application

maize at sowing at rates of 71 kg K ha<sup>-1</sup> and 15 kg ZnSO<sub>4</sub> ha<sup>-1</sup>, respectively, in all treatments except the control. The different fertiliser amendments were applied on 7 December a week before N<sub>2</sub>O measurements commenced. Maize yields were measured at physiological maturity by hand harvesting from 9 m<sup>2</sup> (3 m×3 m) net plots. Grain yields of the maize were corrected for moisture by oven drying to a constant weight (12.5 %).

### 2.3.2 Soil analysis

The bulk density of the soil was measured by the core method. Soil pH was measured from soil-water suspensions (1:5 *v/v*). Total soil C and N contents were determined with NC soil analyzer flash 2000 (Thermo Fisher Scientific, USA). For soil particle size distribution, sand fraction (0.02–2 mm) was measured by sieving, and the silt (0.002–0.02 mm) and clay (<0.002 mm) fractions were determined by the pipette method.

### 2.4 Soil N<sub>2</sub>O emission measurements

In Zimbabwe, N<sub>2</sub>O flux measurements were taken from maize plots using opaque static polythene chambers with a base area of 0.40 m×0.28 m and height of 0.5 m (Khalil et al. 1998; Rees et al. 2006; Mapanda et al. 2010). Each chamber had an airtight septum at the top through which samples were collected. Samples were collected with polypropylene syringe at time 0, 30 and 60 min intervals from 8–11 am. The chambers did not have fans to circulate the air, we assumed that the air would equilibrate after 30 and 60 min. Three chambers were randomly placed between rows for each treatment in maize plots. To reduce gas leakages from the chambers, the chamber edges were fastened using a small chisel and covered with surrounding soil, taking care not to disturb the chamber. Sampling was done five times during the growing season at 2 week intervals, from date of germination in maize.

In China, N<sub>2</sub>O emissions were measured using opaque static chambers whose base was fixed in the fields. The static chamber consisted of a square stainless steel base permanently installed between rows in the field, and a cover box with stainless frames and plastic panels covered with a layer of white film (0.5 m Length×0.5 m Width×0.5 m Height). The chamber cover box was fitted with a sampling outlet in the upper of the lateral plane and equipped with a circulating fan. Gas samples were taken with a 60 ml polypropylene syringe at 0, 8, 16, 24,

and 32 min after chamber deployment. Air temperature inside the chamber was monitored during gas collection (Liu et al. 2009; Yao et al. 2009). Gas sampling for flux measurements was performed between 9–11 am local time (Liu et al. 2011). Sampling was done once per day for a period of 1 week following fertilization and irrigation events. Subsequently, N<sub>2</sub>O flux measurements were performed twice per month between 14 December 2011 and 29 March 2012.

## 2.5 N<sub>2</sub>O analyses and data processing

Samples from Zimbabwe were analysed in the United Kingdom (UK) as there was no gas chromatograph (GC) available in Zimbabwe. Samples from maize plots were analysed for N<sub>2</sub>O emissions by gas chromatography (GC model: Hewlett Packard 5890, Series II, Avondale, PA, USA) at Scottish Agricultural College (SAC) in the UK. The shipment process was assumed to result in negligible changes in the N<sub>2</sub>O concentration of the samples. Batches of standard samples were also sent from the UK to Zimbabwe and returned (within 10 weeks), and the results showed that the concentrations of N<sub>2</sub>O were consistently between 92–100 % of the original values, with a mean of 98 % (Mapanda et al. 2011). In China, syringes containing gas samples were transported to the laboratory on the same day and analysed using a modified gas chromatograph (GC) Aglient-7820 (Aglient Company, Shanghai, China) equipped with an electron capture detector (ECD).

### 2.5.1 Flux calculations

N<sub>2</sub>O fluxes were calculated using linear regression as described by Khalil and Rasmussen (1998) and Ding et al. (2011) for the measurements made in Zimbabwe and China, respectively. The daily N<sub>2</sub>O fluxes were calculated by regressing measured N<sub>2</sub>O concentrations for each sampling date against time. Furthermore, cumulative fluxes were calculated from mean N<sub>2</sub>O emissions by linear interpolation between measurement days to obtain total N<sub>2</sub>O emissions per season.

## 2.6 Statistical analyses

Data of crop yield and N<sub>2</sub>O fluxes were analyzed for variance (ANOVA) using the Genstat Statistical package for Zimbabwe and SPSS 13.0 (SPSS Inc., Chicago, IL, USA) for China. For the data from Zimbabwe, the Kruskal-Wallis one-way analysis of variance was used, and a pair-wise separation of significantly different treatment means was done using the Mann-Whitney test because the data did not meet the assumptions of normality and homogeneity of variance. At each site, the least significant difference (lsd) was used to separate means where there were significant differences. A correlation analysis to determine possible linear relationships between different N inputs and N<sub>2</sub>O emissions was done using PROC CORR in SAS (Version 9.2, SAS institute, Cary, NC).

## 3 Results

### 3.1 Soil characteristics

At Domboshawa study site in Zimbabwe, the soils was classified as is Haplic lixisol derived from granite. The SOC was 6.0 g kg<sup>-1</sup>, total N content was 0.8 g N kg<sup>-1</sup>. At the study site in China the soil (0–20 cm depth) had 6.3 g kg<sup>-1</sup> SOC and a total N content of 0.41 g kg<sup>-1</sup>

(Table 1). The high C:N ratio of 15.3 for the sites in NCP may be attributed to charring of stover during land preparation.

### 3.2 Crop yields

In Zimbabwe, all of the plots receiving fertilizer had significantly higher yields than the control. Maize yields in the treatment that received 120 kg N ha<sup>-1</sup> inorganic N were similar to those in plots that received a combination of both inorganic and organic N (Table 3). The plot receiving 120 kg N ha<sup>-1</sup> as manure, however, had significantly lower yields than the plots receiving only inorganic and a combination of organic and inorganic fertilizers.

In China, during the maize phase, the REC-3 treatment gave the highest yields, at 8 % higher than the conventional treatment (Table 3). Treatments with reduced N application (REC-2) or where integrated nutrient management was used (REC-1) had yields which were not significantly different from the conventional (CON). During the wheat phase in the plots in China, the highest yield of wheat was obtained in REC-1 (62 kg N + 30 organic N), which had 9 % higher yield than the conventional treatment (Table 3).

### 3.3 N<sub>2</sub>O emissions

In Zimbabwe, the soil N<sub>2</sub>O emissions in plots amended with a combination of inorganic N and manure and manure alone were lower compared to those from soils amended with inorganic N

**Table 3** Measured soil N<sub>2</sub>O emissions, applied fertilizers, grain yields and yield-scaled N<sub>2</sub>O emissions from different management practices and crops in China and Zimbabwe for the 2008/2009 cropping seasons

Country	Treatment	Crop	Inorganic N kg N ha <sup>-1</sup>	Organic N kg N ha <sup>-1</sup>	N <sub>2</sub> O Emissions kg N <sub>2</sub> O-N ha <sup>-1</sup>	Yield Mg ha <sup>-1</sup>	Yield-scaled emissions g N <sub>2</sub> O-N kg <sup>-1</sup> yield
China	CK	Wheat	0	–	0.50 b	3,15 d	0.159 a
China	CON	Wheat	300	–	0.94 a	6,79 b	0.138 a
China	REC-1	Wheat	62	30	0.85 a	7,39 a	0.115 c
China	REC-2	Wheat	100	–	0.94 a	6,25 c	0.150 a
China	REC-3	Wheat	92	–	0.77 a	6,38bc	0.121 b
China	CK	Maize	0	–	0.45 c	6,13 c	0.073 b
China	CON	Maize	300	–	1.26 a	9,32 b	0.135 a
China	REC-1	Maize	129	65	0.72 b	8,93 b	0.081 b
China	REC-2	Maize	118	–	0.82 b	9,00 b	0.091 b
China	REC-3	Maize	188	–	0.84 b	10,08 a	0.083 b
Zimbabwe	Control	Maize	0	–	0.32 b	0.48 a	0.68 b
Zimbabwe	Low inorganic N	Maize	60	–	0.52 d	0.86 b	0.60 b
Zimbabwe	High inorganic N	Maize	120	–	0.41 c	1,54 c	0.27 a
Zimbabwe	Integrated	Maize	60	60	0.35 b	1,56 c	0.22 a
Zimbabwe	Low manure	Maize	–	60	0.26 a	1,08 b	0.24 a
Zimbabwe	High Manure	Maize	–	120	0.27 a	1,02 b	0.26 a

N nitrogen, g grams, kg kilograms. CON conventional, (REC-1 recommended regimes 1, REC-2 recommended regimes 2 and REC-3 recommended regimes 3, and CK a control without fertilizer application. N<sub>2</sub>O nitrous oxide. Same letter after numbers indicate lack of significant differences. Mg ha<sup>-1</sup> mega grams per hectare



(Table 3). An additional 0.19 and 0.08 kg N<sub>2</sub>O-N ha<sup>-1</sup> were emitted from plots amended with 60 and 120 kg inorganic N ha<sup>-1</sup>, respectively, when compared to the control (no N applied) or plots where integrated nutrient management (mixing cattle manure and inorganic N) was used (Table 3). In China, N<sub>2</sub>O emissions during the maize phase did not differ significantly between the four treatments, though they were all significantly higher than the CK treatment (no N fertilizer). During the wheat phase, the CON plot had the highest N<sub>2</sub>O emissions. The REC-1, REC-2 and REC-3 treatments did not differ from each other in terms of N<sub>2</sub>O emissions during the wheat phase, though they were all significantly lower than the CON treatment and higher than the CK treatment. There appeared to be a linear relationship between N fertilizer rate and N<sub>2</sub>O emissions in the China experiment ( $R^2=0.65$ ) (Fig. 1). However, for the study site in Zimbabwe, the correlation between N application and N<sub>2</sub>O emissions was poor ( $R^2=0.002$ ).

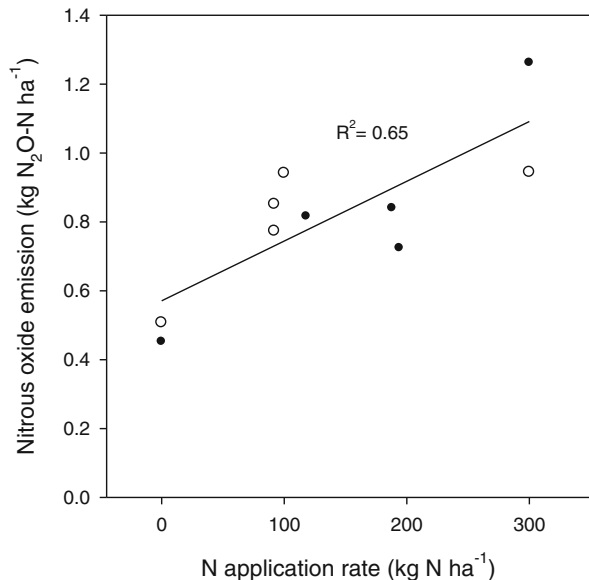
In Zimbabwe, yield-scaled N<sub>2</sub>O emissions were not significantly different in the treatments amended with 120 kg inorganic N, 60 kg inorganic N + 60 kg manure N, 60 kg manure N and 120 kg manure N. All of these treatments decreased yield-scaled emissions by approximately 55 % compared to the control (Table 3). At the study site in China, the yield-scaled soil N<sub>2</sub>O emissions in maize were generally slightly lower than those for wheat due to higher yields in maize compared with wheat (Table 3). The REC-1 treatment (inorganic and organic N fertilisation) had the lowest yield-scaled emissions under wheat. Under maize, none of the three REC treatments differed from the unfertilized (CK) treatment in terms of yield-scaled emissions, and all were lower than the conventional (CON) treatment.

## 4 Discussion

### 4.1 N fertilization and N<sub>2</sub>O emissions

Increasing N fertilizer rates is known to increase soil N<sub>2</sub>O emission and contribute towards climate change (Bouwman et al. 2002). Results from the NCP show that a reduction in N

**Fig 1** Relation between N<sub>2</sub>O emissions and N fertiliser application rate for wheat (open circles) and maize (filled circles) in China





application rates, the combination of manure and fertilizers and the changing of N sources from the commonly used urea to other sources e.g. controlled release urea, resulted in low N emissions compared to the conventional regime for which N application rates exceed crop demand. For the maize crop in China, adopting balanced N fertilization (combining organic and inorganic fertilizers) led to a non-significant reduction in soil N<sub>2</sub>O emissions, but a significant increase in wheat yield. This may be related to the effects of manure on N availability and N release patterns which may have been spread across the growing season thus improving crop N utilization and the observed reduction in N<sub>2</sub>O losses, though not significant. Results from the experiments in Zimbabwe showed significantly lower total soil N<sub>2</sub>O emissions from maize plots amended with organic N or a combination of organic and inorganic N, compared to where only inorganic N fertilizer was applied. For the Zimbabwe site, lower total N<sub>2</sub>O emissions in soils amended with cattle manure can be attributed to initial immobilisation of N because of the low quality of the manure used in this study (1.2–1.6 % N of dry matter) and slow release of mineral N (Mapanda et al. 2011). The slower release of mineral N would also have made less mineral N available for loss as N<sub>2</sub>O. This suggests that combining organic with low rates of inorganic N can be used as mitigation option for reducing N<sub>2</sub>O emissions while retaining similar crop yields. However, if low quality manure is the only source of nitrogen there may be a severe yield penalty (Table 3).

Our research shows that a balance of organic and inorganic nitrogen sources can increase or maintain high crop yields while mitigating soil N<sub>2</sub>O emissions, especially on a per-yield basis. Findings similar to ours were reported in Mali by (Dick et al. 2008) who observed emissions of 1.54 kg N ha<sup>-1</sup> from inorganic N fertilizer (urea) application at a rate of 50 kg ha<sup>-1</sup> compared to 0.97 kg N ha<sup>-1</sup> from plots amended with livestock manures at N fertilisation rates of 96 kg ha<sup>-1</sup>. Similarly, Efthimiadou et al. (2010) reported that combining organic and inorganic N sources was associated with higher or similar grain yields when compared to the application of similar or higher rates of inorganic fertilizer N, indicating improved nutrient use efficiency in the former. Nonetheless, more studies are needed to investigate the long-term implications of this strategy.

Results from the NCP showed a positive correlation between N<sub>2</sub>O and fertilizer application rates. High emissions in cropped land with fertilizers can be attributed to an increase in soil mineral-N concentrations from the applied fertilizers (Bouwman et al. 2002). Similarly, high N application rates which are used in other developed countries like the Netherlands (Kuikman et al. 2003) are also associated with high soil N<sub>2</sub>O emissions (Smith et al. 2007). Thus, it is vital to evaluate the potential impacts of adopting balanced N fertilization (reducing N input) methods, conservation tillage practices and improved soil moisture management practices on sustaining grain yields and decreasing N<sub>2</sub>O emissions. This is especially important if we consider that current high N rates at the China site did not increase grain yields above those obtained with only about half the amount of fertilizer N applied. Moreover, the high N rates may be associated with serious environmental problems, not only through high soil N<sub>2</sub>O emissions but also through ammonia volatilisation and nitrate leaching losses, which are also indirect sources of N<sub>2</sub>O (IPCC 2006).

At the study site in Zimbabwe there was no correlation between soil N<sub>2</sub>O emission and fertiliser application rates ( $R^2=0.002$ ). A review of field studies by (Snyder et al. 2009) indicates that the effect of N fertilizer level on N<sub>2</sub>O fluxes is inconsistent. McSwiney and Robertson (2005) reported that the relationship between N levels and N<sub>2</sub>O emissions may be rather complex, particularly where N application rates have not reached the N threshold level beyond which N<sub>2</sub>O emissions increase. A study by Malhi et al. (2006) reported that N<sub>2</sub>O emissions increased only when fertilized N levels exceeded 80 kg N ha<sup>-1</sup>, while Kachanoski et al. (2003) reported increases in soil N<sub>2</sub>O emissions at N levels above 100 kg N ha<sup>-1</sup> for soils

under maize. Soils from Zimbabwe had very low N content, thus when N application rates were increased the additional N was likely taken up by the maize crop leaving low amounts of N available for microbial use and loss as N<sub>2</sub>O (Mapanda et al. 2011). Peng et al. (2011) suggested that N<sub>2</sub>O emissions exhibit a threshold response to N inputs because N<sub>2</sub>O emitting pathways compete for N with assimilatory N immobilization by both microbes and plants and it is only when N applied to soil exceeds microbial immobilization and plant N demand that N<sub>2</sub>O emissions increase (Hodge et al. 2000; McSwiney and Robertson 2005).

A combination of smallholder management practices that are based on low N inputs (15–120 kg N ha<sup>-1</sup>) as well as inherently low soil C and N contents make soils from Zimbabwe weak sources of N<sub>2</sub>O. Additionally, while the low soil C contents implies a reduced energy source for microbes responsible for processes such as denitrification, the low soil N means there is low substrate to drive both nitrification and denitrification which are responsible for the production of N<sub>2</sub>O (Glatzel and Stahr 2001; Chapuis-Lardy et al. 2007). Consequently, the soil N<sub>2</sub>O emissions recorded at the Zimbabwe site were generally low and consistent with other studies conducted on arable African soils, which are generally below 2.0 kg N<sub>2</sub>O-N ha<sup>-1</sup> (Scholes et al. 1997; Dick et al. 2008). In contrast, high N input and higher inherent fertility makes soils from smallholder farms in China stronger sources of N<sub>2</sub>O. Ju et al. (2009) showed that current agricultural N rates (550–600 kg N ha<sup>-1</sup>) are above the rates that provide optimal yields in the NCP. In our study we observed that balanced N fertilization (reducing N input) could both maintain relatively high grain yield and reduce the risk of high N<sub>2</sub>O emissions.

#### 4.2 Yield-scaled N<sub>2</sub>O emissions

Maize yields in Zimbabwe were low compared to maize yields in China. The corresponding yield-scaled N<sub>2</sub>O emissions from China were lower than those in Zimbabwe, highlighting a need to improve N fertiliser use efficiency for smallholder farmers in Zimbabwe. For sustainable farming strategies, it is more important to minimize yield-scaled N<sub>2</sub>O emissions than only focusing on absolute N<sub>2</sub>O emissions (Scheer et al. 2012).

Possible challenges to promoting the management approach of combining organic and inorganic amendments to fertilizers to cereal crops in the smallholder sector of tropical countries such as Zimbabwe could be the scarcity of organic material and high inorganic fertilizer costs. Availability and competing uses of organic material such as manure or compost is a nearly universal constraint in smallholder farming systems, and may require agronomic as well as policy solutions. Availability and price of mineral fertilizer is a constraint in most countries in sub-Saharan Africa, while prevailing overuse of mineral fertilizer is a challenge in countries such as China and other countries in the developed world. The constraint of low fertiliser availability in the smallholder farming sector in Zimbabwe can be partially addressed by governments increasing resource allocation to agriculture and enacting policies aimed at reducing the cost of inorganic fertilizer for smallholder farmers and improving the development of infrastructure to improve fertilizer availability. An example of such initiatives is the Community Based Rural Land Reform Programme (CBRLDP) in Malawi which was sponsored by the World Bank and was launched in 2004 (Chinsinga 2009; World Bank 2009). However, most smallholder farmers in China may need to reduce the amount of N fertilizer that they apply to their soils. This may also require a policy restricting the amount of N fertilizer permissible for different crops, or an emphasis on fertilizer use efficiency in agricultural extension systems.

In resource constrained environments such as Zimbabwe, increased access to development assistance and government fertilizer subsidies as well as reducing fertilizer prices through better infrastructure and retailing may enable smallholder farmers to afford and apply more

inorganic fertilizers. Alternatively, farmers may decide to focus their limited resources on a smaller farming area leading to application of higher fertiliser rates and, consequently, high N<sub>2</sub>O emissions. Therefore, in anticipation of these possible changes, there is need for further studies targeted at determining which factors and management practices influence N<sub>2</sub>O emissions in the smallholder farming sector of developing countries.

The quantity and quality of organic resources could be increased through the adoption of improved manure management practices. In addition, inclusion of drought tolerant plant species in smallholder cropping systems could improve biomass production under moisture stressed tropical conditions potentially leading to increased availability of organic resources. Increasing water use efficiency to allow for cover crops and thus more organic inputs can also be added. Conservation agriculture is a potential option for increasing water use efficiency in the smallholder farming sector (Corbeels et al. 2013; Thierfelder et al. 2013) and there is need for the promotion of this technology together with improved fertilizer use efficiency (Vanlauwe et al. 2014).

### 4.3 Conclusions and recommendations

We conclude that the combined use of organic and inorganic amendments could contribute to climate change mitigation by reducing soil N<sub>2</sub>O emissions in the smallholder farming sector without compromising crop yields under both tropical and temperate conditions. Mineral and organic fertility sources are sometimes regarded as contrasting options for fertility management, particularly in the African context. However, in Zimbabwe and most countries in sub Sahara Africa, increased N inputs and N use efficiency are necessary to close yield gaps. In areas such as China where N inputs are currently high, dramatically reducing N fertilization rates may be politically infeasible. Policies that both promote and restrict inorganic N fertilizer use may need to be explored in Zimbabwe and China, respectively. However, this may be more difficult to achieve in tropical developing countries where resource constrained governments will have to increase resource allocation to agriculture at the expense of other socio-economic challenges. In the case of China, and other countries in the developed world where high N applications are use, political will, improved extension messages and appropriate policies may be necessary to stimulate change.

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