Final Technical Report
CRRP2016-05MY-Rowlings

Managing organic amendments to reduce Greenhouse gas emissions and supplement fertilizer nitrogen inputs in tropical Indian and Sri Lankan agricultural soils

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1. Project Overview

Project Duration	:	2 years
Funding Awarded	:	US$ 40,000 for Year 1; US$ 40,000 for Year 2
Key organisations involved	:	Queensland University of Technology International Cropping Research Institute for the Semi-Arid Tropics (ICRISAT) University of Ruhuna

Project Summary

Organic amendments (OA) such as crop residues, manures and composts offer valuable and cost effective sources of nitrogen (N) for tropical agricultural production systems in developing countries. Matching N release from the OA with crop N demand is critical for maintaining adequate crop growth and ensure high yield. As such farmers often over apply N, either as OA or with synthetic fertilizer N. As well as reducing farm profitability, this results in substantial N losses, contributing to pollution of waterways and the production of the powerful greenhouse gas N_2O.

This project examined the impact of two contrasting scenarios of organic amendment use in India and Sri Lanka on productivity, soil properties and greenhouse gas emissions. At the Indian site, three different (poultry manure, farm-yard manure and vermi-compost) were applied to a paddy rice crop and the potential nutritional and the soil quality benefits followed through to a post-rice chickpea crop. In Sri Lanka, we tested the optimal combination of synthetic nitrogen fertilizer rates when using green-waste compost in a multi-year maize-soybean rotation.

Results at both trial sites saw an increase in crop yields under organic amendment application, in particular chickpea yield from farm-yard manure and after repeated application of green-waste compost. However, all OA treatments increased GHG emissions in the form of nitrous oxide or methane due to the additional nitrogen or carbon applied. Furthermore, the low nutrient content and relative high costs of the OA's, particularly the composts, made them uneconomical as nutrient sources compared to conventional fertilizers, while further research is needed to determine if the additional improvements to soil health offset the increased costs.

Keywords

Organic amendments, composts, manures, NUE, Greenhouse gases

Project outputs and outcomes

Project outputs

As well as fostering the continued research collaborations between QUT, ICRISAT and University of Colombo, the project produced the following core outputs to address a key gap in the global database on GHG emissions as well as providing critical information required to promote the sustainable nitrogen use by farmers:

A. High quality, scientifically defensible datasets of N_2O, CH_4 and CO_2 from maize and soybean rotations (Sri Lanka) and lowland rice and legume rotations (India) following the application of organic amendments (manures, green waste, composts, crop residues) encompassing two key tropical climatic zones (wet tropics and semiarid tropics) and inter-annual climate variation.
B. Identification of the key drivers of emissions, annual GHG budgets and fertilizer emission factors for the key agricultural tropical crops
C. Nitrogen release curves from different types of OAs and recommendations for the timing and rates of supplementary synthetic N fertilizer to maximise yields, reduce N losses and limit GHG emissions.
D. Transfer of scientific knowledge and methodologies from QUT to researchers at the University of Ruhuna and ICRISAT including the establishment and running of field trials, determination of N mineralisation rates, sampling protocols and techniques for the collection of GHG emissions from field trials, analytical chemistry including the operation and maintenance of gas chromatographs for the analysis of N_2O, CH_4 and CO_2 gas samples, quality control, processing, statistics, interpretation and publication of data.

Project outcomes

A. Datasets provided for updated national inventories of GHG emissions from key national crops
B. Improved knowledge of biogeochemical processes to feed into simulation models for improved yield and GHG emission prediction from different climates and land management
C. Improved baselines, emission factors for calculating region-specific, crop specific emission reductions
D. The findings of the APN work informed the design (in regards to mitigation) of the following Climate Smart Agriculture (CSA) framework: Co-developed a framework and strategy for up scaling CSA in Telangana state. It includes mandal level climate analysis, prioritization of CSA practices, identifying barriers to CSA, actors' role and incentives and ex-ante assessment for returns on investment for each CSA practice. Environment Protection Training and Research Institute (EPTRI), India, Nodal agency for climate change research in Telangana state (India), has accepted and using these findings to develop the State Action Plan on Climate Change for agriculture sector, unifying the state-level approach to implementing climate-smart agriculture. National Bank for Agriculture and Rural Development (NABARD), India uses it for allocating financial resources for scaling up CSA in Telangana. https://cgspace.cgiar.org/handle/10568/90627

Key facts/figures

- The local retail price of organic amendments ranges from \$40-\$48 USD Mg^{-1} for poultry and farm-yard manure to \$55-\$70 USD Mg^{-1} for green-waste and vermi-composts. Simple economic analysis places the value of nutrients in green-waste compost, vermi-compost, farm-yard manure and poultry manure at approximately \$12, \$10, \$20 and \$46 USD Mg^{-1} respectively.
- OA application increased maize yields by 21% or allowed potential fertilizer savings of \$48 ha^{-1} in urea costs.
- OA application increased yields in post-rice chickpeas by up to 1200 kg ha^{-1} DW.
- OA application increased greenhouse gases by up to 30%.

Potential for further work

Longitudinal studies are required to demonstrate the long-term, cumulative soil benefits of repeated OA application across a range of management and amendment types. This would allow lower application rates to be examined, increasing the economic viability, as well as environmental sustainability of these products. Ultimately user friendly tools are required that help farmers navigate the complexity of using organic amendments, allow greater confidence in nutrient release predictions and allow farmers to reduce their GHG footprint while increasing agricultural sustainability. This is the current aim of a newly commenced national project across 12 sites and agricultural industries in Australia which will provide the scientific basis, quality predictions and farmer tools to assist farmers across the tropics better manage their organic amendments.

Publications

Thornton, P.K., Whitbread, A., Baedeker, T., Cairns, J., Claessens, L., Baethgen, W., Bunn, C., Friedmann, M., Giller, K.E., Herrero, M., Howden, M., Kilcline, K., Nangia, V., Ramirez-Villegas, J., Kumar, S., West, P.C., Keating, B. (2018) Ex-ante priority setting for climate-smart agriculture research. Agricultural Systems 167, 161-175. https://doi.org/10.1016/j.agsy.2018.09.009

Liyanage, A., Grace P.R., Rowlings, D.W., Scheer, C., 2016. *Influence of nitrogen fertilizer and compost mix application on greenhouse gas emissions from humid subtropical soils.* Proceedings of the 2016 International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", 4 – 8 December 2016, Melbourne, Australia. www.ini2016.com

Pull quote

'This project has helped us understand the negative impact, improper crop management can have on environment, i.e., about GHG emissions and what can be done to control the intensity of emissions produced'- K Mahender, Field Technician

Acknowledgments

This work was enabled by use of the Central Analytical Research Facility hosted by the Institute for Future Environments at the Queensland University of Technology.

Special thanks to the University Grants Commission of the Sri Lankan government for supporting the scholarship and operational costs of the PhD student Anuga Liyanage.

2. Introduction

Organic amendments (OA) such as crop residues, manures and composts offer valuable and cost effective sources of nitrogen (N) in developing countries. The amount and timing of N available for crop growth following OA application to the soil however is difficult to predict due to complex interactions between added N and associated carbon (C) and the soil microbial biomass, climate and management. Matching N release from the OA with crop N demand is critical for maintaining adequate crop growth and farmers often over apply N, either with OA or synthetic fertilizer N. As well as reducing farm profitability, this results in substantial N losses to the environment including the production of the powerful greenhouse gas N_2O.

The proposal uses the latest greenhouse gas and agronomy research technology developed in Australia and established in field experiments Sri Lanka and India to improve the N use efficiency (NUE) of key tropical crops and provide farmers with tools for predicting N availability from OA. The project enabled the ongoing collaboration between researchers in Australia, India and Sri Lanka, and ensured local researchers have the capacity and knowledge required to continue climate change research and improve resource utilization by increasing nitrogen use efficiency (NUE).

3. Methodology

3.1 Sri Lanka, Maize-soybean rotation

The trial at Matara, Sri Lanka, extended an existing compost by fertiliser rate experiment in maize conducted from October 2015 to February 2016 for an additional three seasons, allowing the long-term impact of compost addition over full cropping rotations to be determined. Data from the entire 2.5 year-long experiment is presented here.

3.1.1 Site description

Matara sits in the Southern province of Sri Lanka, and has a climate characterised as tropical rainforest climate (AF) by the Köppen-Geiger classification, with an average annual precipitation of 2338 mm and mean annual temperature of 29.8 °C. The average daily evaporation rate is around 4.5 mm (Department of Meteorology, Sri Lanka). Prior to the establishment of the experiment the site had been under weedy fallow for four months as is common in the regions and previously cultivated for short term vegetable crops.

The soil at the site is an Orthic Acrisols (FAO, 1998), characterized by an argic horizon (a subsurface soil horizon, at least one-tenth the thickness of the overlying horizon) starting from 40-75cm from the soil surface. Low-activity clays within the argic horizon are characterised by relatively low nutrient availability and base saturation (World soil resources report, 2014). The main soil properties of the field site and characteristics of compost are shown in Table 1. The site was hand cleared of weeds with all residues removed from the plots, and tilled 2 times: primary tillage (subsoil tillage) followed by secondary tillage (surface tillage) was done prior to the establishment of the experiment.

3.1.2 Experimental design

Five crops were grown in a multi-year rotation under the same management and treatment plots for three consecutive rotations; Maize 1, Soybean 1, Maize 2, Soybean 2 and Maize 3. The trial had eight treatments in a factorial experiment of two compost rates, zero (0C) and 15 t ha^{-1} (+C) on dry weight, and four N rates; zero N (0N), Low N (LN), Medium N (MN) and High N (HN). The N application rate MN was designed to represent normal farming practice of the region (150 N kg ha^{-1} for maize and 70 N kg ha^{-1} for soybean) as recommended by Department of Agriculture, Sri Lanka. Experimental plots were laid out in a randomised design with four replicate blocks. Compost, produced locally from municipal solid waste in Matara, Sri Lanka, was applied twice (15 t ha^{-1} per application ~ 105 kg N ha^{-1}) as dry weight basis at the beginning of each crop in the rotation before planting and incorporated into a depth of 20 cm. Agronomic management followed the local farmer practice of the region. The composition of the compost is shown in Table 1.

3.1.3 Maize establishment and management

Planting, harvest and fertilizer application dates, along with N and compost rates for each of the cropping periods are listed in Table 2. Maize (*Zea maize* L. Var. MI) was planted between late October and early November at a depth of 3 cm and according to the recommended row spacing of 60 cm, with 30 cm between plants, keeping the same treatment plots throughout the experiment (Figure 1). Weeds were controlled by a manual chipping or hand removal. Nitrogen fertiliser was applied before sowing by evenly broadcasting onto the soil surface before being forked into a depth of 20cm. Nitrogen fertiliser was applied as urea in two splits: immediately prior to sowing and 6 weeks after planting and also forked and mixed with top soil. A basal application of 100 kg ha^{-1} Triple Super Phosphate (TSP) and 50 kg ha^{-1} Muriate of Potash (MOP) were applied to supply P and K for crop growth prior to each crop. Plants were harvested in early February at physiological maturity and dried at 40°C. Dry matter (DM) yields were expressed as total crop biomass dry matter (stover + grain). All residues removed from the plots before cultivation for the next crop.

3.1.4 Soybean establishment and management

Soybean (*Glycine max L.* Var. PB 1) was sown in the same experimental plots as the previous maize experiment. Soybean seeds were planted to a depth of 3 cm and a spacing of 40 cm between rows with plants 10 cm apart (Figure 2). Manual weeding was done throughout the cropping season with residues returned to the plots. The three rates of basal N fertiliser (urea) were applied to the non-zero treatments at planting, and side dressed four weeks later. Triple Super Phosphate at 150 kg ha^{-1} and MOP at 75 kg ha^{-1} were applied with basal application to supply P and K for crop growth. Soybean was harvested between late August and early at physiological maturity and dried at 40°C. Dry matter (DM) yields were expressed as total crop biomass dry matter (stover+grain). All crop residues were removed from the plots before the next crop.

3.1.5 N_2O and CO_2 flux measurements

The soil borne N_2O and CO_2 fluxes were measured over the entire 2.5 years, including all five cropping seasons and fallow seasons from October 2015 to April 2018. N_2O emissions from field plots were monitored using manual closed chamber method as described in (Parkin and Venterea, 2010). Manual chambers were placed in each of the 32 plots midway between two crop rows. Chambers consisted of PVC cylinders 20 cm in diameter with 20 cm of headspace height inserted 10 cm into the soil. Chambers remained in situ throughout the experiment, being removed only for cultivation events. Chambers were closed with a lid fixed with a rubber seal to generate an air tight seal. The exact amount of fertiliser required for the chamber surface area was weighed and applied separately.

The sampling frequency was optimised according to the recommendations of (Reeves and Wang, 2015). Flux measurements were obtained three times a week for at least the first week after fertilisation and large rainfall events and weekly over the remaining cropping period and once every two weeks during fallow period. Sampling was completed from all plots in the morning between 7 am and 11 am. Gas samples were collected by extracting 20 mL of chamber headspace air using a syringe fitted with a Luer-lock valve at 0, 30 and 60 minutes after chamber closure and injected into 12ml pre-evacuated glass vials (Exetainers) fitted with a double nylon cap. Samples were stored at room temperature prior to analysis for N_2O and CO_2 using a Shimadzu GC-2014 Gas Chromatograph (Kyoto, Japan) at the Central Analytical Research Facility at the Queensland University of Technology, Australia. Gas samples were calibrated against a calibration curve plotted using a range of seven identified high purity standards (Air Liquide, Houston, TX, USA) ranging from 795 ppm to 10 000 ppm CO_2 and 0.5 ppm to 24.5 ppm N_2O.

3.1.6 Ancillary measurements

Local weather variables were obtained by a weather station from the Department of meteorology, Sri Lanka at Matara, 2 km from the research site. The station recorded daily values of air temperature (maximum, minimum and average), relative humidity and rainfall. From three random locations across the experimental site deep soil samples (0-20, 20-40, 40-70, and 70-90 cm) were collected prior to the commencement of the experiment and analysed for pH, total carbon (C %) and total nitrogen (N %) and cation exchange capacity (CEC). During the experimental period, soil samples to 20 cm (four bulked per plot) were collected every two weeks and weekly before and after incorporation of fertiliser for analysis of NO_3^- and NH_4^+ using 1:5 2M KCl soil extracts. Soil moisture content was determined every two days from each plot by gravimetric soil moisture after drying soil for 24 h at 105°C and converted to water filled pore space (WFPS). At harvest, yield of maize and soybean were measured in each plot by harvesting middle strips 1.2 m wide for the entire plot length and dried for 40°C.

3.1.7 Statistical analysis and calculations

The N_2O and CO_2 fluxes were calculated from the slope of the linear concentration increase of the three measurements taken over the 60-minute chamber closure time. Flux quality control was performed by using a coefficient of determination (r^2), and fluxes with $r^2 < 0.80$ were discarded. Fluxes were corrected according to air temperature and site pressure using equations described in (Scheer *et al.*, 2015) and expressed on an elemental weight basis. Data gaps were filled using linear interpolation by individual chamber across the missing day. Cumulative N_2O fluxes (g N_2O ha^{-1}) were calculated by summing the measured and interpolated daily average of each individual chamber.

The effects of compost application and different rates of N-fertilizer applications were tested using two-way analysis of variance (ANOVA), and pairwise differences, with an α level of 0.05, were identified by the LS means package (Lenth, 2016), using the Tukey multiple-comparison test.

Emission factors/ EF of the N fertiliser were calculated using the following formula:

$$EF_{OA} = \left(\frac{N_2O{-}N_{treatment} - N_2O{-}N_{0N}}{Total\ N\ fertiliser\ applied}\right) \times 100 \quad \text{Eqs 1}$$

Where EF is the percentage of the total N fertiliser applied that was emitted as N_2O-N, N_2O-N is the total N_2O emitted over one-year kg N ha^{-1} $year^{-1}$) for a N fertiliser rate and total N applied is the amount of N fertiliser applied (kg N ha^{-1} $year^{-1}$).

Table 1. Selected characteristics of soil and compost used for the experiment at Matara, Sri Lanka.

Parameter	**Soil 0-20cm**	**Compost**
pH	6.6	7.2
CEC	4.9 cmol kg^{-1}	21.9 cmol kg^{-1}
Total C %	1.8	19.20
Total N%	0.18	0.70
C:N	10	
Clay	41%	
Silt	31%	
Sand	28%	
Bulk density	1.2	

Table 2. Nitrogen fertiliser rates (kg N ha^{-1}) and agronomic management timeline for the Maize and Soybean crops at Matara, Sri Lanka. Fertilizer rates were applied at two compost rates (0 and 15 t ha^{-1}).

Date	Management	Treatments							
Year 1	**Maize 1**	**0N**	**LN**	**MN**	**HN**	**0N+C**	**LN+C**	**MN+C**	**HN+C**
20/10/2015	Compost (Mg ha^{-1})	-	-	-	-	15	15	15	15
28/10/2015	Basal fertilizer (kg N ha^{-1})	-	23	50	66	-	23	50	66
01/11/2015	Planting								
19/12/2016	Top-dressing	-	47	100	134	-	47	100	134
15/02/2016	Harvest								
Total fertilizer (kg N ha^{-1})		0	70	150	200	0	70	150	200
	Fallow								
	Soybeans 1								
20/06/2016	Compost (Mg ha^{-1})	-	-	-	-	15	15	15	15
27/06/2016	Basal fertilizer (kg N ha^{-1})	-	10	23	33	-	10	23	33
27/06/2016	Planting								
05/08/2016	Top-dressing	-	20	47	67	-	20	47	67
03/10/2016	Harvest								
Total fertilizer (kg N ha^{-1})		0	30	70	100	0	30	70	100
Year 2	**Maize 2**								
29/10/2016	Compost (Mg ha^{-1})	-	-	-	-	15	15	15	15
09/11/2016	Basal fertilizer (kg N ha^{-1})	-	23	50	66	-	23	50	66
10/11/2016	Planting								
08/12/2016	Top-dressing	-	47	100	134	-	47	100	134
15/02/2017	Harvest								
Total fertilizer (kg N ha^{-1})		0	70	150	200	0	70	150	200
	Fallow								
	Soybean 2								
01/05/2017	Compost (Mg ha^{-1})	-	-	-	-	15	15	15	15
15/05/2017	Basal fertilizer (kg N ha^{-1})	-	10	23	33	-	10	23	33
15/05/2017	Planting								
14/06/2017	Top-dressing	-	20	47	67	-	20	47	67
22/08/2017	Harvest								
Total fertilizer (kg N ha^{-1})		0	30	70	100	0	30	70	100
	Fallow								
Year 3	**Maize 3**								
31/10/2017	Compost (Mg ha^{-1})	-	-	-	-	15	15	15	15
08/11/2017	Basal fertilizer (kg N ha^{-1})	-	23	50	66	-	23	50	66
09/11/2017	Planting								
14/12/2017	Top-dressing	-	47	100	134	-	47	100	134
09/02/2018	Harvest								
Total fertilizer (kg N ha^{-1})		0	70	150	200	0	70	150	200
Annual N fertilizer application		0	100	220	300	0	100	220	300

Figure 1. *Compost by fertilizer rate plots and manual chambers shortly after maize sowing and at 5 weeks of age, Matara, Sri Lanka.*

Figure 2. *Dr Liyanage checking the soybean crop at grain filling stage, Matara, Sri Lanka.*

3.2 India Rice-fallow crops 2017-18

Kharif (wet season) rice was transplanted into the plots on the 26 July 2017, and harvested on the 24th October (Figures 3 and 4). The 6m x 6m plots were individually bunded to prevent water and nutrient movement between plots and allow for a randomised block design. Organic amendments selected for the study represented the more common types available in the area and a wide range of nutrient qualities to ensure the study is as relevant as possible to local farmers. OA treatments were applied immediately prior to planting on the 26th July 2017 at the higher end of local farmer practice to maximise treatment differences while ensuring economic feasibility. Irrigation was maintained at 2 cm throughout the rice growing period with the last irrigation applied one month prior to harvest. Treatments were as follows:

- T_1 - Farmer practice (Recommended Dose of Fertilizer 120-60-40 kg NPK ha^{-1})
- T_2 – 25% of RDF through Vermi compost + 75% RDF from urea
- T_3 – 25% of RDF through Farmyard Manure + 75% RDF from urea
- T_4 – 25% of RDF through Poultry manure + 75% RDF from urea

The chickpea fallow crop was planted shortly after rice harvest on the 26th October 2017 to capitalise on any residual soil moisture and late kharif rainfall, and was harvested on the 24th January 2018. No additional fertilizer was applied. Seeds were direct drilled by hand as per standard farmer practice for the respective crops.

Table 3. Selected characteristics of compost and soil properties at the paddy soil research site at ICRISAT, India.

	Vermi-compost	**Farmyard manure**	**Poultry manure**	**Paddy soil (0-15 cm)**
Application rate- Dry weight (kg ha^{-1})	5,000	5,000	1,500	-
Application rate - Wet weight (kg ha^{-1})	11,390	8,368	2,129	-
Total C (%)*	10.1	24.3	19.0	0.45
CN ratio	9.2	9.5	6.0	3.3
Total N (%)*	1.1	2.6	3.2	0.14
Total N (kg ha^{-1})	55.2	128.5	47.7	2167
Inorganic N (NO_3^- + NH_4^+ - kg ha^{-1})	4.7	9.9	1.4	
Total P (%)*	0.34	0.66	2.4	0.07
Total P (kg ha^{-1})	17.0	32.8	36.8	1161
Total K (kg ha^{-1})	51.3	114.2	45.1	8357

Table 4. Nitrogen fertiliser rates (kg N ha^{-1}), organic amendment application rate (Mg DM ha^{-1}) and agronomic management timeline for the Maize and Soybean crops at ICRISAT, India.

Date	Activity	Treatments			
		Farmer practice	Vermi-compost	Farmyard manure	Poultry manure
26 July 2017	Manure applied (Mg ha^{-1})	0	5	5	1.5
	Rice planted				
	Basal fertilizer (kg N ha^{-1})	60	40	40	40
26 Aug 2017	Top-dressing 1 (kg N ha^{-1})	30	25	25	25
21 Sept 2017	Top-dressing 2 (kg N ha^{-1})	30	25	25	25
24 Oct 2017	Rice harvest				
26 Oct 2017	Sowing chickpea				
24 Jan 2018	Chickpea harvest				

Figure 3. PhD student Mrs K Mamatha supervising the planting of the rice crop at ICRISAT, India in July 2017.

Figure 4. Sowing of millet for the 2016 cover crop experiment and field preparation for the 2017-18 rice crop.

3.2.1 Field measurements

The pneumatically operated automated chambers (non-steady-state, non-flow-through) were connected to the automated gas sampling system and in situ gas chromatograph described by Rowlings *et al.* (2012). The clear acrylic chambers covered a surface area of 0.25 m^2 (500 mm x 500 mm) with a height of 150 mm and were secured to stainless steel bases inserted permanently into the soil to a depth of 100 mm. Two inlets fitted with valves were installed in the chamber just above the soil surface which were opened periodically to allow the flushing of water from within the chamber to the bulk plot. Nitrogen fertiliser within the chamber base was applied manually to ensure accurate and even distribution and application of the fertiliser within the chamber. To account for the growing rice plants within the chamber, 50 cm high extensions were added to the chamber bases. A temperature probe was installed in one chamber in each set and the chambers programmed to open automatically if chamber temperatures exceeded 50 °C to minimise plant damage. The installed chambers, extensions and sample lines can be seen in the flooded rice in Figure 5.

Nitrous oxide and CH_4 concentrations were determined using a gas chromatograph (SRI GC8610, Torrance, CA, USA) equipped with ^{63}N Electron Capture Detector and a Flame Ionisation Detector for CH_4 (SRI GC8610, Torrance, CA, USA). Carbon dioxide was measured continuously with a non- dispersive infrared CO_2 analyser (LI-820; LI-COR, Lincoln Nebraska, USA). To minimise interference from CO_2 on N_2O measurement, a pre-column filled with sodium hydroxide coated silica was installed ahead of the analytical column and changed regularly. A full measurement cycle for flux determination commenced with lid closure and finished when the lids opened 60 minutes later. One replicate chamber per treatment was closed at any one time. The closed chambers were sequentially sampled for 3 minutes followed by a known calibration standard (0.5 ppm N_2O, 3.7 ppm CH_4, 800 ppm CO_2, Scott-Marrin, Riverside, CA, USA). This process was repeated after 15 minutes, collecting 4 samples from each chamber over the closure period. The lids remained open for a further 120 minutes before the commencement of the next cycle, enabling for 8 flux measurements from each chamber per day.

Fluxes of N_2O, CH_4 and CO_2 from the automated chambers were calculated from the slope of the linear increase or decrease of the four headspace concentrations over the closure time and corrected for chamber temperature and local air pressure. CO_2 fluxes were calculated from the linear increase in chamber headspace concentration over the initial 18-30 minutes after closure. The reliable detection limit (RDL) was calculated as ±5 µg N_2O-N m^{-2} h^{-1} using the method described by (Swyngedouw and Lessard, 2008). Flux rates above the RDL were discarded if the regression coefficient (r^2) was <0.81 for N_2O and CH_4 and <0.90 for CO_2.

Water content in the fallow was logged at 5 minute intervals from each treatment using TDR probes (0-8 cm) and fortnightly to 1 m using manual access FDR tubes (Diviner 2000, Sentec, Stepney, Australia) and neutron probes. Soil temperature (0-10 cm) was logged at 30 minute intervals. Initial soil samples were collected at 15 cm intervals to 30 cm, and 30 cm intervals to 120 cm and analysed for texture, pH, EC, organic C, total N, available P, exchangeable K and available S. Soil samples collected every two weeks from 0-10 and 10-20 cm depth and analysed for nitrate and ammonium using a 1:5 soil:KCl extract on a continuous flow analyser (Skalar San, Netherlands). Water use via irrigation was monitoring during both the rice crop and establishment of the fallow crops using an in-line flow meter.

Figure 5. *Automated chambers in the Rice plots at ICRISAT, India, December 2016.*

4. Results & Discussion

4.1 Sri Lanka

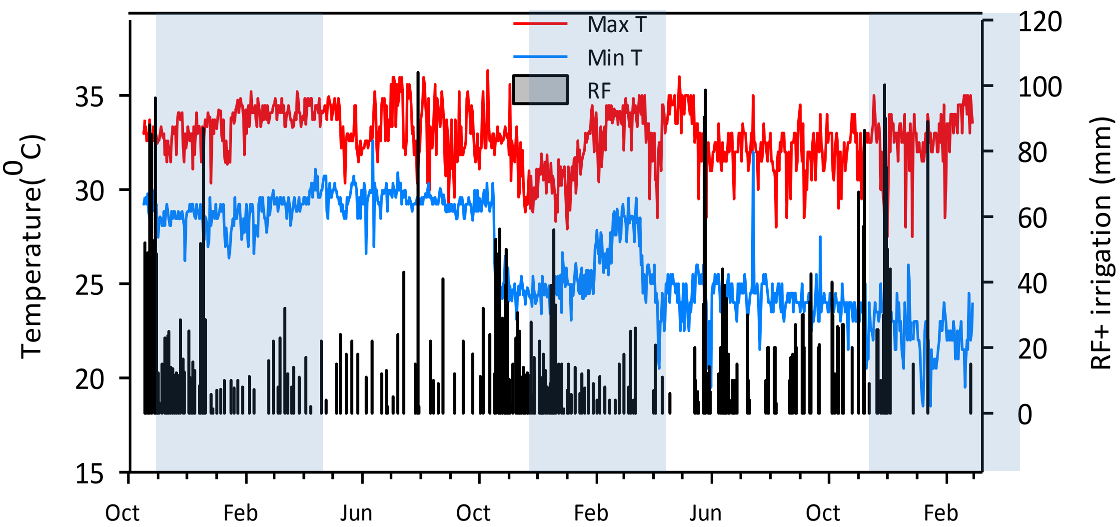

Figure 6. *Daily rainfall, minimum and maximum temperature and soil water-filled pore space (WFPS) from Matara, Sri Lanka for the 2015-2017 maize/soybean/maize (shaded blue areas) crops.*

Over the study period (Oct 2015– Feb 2018) annual rainfall at Matara, Sri Lanka was below the long-term average with 1926, 2212 and 783 mm falling over the 12 months from October 2015, 2016 and October 2017 to February 2018 respectively (Figure 6). This included 11 large daily rain events of >85 mm each, with around 60% of the annual rainfall was concentrated within the traditional October to December rainy season. The mean air temperature was 27.6°C, with the annual maximum temperature recorded of 36.0°C and a minimum of 18.5 °C.

4.1.1 Effect of N rate on Maize and Soybean yield

Maize dehulling to separate grain from stover yields was only performed in the maize 3 crop, with yield from all other crops presented as total above-ground biomass (AGB). Maize 3 grain yield showed a strong response to N fertilizer rate at the lower application rates, increasing by over 65% from the 0N to the LN treatment (Table 5). Additional N application in the MN and HN further increased yields though at a slower rate, with yields plateauing and no significant difference being observed between the MN and HN rates (Figure 7a). A similar pattern was observed in the stover and total AGB, though stover yields continued to increase even at the higher N rates.

Nitrogen uptake in the maize 3 crop increased from 87.6 kg N ha^{-1} removed from the AGB in the 0N plots to over 166 kg N ha^{-1} in the HN treatment (Figure 8a), with grain N representing around 47-49% of total N uptake across treatments. The marginal N response of grain and N uptake in the AGB, calculated as the increase in yield or N uptake per unit of additional N applied, reduced as N rate increased (Figure 9). This resulted from the lower response of additional N at the higher application rates as plants became limited by other environmental parameters or their genetic production limit. As such the benefit applying N decreased steeply from ~20 kg of grain per kg of N applied between 0 to 70 kg N ha^{-1} rate to less than 5 at the 70 to 150-200 kg of N. Likewise, N content in the AGB also decreased from 0.6 kg N per kg of fertilizer N applied at 70 kg N ha^{-1} (LN) to less than 0.2 at the 200 kg N ha^{-1} (HN) application rate. This is also reflected in the apparent N use efficiency, the amount of N applied recovered in the total above-ground biomass, which decreased with increasing N rates from just over 60% in the LN to under 40% in the HN treatment accounting for background N uptake in the 0N plots (Table 5).

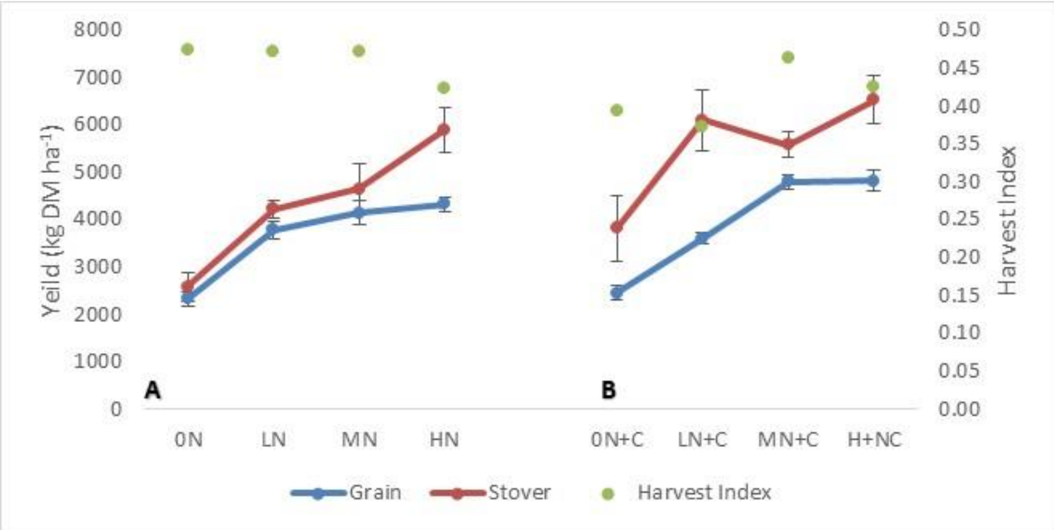

Figure 7. *Grain and stover yield and crop harvest index for the 0N, LN (70 kg N ha^{-1}), MN (150 kg N ha^{-1}) and HN (200 kg N ha^{-1}) treatments with and without compost addition (+C) for the maize 3 crop, October 2017 to February 2018 at Matara, Sri Lanka.*

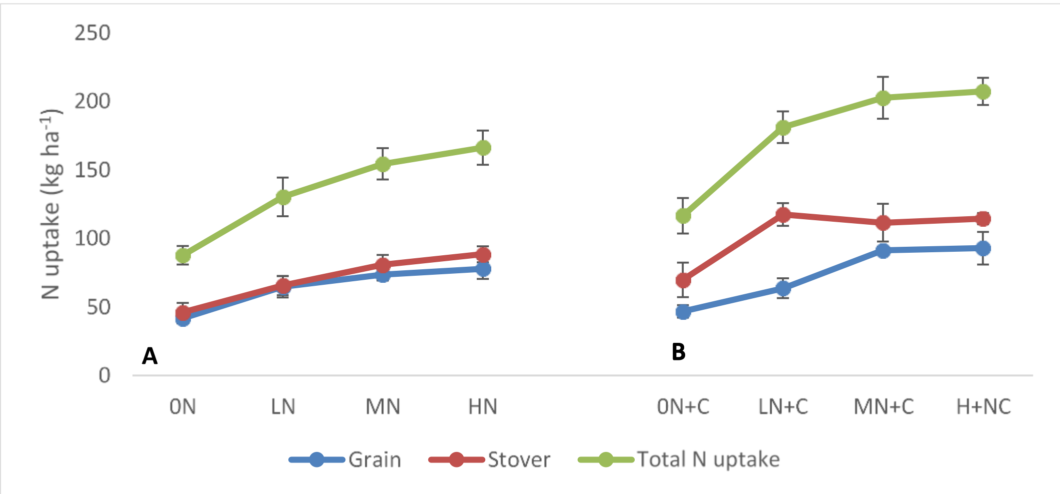

Figure 8. *Grain, stover and total nitrogen (N) uptake for the 0N, LN (70 kg N ha^{-1}), MN (150 kg N ha^{-1}) and HN (200 kg N ha^{-1}) treatments with and without compost addition (+C) for the maize 3 crop, October 2017 to February 2018 at Matara, Sri Lanka.*

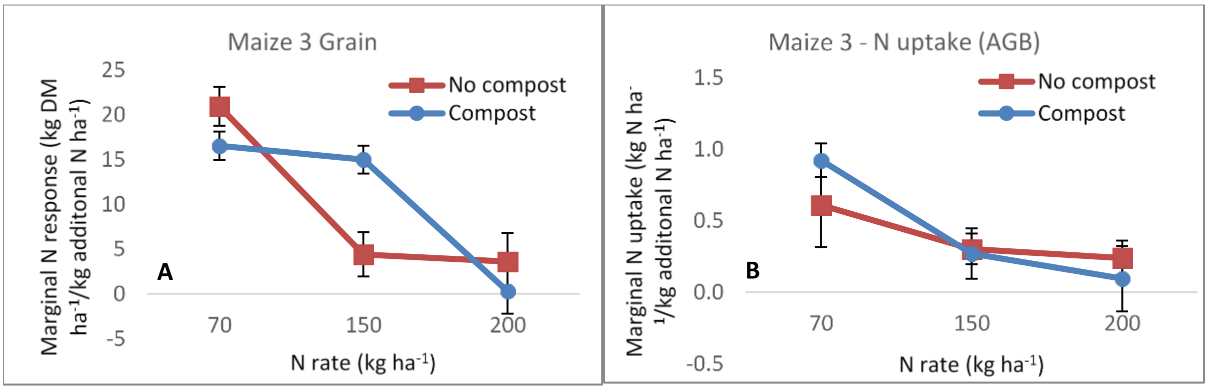

Figure 9. *The marginal N response for grain (kg DM ha^{-1}) and total nitrogen (kg N ha^{-1}) uptake in the above-ground biomass (AGB) per kg of fertilizer N applied for maize 3 with and without compost addition (+C) for the maize 3 crop, October 2017 to February 2018 at Matara, Sri Lanka.*

In contrast to maize 3, total AGB yields in the soybean 2 crop only showed a significant N response at the highest N application rate of 100 kg N ha^{-1} (HN), while total AGB N uptake was significant from the 0N only above the MN (70 kg N ha^{-1}) fertilizer rate (Table 5). AGB yield increased >41% and total N uptake by >71% compared to <30% for the previous N increment. Without separated grain data it is not possible to determine if this resulted in a flush of vegetative growth which didn't translate to higher yields at the highest N rate or if the harvest index (proportion of grain yield to the total AGB) remained constant across N rates as was seen in maize. If so one possibility is the legume may have preferentially fixed atmospheric N at the lower rates, reducing the N limitations at lower application rates while simultaneously expending significant resources during the energy intensive fixation process. At the highest N application rate however, it is possible the high available N in the soil led the legume to solely rely on applied fertilizer N, reducing the metabolic cost of N fixation and therefore dramatically increasing AGB yields. This resulted in the marginal N response showing the opposite response to maize 3, with highest response of >50 kg AGB and 1 kg N per kg of additional N observed in the highest N rate. As such NUE was also highest at the high N rate, increasing from ~39% in the LN to almost 53% in the HN treatment.

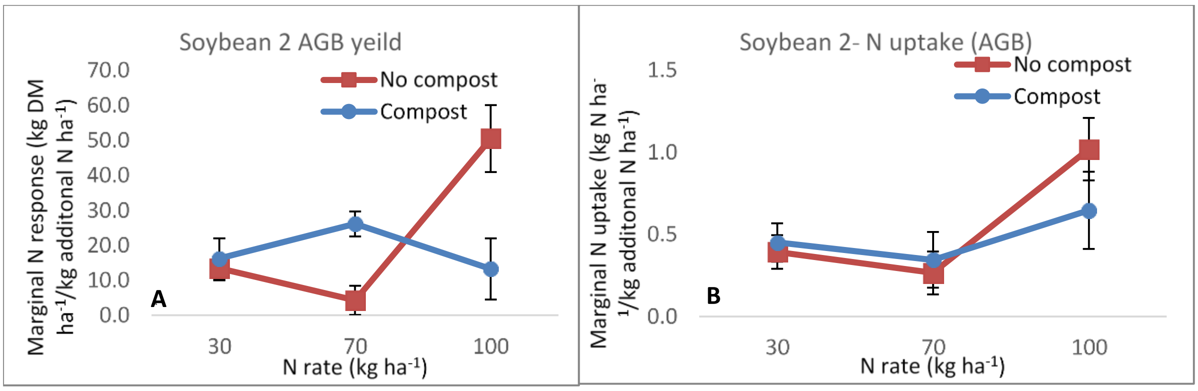

Figure 10. *The marginal N response for AGB (kg DM ha^{-1}) and total nitrogen (kg N ha^{-1}) AGB uptake (AGB) per kg of fertilizer N applied for soybean 2 with and without compost addition (+C) for the maize 3 crop, October 2017 to February 2018 at Matara, Sri Lanka.*

4.1.2 Effect of compost application on yields

Over the 2.5 years total AGB yields in the no-compost treatments remained relatively consistent, with only the 0N treatment AGB yields lower (P<0.05) in year one compared to subsequent crops in both the maize and soybean though the reason for this is not clear. Compost addition (0N+C LN+C MN+C HN+C) did not have a significant effect in the first maize crop, but in the second and third crops significant increases in DM yield were observed in all C added treatments at the higher N rates (p< 0.05, Table 5). In maize 3, the greatest response to compost addition was seen in the MN treatment which increased AGB, grain yield and total N uptake by 21%, 14.5% and 31% respectively (Figure 8b).

In the first soybeans crop, AGB yields were not significantly (p>0.05) affected by application of compost at any of the plus N rates; though they did increase yields in the 0N by 28%. As with maize, there was a significant (p< 0.05) effect of compost application on soybean biomass across all treatments in year 2. Highest responses in soybean 2 were seen in the LN and MN treatments, with compost application increasing total AGB and total AGB N content by 37% and 42% for the LN and 71% and 39% for the MN respectively.

This increase in yields associated with compost addition was evident across all metrics including a 11 to 116% increase in NUE in the soybean 2 and a 52-119% NUE increase in maize 3. The benefit of compost application on biomass yields in both crops became most evident after repeated applications in years 2 and 3 (Figure 11). Yield obtained from the MN treatments plus compost was equivalent to yields from the higher N rate (HN) under no-compost. This increased the marginal N rate for the MN treatment in both the soybean and maize to be equivalent or higher than the LN (Figures 9b, 10b), increasing the return on investment for applied N. This would allow for a potential reduction of N fertilizer application rates from the HN to MN, saving 50 kg N ha^{-1} $year^{-1}$ in fertilizer for the maize and 30 kg N $year^{-1}$ in the soybean, without a yield penalty (Figure 11).

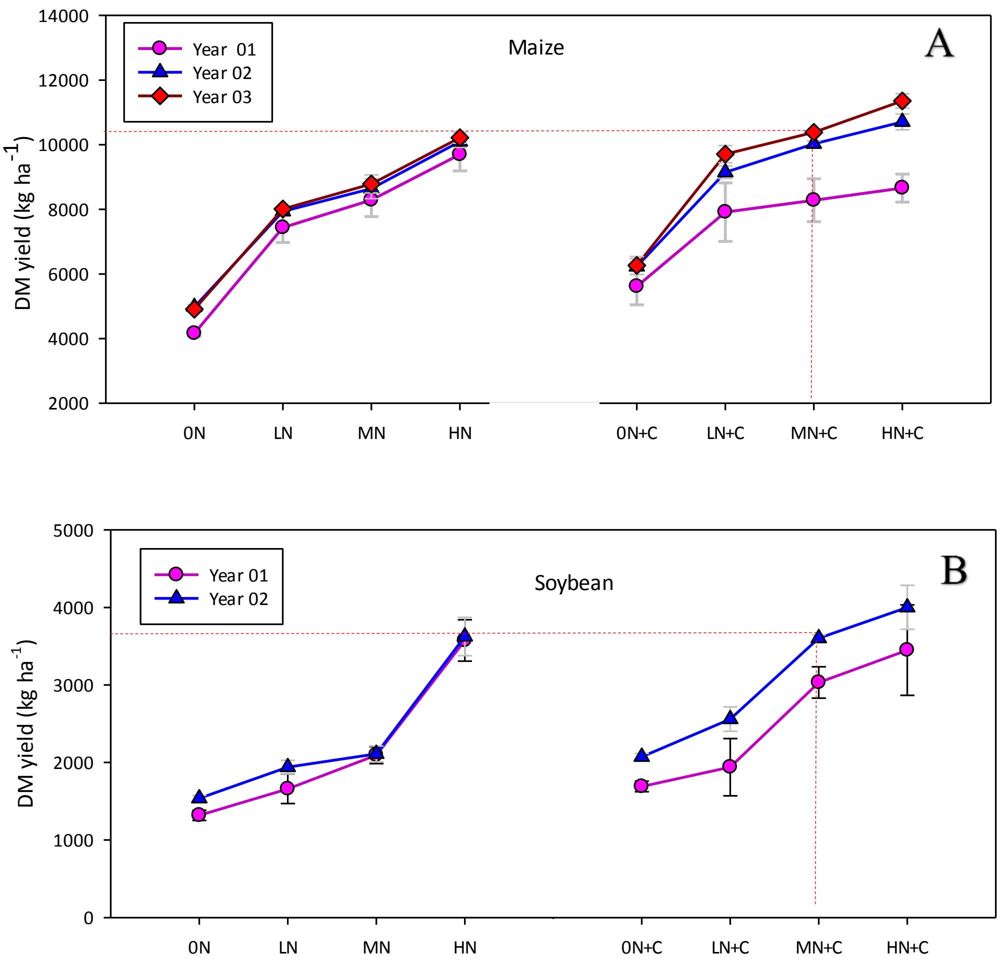

Figure 11. *Comparison annual total biomass (stover + grain) dry matter yield of (A) maize and (B) soybean with and without compost from 3 consecutive years from 2015-2018 from Matara, Sri Lanka. Dotted red lines represents potential economic benefits associated with the application of compost at lower N application rates.*

4.1.3 Economics of compost application

At a conservative price of 50 Sri Lankan Rupees (LKR) per kg of urea, the 80 kg N ha^{-1} reduction associated with reducing N inputs from the HN rate to the MN rate while achieving comparable yields represents an annual saving of 8,700 LKR (~$48 USD) per hectare. Alternatively, compost also increased grain yields at the highest N rate by 0.5 Mg ha^{-1}, equivalent to 20,000 LKR ha^{-1} (at a price of 40 LKR kg^{-1} maize grain), with more value in the stover depending on local markets. The retail price of green waste compost in Sri Lanka has been reported as being between 10 to 25 LKR per kg ($55-$140 USD Mg^{-1}). At the application rate of 15 Mg per crop (30 Mg per year) this corresponds to a per hectare price of 300,000 LKR ($1650 USD) per year, far in excess of the potential savings associated with lower urea application or increased yields. At 50 LKR per kg urea, the value of N (Table 1) applied in the compost is only 22,826 LKR ($126 USD) ha^{-1}, and even accounting for other macronutrients (P and K) can only replace (assuming 100% availability over time) 65,900 LKR ($363 USD or $12.10 USD Mg^{-1}) worth of bagged fertilizer, well short of the 300,000 LKR application cost. This is reflected in the input cost per unit of grain and stover produced in maize 3 (Figure 12), which increases from 2 to 5 LKR kg^{-1} (grain) for urea as N rate increases and marginal returns diminish, compared to 123- 66 LKR kg^{-1} for the compost.

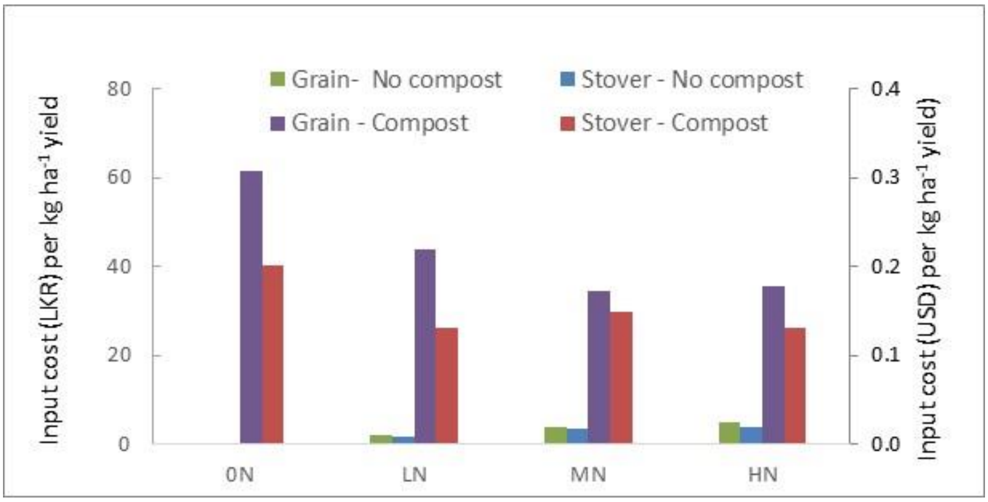

Figure 12. *Nitrogen input costs in Sri Lankan Rupees (LKR – left axis) and USD (right axis) per unit of grain or stover produced for the maize 3 crop using urea only or green-waste compost combined with urea at different application rates. Urea was priced at 50 LKR kg^{-1} (0.28 USD) and compost at 10 LKR kg^{-1}.*

4.1.4 Annual variation of GHG emissions under repeated application of N fertilizer and compost

4.1.5a. Temporal dynamics of N_2O and CO_2 fluxes

Daily N_2O fluxes and cumulative emissions for the annual rotation were divided into the following five periods: maize 1, soybean 1, maize 2, soybean 2 and maize 3 cropping seasons. Lowest emissions were recorded from the 0N treatment which averaged 7.8 g N ha^{-1} day^{-1} over the three years, with the highest daily emission of 71 g N ha^{-1} day^{-1} occurred in mid-November 2016 (Figure 13). The highest daily N_2O emissions occurred following the basal application of urea in the maize 3 crop on the 9th November 2017 when average N_2O emissions exceeded 360 g N ha^{-1} day^{-1} in HN+C fertilised treatment (Table 6).

Highest daily N_2O emissions typically occurred following the basal application of urea following planting of maize or soybean, with a second subsequent peak followed top-dressing. In year one, approximately 70% of the annual increase in N_2O associated with compost addition in the LN and HN treatments occurred following the two fertilizer application in maize, with only minor increases in the 0N and MN treatments.

The highest daily CO_2 emissions occurred following the basal application of urea in the soybean 2 when CO_2 emissions exceeded 118 kg ha^{-1} day^{-1} in MN+C fertilised treatment (Figure 14). Significant differences were observed between mean daily CO_2 fluxes measured from the compost treatments compared to no compost treatments in Soybean 2 and maize 3 at the higher N rates, though this was not reflected in the average annual emissions from year 2 (Table 6).

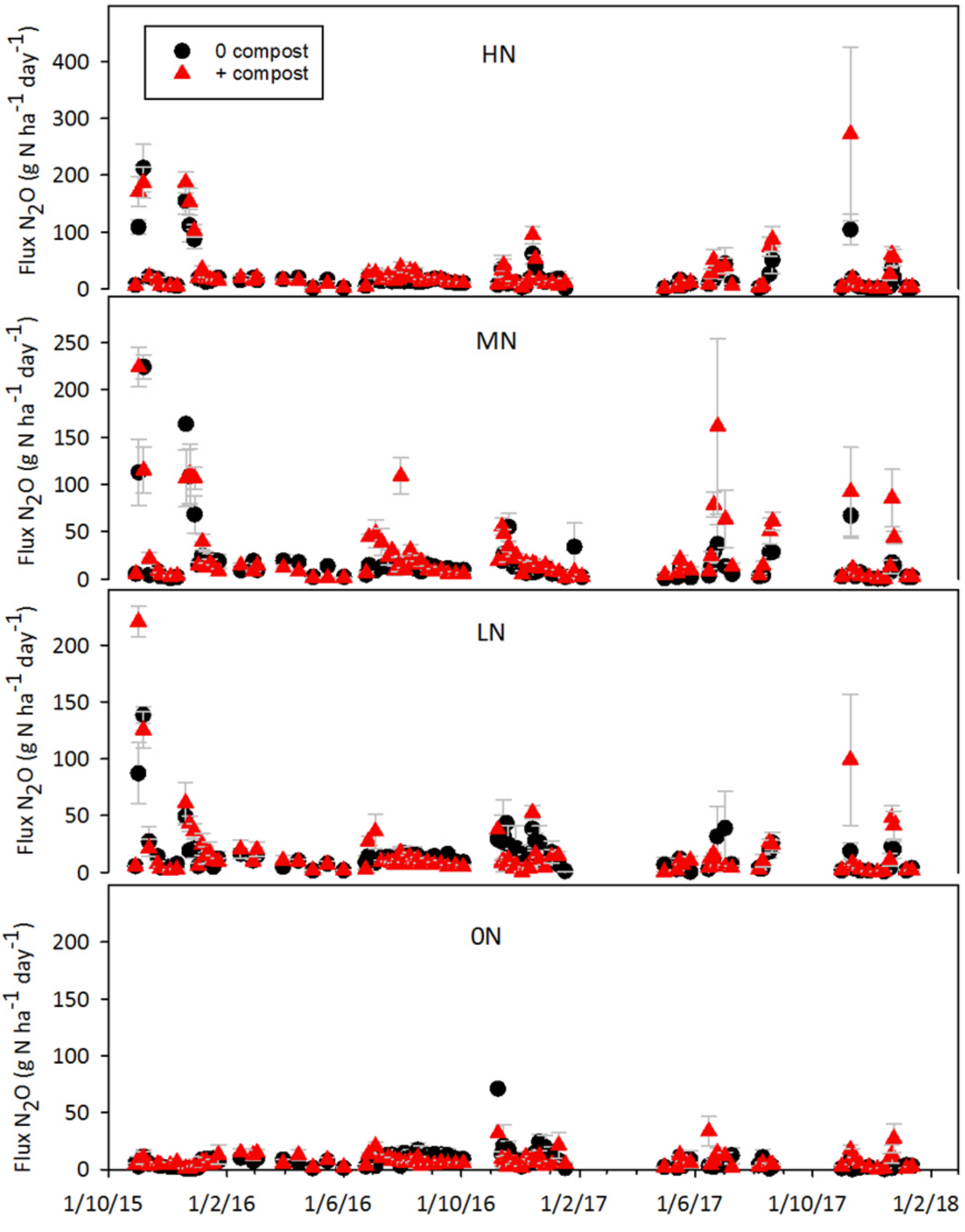

Figure 13. *Daily soil N_2O fluxes (g N ha^{-1} day^{-1}) for four N rates 0N, LN, MN, HN with compost and no compost during a 3 years crop rotation from October 2015 to February 2018 at Matara, Sri Lanka.*

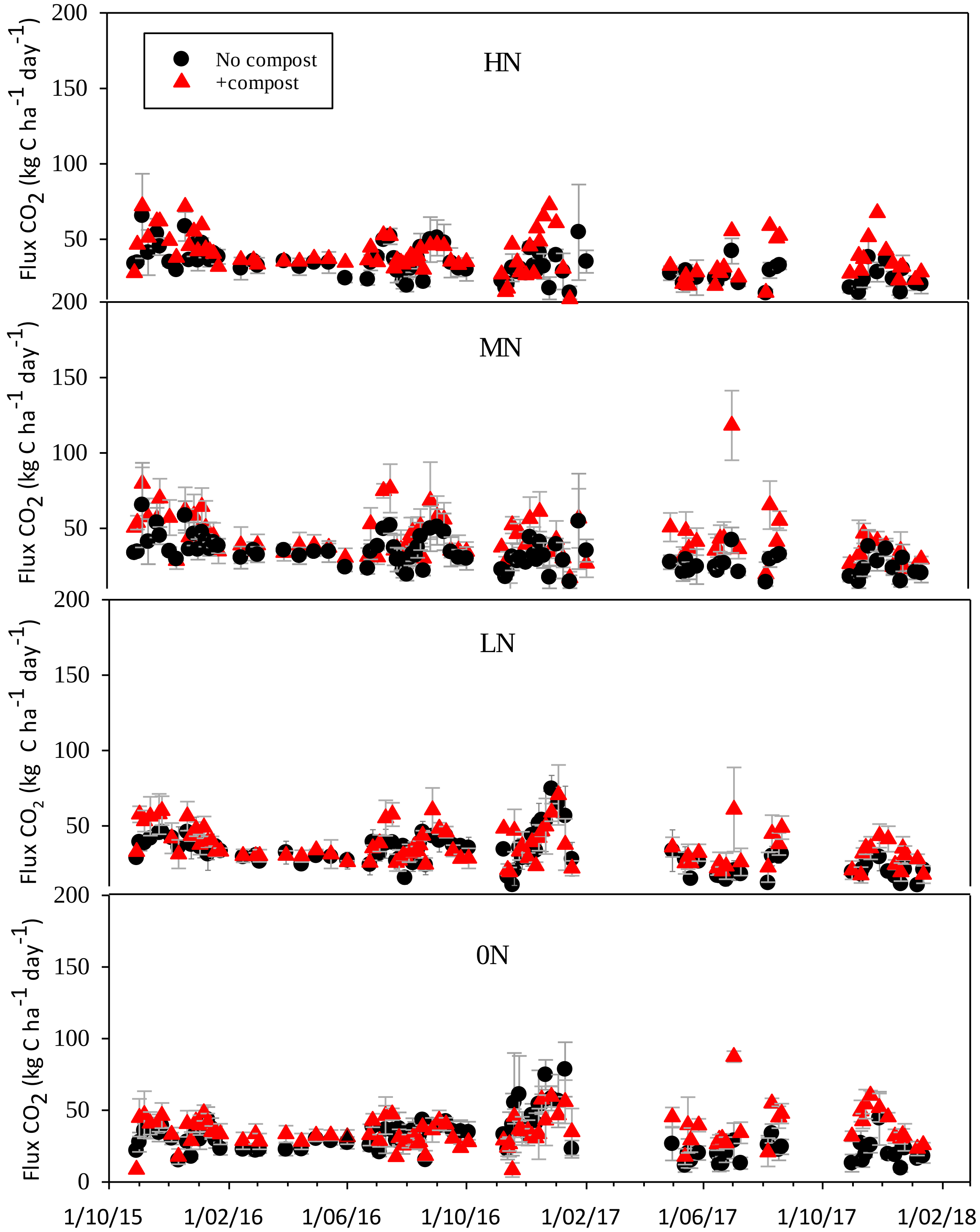

Figure 14. *Daily soil CO_2 fluxes (kg N ha^{-1} day^{-1}) for four N rates 0N, LN, MN, HN with compost and no compost during a 3 years crop rotation from October 2015 to February 2018 at Matara, Sri Lanka.*

4.1.5b Cumulative fluxes and N_2O emission factors

Cumulative emissions ranged from 2.4 ± 0.5 kg N_2O-N ha^{-1} $year^{-1}$ in the 0N-no compost to 9.2 ± 0.4 kg N_2O-N ha^{-1} $year^{-1}$ in the HN+C treatment (Table 3). The 108 day maize cropping period accounted for the majority (54-64%) of annual emission in the N treatments but only for 24-30% in the 0N treatments. Emissions were generally lower across all treatments in years 2 and 3, averaging between 1.7 – 3.2 kg N ha^{-1} for the no compost and 1.9 to 4.5 kg N ha^{-1} in the compost (Figure 15).

There was an overall effect of N rate on annual N_2O emissions, which increased significantly with the increasing N fertilizer rate. Significant differences in cumulative N_2O emissions were observed between treatments that received N fertilizer and 0N but between fertilizer rates significance varied between crops (Table 6). Average annual emissions showed an increase in N_2O at the higher fertilizer rates in year 1 but no significant difference between rates in year 2. By contrast average N_2O emissions increased significantly with increasing N rates in both years in the treatments that received compost application.

The application of compost significantly ($P<0.05$) increased average annual N_2O emissions by 39% in year 1 and 77% in year 2 at the highest N fertilizer rate, and 73% in the MN rate year 2 ($P=0.063$). While similar increases were observed in maize in the third year of the experiment, increasing spatial error between replicates resulted in no significant differences being observed. The application of compost increased CO_2 emissions only marginally, increasing emissions by 23% though no significant differences were observed due to high spatial error.

The seasonal emission factors (EF's) calculated for the cropping seasons were highest (2.3-3.9%) in maize 1, reflecting the very large emissions measured during this period, and decreased to <1.5% for the subsequent crops (Figure 16). Despite this EF's showed a similar response to N rate and compost throughout the experiment, with highest EFs from LN treatments without compost, with a decreasing or flat trend with increasing N rate (Figure 16). Compost addition resulted in generally higher EFs, though with much greater error possibly due to the heterogeneous nature of GWC. In the MN and HN treatments this increase was by as much as 50% compared to the same N rate with no compost. In Maize 3 compost addition increased EFs in all N rates compared to no compost treatments obtaining the greatest treatment EFs effect from all seasons (increasing 240% in the HN+C treatment), though once again spatial variability was very high.

N_2O intensities (the ratio of N_2O emitted and grain produced) did not differ significantly across treatments in same year compared to 0N, though seasonal N_2O intensities significantly reduced in year 2 and 3 cropping seasons compared to year 1 cropping season in both Maize and soybean crops without negatively impacting cumulative yields (Figure 17). In year 2 and 3 maize cropping season N_2O intensities remained very low (below 0.27) compared to the higher intensities in year 1 cropping season (max 0.69).

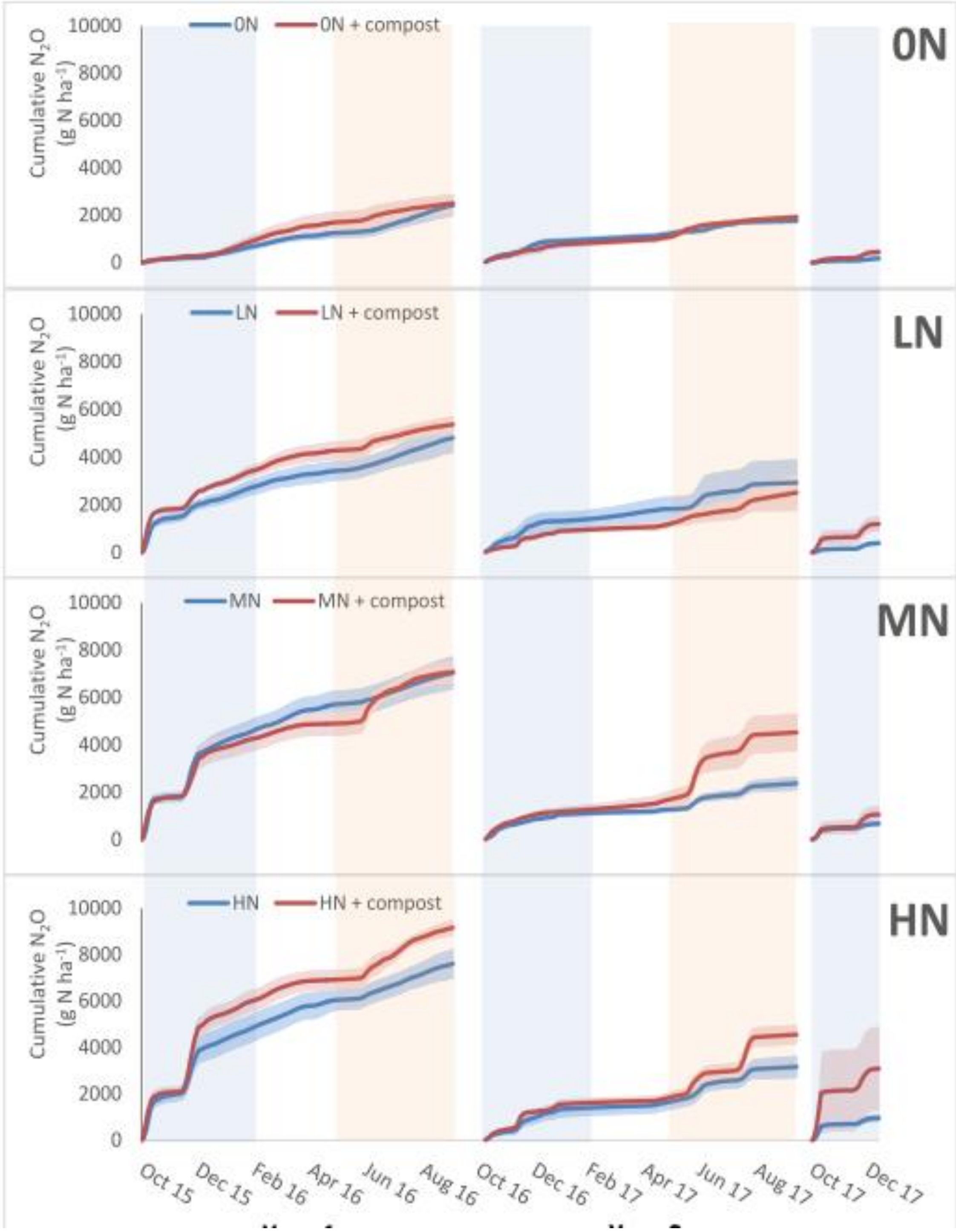

Figure 15. *Cumulative N_2O fluxes (g N ha^{-1}) for four N rates 0N, LN, MN, HN with compost and no compost during a 2.5 year crop rotation from October 2015 to February 2018 at Matara, Sri Lanka.*

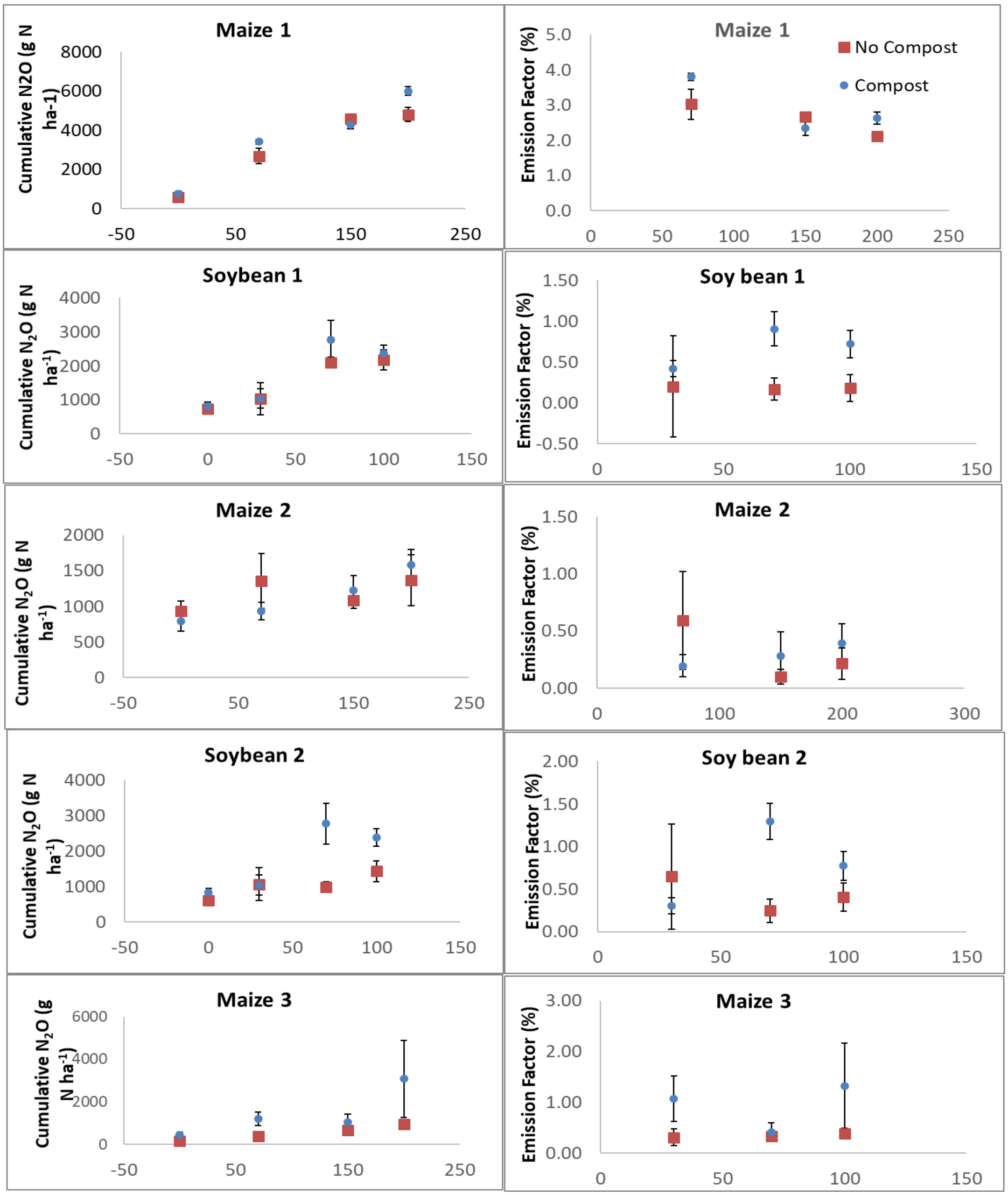

Figure 16. *Seasonal cumulative N2O emissions and fertilizer emission factors with and without compost application for the 2.5 year cropping rotation from October 2015 to February 2018 at Matara, Sri Lanka.*

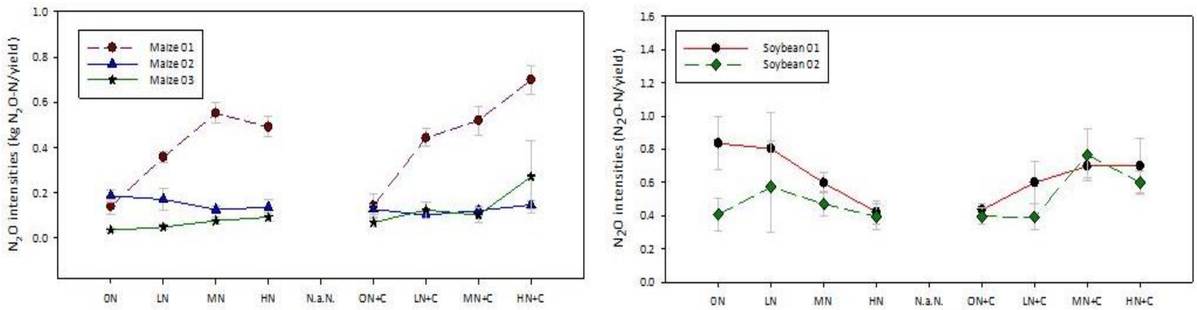

Figure 17. *N_2O intensities calculated as kg N_2O-N per kg of AGB yield for the three maize crops and 2 soybean crops with and without compost application at Matara, Sri Lanka.*

While this study applied compost rates far in excess of typical farmer practice in order to simulate repeated, long-term compost application in a short (<3 years) crop rotation, even at extremely high rates the additional benefits around nutrient supply and retention, improvements in NUE and any benefits on improvement in soil health had on crop growth were not enough to justify the large additional cost of the compost application. In subsidized crops such as rice (20% of the retail price), these cost discrepancies would be even greater and the incentives to pay for composts even less. While further work is required at lower, more economical application rates to determine if similar benefits can be derived over the long term at lower cost, cheaper alternatives to GWC also need to be considered to increase sustainability of tropical cropping systems.

The application of increasing rates of synthetic N fertilizer was the main factor responsible for increasing N_2O emissions in both plus compost and zero compost treatments. Emissions at the site were dominated by the maize cropping period, with highest fluxes immediately after large rain events at both basal and top-dressing fertilizer application. Cumulative N_2O emissions from this Sri Lankan site were very high in all N fertilised treatments, with the annual emissions from the typical regional farmer rate (MN - >7 kg N_2O-N ha^{-1} $year^{-1}$) greater than most global non-irrigated broadacre cropping rotations (Shcherbak *et al.*, 2014; Albanito *et al.*, 2017). Annual emissions were also far in excess of emissions reported from similar climatic regions, such as the 0.2 to 3.9 kg N_2O-N ha^{-1} reported from fertilised maize rotations in tropical Thailand and Malaysia (Watanabe *et al.*, 2000; Khalil *et al.*, 2002) and the 2.0 kg N_2O-N ha^{-1} reported from wheat-maize in sub-tropical Australia (De Antoni Migliorati *et al.*, 2014), and comparable to high N input intensive horticulture (Pfab *et al.*, 2011; Riches *et al.*, 2016).

The high emissions at the site resulted in substantially higher EF's (up to 2.9%) than reported in other broadacre systems and well above the mean of 1.1% reported by Albanito *et al.* (2017) for South Asia. Overall, annual EF's in all treatments above the IPCC default of 1% (IPCC 2006) and increased under repeated compost applications at the higher N application rate. This study demonstrates the potential of low CEC tropical soils for producing high N_2O emissions under extreme temperature and rainfall conditions. However, despite relatively high total C availability as determined by high soil CO_2 emissions, C can still appear limiting to N_2O emissions during crucial loss moments such as when soil mineral N is high following fertilizer application. While the addition of compost appears to have yield benefits at lower N fertilizer application rates, the long term effect of additional C on N losses needs to be considered in these highly weathered soils.

Table 5. *Total above ground biomass yields and (where available) grain and stover yields (Mg DW ha^{-1}), grain and stover N content (kg N ha-1) and apparent nitrogen use efficiency (NUE)* for each crop in the 2.5 year rotation (2015-2018) at Matara, Sri Lanka. Presented P values represent pairwise differences between with and without compost the student 2-way t-test (blue colouring represents α >0.05), while subscript letters indicate significance (P>0.05) between N fertilizer rates (grouped for compost treatment) via analysis of variance (ANOVA) and the post-hoc Tukey multiple-comparison test. All yield data is presented on a dry weight (DW) basis.*

Measurement	**N rates**							
	0N		**LN**		**MN**		**HN**	
Maize 1	0C	15C	0C	15C	0C	15C	0C	15C
Total above ground biomass (Mg ha^{-1})	4.2 ± 0.1^{a}	5.6 ± 0.6^{a}	7.4 ± 0.5^{b}	7.9 ± 0.9^{ab}	8.3 ± 0.5^{bc}	8.3 ± 0.7^{ab}	9.7 ± 0.5^{c}	8.7 ± 0.4^{b}
P value	*0.045*		*0.655*		*0.995*		*0.170*	
Soybean								
Total above ground biomass (Mg ha^{-1})	1.3 ± 0.1^{a}	1.7 ± 0.1^{a}	1.7 ± 0.2^{ab}	1.9 ± 0.4^{ab}	2.1 ± 0.1^{b}	3.0 ± 0.2^{ab}	3.6 ± 0.3^{c}	3.5 ± 0.6^{b}
P value	*0.007*		*0.525*		*0.007*		*0.852*	
Maize 2								
Total above ground biomass (Mg ha^{-1})	5.0 ± 0.1^{a}	6.2 ± 0.2^{a}	7.9 ± 0.0^{b}	9.1 ± 0.2^{b}	8.6 ± 0.3^{b}	10.0 ± 0.1^{c}	10.1 ± 0.2^{c}	10.7 ± 0.2^{c}
P value	*0.003*		*0.001*		*0.005*		*0.095*	
Total N content (kg N ha^{-1})	45.9 ± 4.5^{a}	74.4 ± 3.6^{a}	106.3 ± 4.4^{b}	124.2 ± 11.5^{b}	140.5 ± 5.6^{b}	158.8 ± 19.4^{c}	141.5 ± 9.1^{c}	164.2 ± 19.1^{c}
P value	*0.004*		*0.198*		*0.399*		*0.325*	
Apparent NUE (%)			***83.5 ± 7.4***	***109.0 ± 18.6***	***61.7 ± 4.4***	***73.9 ± 14.5***	***46.8 ± 4.4***	***58.2 ± 10.1***
Soybean 2								
Total above ground biomass (Mg ha^{-1})	1.5 ± 0.0^{a}	2.1 ± 0.0^{a}	1.9 ± 0.1^{a}	2.6 ± 0.2^{a}	2.1 ± 0.1^{a}	3.6 ± 0.0^{b}	3.6 ± 0.2^{b}	4.0 ± 0.3^{b}
P value	*0.000*		*0.002*		*0.000*		*0.852*	
Total N content (kg N ha^{-1})	20.5 ± 1.3^{a}	32.4 ± 2.8^{a}	32.3 ± 2.1^{ab}	45.9 ± 5.2^{ab}	42.9 ± 3.8^{b}	59.7 ± 2.5^{bc}	73.4 ± 5.2^{c}	79.0 ± 9.0^{c}
P value	*0.008*		*0.050*		*0.010*		*0.609*	
Apparent NUE (%)			***39.2 ± 10.3***	***84.7 ± 13.3***	***31.9 ± 3.7***	***56.0 ± 4.7***	***52.9 ± 5.3***	***58.5 ± 9.0***
Maize 3								
Total above ground biomass (Mg ha^{-1})	4.9 ± 0.2^{a}	6.3 ± 0.6^{a}	8.0 ± 0.1^{b}	9.7 ± 0.5^{b}	8.8 ± 0.6^{c}	10.4 ± 0.1^{b}	10.2 ± 0.3^{d}	11.4 ± 0.4^{c}
P value	*0.017*		*0.012*		*0.001*		*0.030*	

Grain yield (Mg ha^{-1})	2.3 ± 0.2^{a}	2.4 ± 0.2^{a}	3.8 ± 0.2^{b}	3.6 ± 0.1^{b}	4.1 ± 0.3^{bc}	4.8 ± 0.1^{c}	4.3 ± 0.1^{c}	4.8 ± 0.2^{c}
P value	*0.303*		*0.149*		*0.004*		*0.008*	
Grain N content (kg N ha^{-1})	41.6 ± 3.5^{a}	46.7 ± 4.6^{a}	64.6 ± 7.8^{ab}	63.6 ± 7.2^{a}	73.5 ± 4.3^{b}	91.2 ± 2.5^{b}	77.8 ± 7.3^{b}	92.8 ± 11.8^{b}
P value	*0.408*		*0.925*		*0.012*		*0.322*	
Stover yield (Mg ha^{-1})	2.6 ± 0.3^{a}	3.8 ± 0.7^{a}	4.2 ± 0.2^{b}	6.1 ± 0.7^{bc}	4.6 ± 0.5^{c}	5.6 ± 0.3^{b}	5.9 ± 0.5^{d}	6.5 ± 0.5^{c}
P value	*0.018*		*0.001*		*0.022*		*0.116*	
Stover N content (kg N ha^{-1})	46.0 ± 7.0^{a}	69.8 ± 12.6^{a}	65.5 ± 7.0^{ab}	117.4 ± 8.2^{b}	80.7 ± 7.2^{b}	111.3 ± 13.8^{ab}	88.4 ± 5.8b	114.4 ± 4.0^{b}
P value	*0.150*		*0.003*		*0.096*		*0.010*	
Total N content (kg N ha^{-1})	87.6 ± 6.7^{a}	116.5 ± 12.9^{a}	130.2 ± 14.2^{ab}	181.0 ± 11.6^{b}	154.3 ± 11.4^{b}	202.5 ± 15.3^{b}	166.2 ± 12.5^{b}	207.2 ± 9.9^{b}
P value	*0.094*		*0.032*		*0.045*		*0.042*	
Apparent NUE (%)			***60.8 ± 11.8***	***133.4 ± 20.1***	***44.4 ± 5.4***	***76.6 ± 10.6***	***39.3 ± 3.6***	***59.8 ± 5.5***

*NUE calculated accounting for N uptake in the respective 0N treatments divided by synthetic N application rate applied for each crop

Table 6. *Seasonal average and cumulative N_2O and CO_2 fluxes and average annual emissions for Oct 2015 to Oct 2016 (year 1) and Oct 2016 to Oct 2017 (year 2). Presented P values represent pairwise differences between with and without compost the student 2-way t-test (blue colouring represents α >0.05), while subscript letters indicate significance (P>0.05) between N fertilizer rates (grouped for compost treatment) via analysis of variance (ANOVA) and the post-hoc Tukey multiple-comparison test.*

Measurement	**N rates**							
	0N		**LN**		**MN**		**HN**	
Maize 1	0C	15C	0C	15C	0C	15C	0C	15C
Average flux (g N_2O-N ha^{-1} day^{-1})*	5.1 ± 1.2^{a}	5.8 ± 1.7^{a}	25.1 ± 3.2^{b}	35.0 ± 2.0^{b}	45.8 ± 6.3^{c}	45.9 ± 5.2^{c}	47.4 ± 6.3^{c}	62.6 ± 5.1^{c}
Cumulative flux (kg N_2O-N ha^{-1} $season^{-1}$)*	0.6 ± 0.1^{a}	0.8 ± 0.2^{a}	2.7 ± 0.3^{b}	3.4 ± 0.2^{b}	4.6 ± 0.5^{b}	4.3 ± 0.5^{b}	4.8 ± 0.6^{b}	6.0 ± 0.4^{b}
Average flux (kg CO_2 ha^{-1} day^{-1})*	30.4 ± 3.8^{a}	36.2 ± 6.2^{a}	38.1 ± 4.3^{a}	44.5 ± 4.5^{a}	41.7 ± 4.2^{a}	52.4 ± 9.2^{a}	47.3 ± 7.3^{a}	48.7 ± 5.1^{a}
Cumulative flux (Mg CO_2 ha^{-1} $season^{-1}$)*	3.2 ± 0.4^{a}	4.0 ± 0.7^{a}	4.2 ± 0.4^{a}	4.8 ± 0.6^{a}	4.5 ± 0.5^{a}	5.6 ± 1.0^{a}	5.1 ± 0.8^{a}	5.2 ± 0.5^{a}
Fallow								
Average flux(g N_2O ha^{-1} day^{-1})*	5.8 ± 1.0^{a}	8.2 ± 1.9^{a}	7.2 ± 0.9^{a}	8.6 ± 1.3^{a}	11.8 ± 2.1^{a}	6.6 ± 0.8^{a}	12.3 ± 1.5^{a}	9.2 ± 0.9^{a}
Cumulative flux (kg N_2O ha^{-1} $season^{-1}$)*	0.7 ± 0.1^{a}	1.0 ± 0.2^{a}	0.9 ± 0.1^{a}	0.9 ± 0.2^{a}	1.1 ± 0.1^{a}	0.7 ± 0.1^{a}	1.3 ± 0.2^{a}	1.0 ± 0.1^{a}
Average flux (kg CO_2 ha^{-1} day^{-1})*	25.1 ± 2.2^{a}	31.4 ± 2.2^{a}	28.6 ± 2.4^{a}	30.3 ± 3.0^{a}	32.6 ± 2.0^{a}	36.1 ± 5.1^{a}	35.5 ± 2.7^{a}	35.6 ± 5.1^{a}
Cumulative flux (Mg CO_2 ha^{-1} $season^{-1}$)*	3.5 ± 0.3^{a}	4.1 ± 0.5^{a}	3.6 ± 0.2^{a}	3.9 ± 0.4^{a}	4.1 ± 0.3^{a}	4.6 ± 0.7^{a}	3.4 ± 0.3^{a}	4.6 ± 0.1^{a}
Soybean								
Average flux(g N_2O ha^{-1} day^{-1})*	10.4 ± 2.2^{a}	7.4 ± 0.7^{a}	12.3 ± 2.9^{a}	10.7 ± 0.5^{a}	12.3 ± 1.1^{a}	22.8 ± 4.8^{b}	14.9 ± 1.7^{b}	23.1 ± 4.8^{b}
Cumulative flux (kg N_2O ha^{-1} $season^{-1}$)*	1.1 ± 0.3^{a}	0.7 ± 0.1^{a}	1.3 ± 0.3^{a}	1.0 ± 0.1^{a}	1.4 ± 0.2^{b}	2.1 ± 0.2^{b}	1.5 ± 0.3^{b}	2.2 ± 0.5^{b}
Average flux(kg CO_2 ha^{-1} day^{-1})*	33.2 ± 3.8^{a}	31.9 ± 2.7^{a}	33.9 ± 3.7^{a}	36.9 ± 3.1^{a}	35.4 ± 5.5^{a}	45.4 ± 8.6^{a}	37.3 ± 4.8^{a}	39.0 ± 1.5^{a}
Cumulative flux (Mg CO_2 ha^{-1} $season^{-1}$)*	3.1 ± 0.4^{a}	3.4 ± 0.3^{a}	3.6 ± 0.4^{a}	4.0 ± 0.4^{a}	3.8 ± 0.7^{a}	4.8 ± 0.4^{a}	5.1 ± 0.8^{a}	4.1 ± 0.3^{a}
Maize 2								
Average flux (g N_2O-N ha^{-1} day^{-1})*	11.8 ± 1.0^{a}	9.3 ± 2.0^{a}	18.2 ± 4.0^{a}	12.4 ± 1.7^{a}	14.9 ± 0.4^{a}	19.5 ± 1.4^{a}	18.5 ± 3.1^{b}	24.0 ± 1.1^{b}
Cumulative flux (kg N_2O-N ha^{-1} $season^{-1}$)*	0.94 ± 0.1^{a}	0.8 ± 0.1^{a}	1.4 ± 0.4^{a}	0.9 ± 0.1^{a}	1.1 ± 0.1^{a}	1.1 ± 0.2^{a}	1.4 ± 0.4^{a}	1.6 ± 0.2^{a}
Average flux (kg CO_2-C ha^{-1} day^{-1})*	45.6 ± 4.3^{a}	35.5 ± 2.1^{a}	36.7 ± 2.5^{a}	33.7 ± 1.9^{a}	27.2 ± 0.5^{a}	39.3 ± 2.9^{a}	32.5 ± 1.5^{a}	37.0 ± 1.7^{a}
Cumulative flux (Mg CO_2-C ha^{-1} $season^{-1}$)*	4.7 ± 0.5^{a}	4.0 ± 4.2^{a}	4.1 ± 0.3^{a}	3.9 ± 3.1^{a}	3.1 ± 0.3^{b}	3.6 ± 3.4^{a}	3.8 ± 0.2^{a}	3.9 ± 3.9^{a}

Soybean 2								
Average flux(g N_2O-N ha^{-1} day^{-1})*	3.6 ± 0.6^{a}	7.0 ± 0.4^{a}	10.1 ± 2.8^{a}	9.7 ± 1.1^{a}	12.0 ± 0.8^{b}	32.8 ± 3.1^{c}	14.2 ± 1.9^{b}	32.0 ± 2.6^{c}
Cumulative flux (kg N_2O-N ha^{-1} season^{-1})*	0.6 ± 0.1^{a}	0.8 ± 0.1^{a}	1.1 ± 0.5^{a}	1.0 ±0.3^{a}	1.0 ± 0.2^{b}	2.8 ± 0.6^{b}	1.4 ± 0.3^{b}	2.4 ± 0.3^{b}
Average flux(kg CO_2-C ha^{-1} day^{-1})*	15.2 ± 2.4^{a}	35.3 ± 2.6^{b}	19.6 ± 1.9^{a}	29.7 ± 4.0^{b}	24.8 ± 0.9^{a}	46.1 ± 3.6^{c}	21.9 ± 2.2^{a}	30.2 ± 2.2^{c}
Cumulative flux (Mg CO_2 ha^{-1} season^{-1})*	2.3 ± 0.3^{a}	4.1 ± 0.4^{b}	2.4 ± 0.3^{a}	3.4 ± 0.9^{b}	2.7 ± 0.2^{a}	4.9 ± 0.8^{b}	2.6 ± 0.3^{a}	3.3 ± 0.2^{b}
Maize 3								
Average flux (g N_2O-N ha^{-1} day^{-1})*	1.9 ± 0.4^{a}	6.4 ± 0.9^{a}	5.9 ± 0.4^{a}	19.2 ± 2.7^{b}	10.1 ± 0.8^{a}	18.0 ± 3.4^{b}	13.9 ± 1.1^{b}	46.0 ± 12.8^{c}
Cumulative flux (kg N_2O ha^{-1} season^{-1})*	0.2 ± 0.1^{a}	0.4 ± 1.3^{a}	0.4 ± 0.1^{a}	1.2 ± 0.3^{a}	0.7 ± 0.1^{a}	1.1 ± 0.4^{a}	1.0 ± 1.7^{a}	3.1 ± 1.8^{a}
Average flux(kg CO_2-C ha^{-1} day^{-1})*	17.5 ± 1.4^{a}	38.2 ± 2.0^{b}	20.3 ± 0.5^{a}	28.1 ± 1.7^{b}	23.0 ± 1.7^{a}	31.3 ± 2.3^{b}	20.3 ± 1.2^{a}	34.7 ± 0.6^{b}
Cumulative flux (Mg CO_2-C ha^{-1} season^{-1})*	1.5 ± 0.1^{a}	2.6 ± 0.3^{b}	1.4 ± 0.1^{a}	2.1 ± 0.2^{b}	1.7 ± 0.2^{a}	2.2 ± 0.3^{b}	1.5 ± 0.2^{a}	2.5 ± 0.1^{b}
Annual								
Year 1: average flux (g N_2O-N ha^{-1} day^{-1})*	7.7 ± 1.5^{a}	6.9 ± 0.7^{a}	16.5 ± 2.4^{ab}	19.7 ± 0.9^{b}	25.0 ± 2.8^{bc}	29.2 ± 1.8^{c}	27.0 ± 2.9^{c}	36.2 ± 1.1^{d}
P value	*0.656*		*0.277*		*0.264*		*0.043*	
Year 2: average flux (g N_2O-N ha^{-1} day^{-1})*	9.2 ± 1.2^{a}	8.8 ± 1.5^{a}	14.8 ± 6.6^{a}	11.7 ± 2.4^{a}	14.0 ± 1.4^{a}	24.5 ± 3.8^{b}	17.2 ± 2.9^{a}	29.0 ± 2.9^{b}
P value	*0.833*		*0.678*		*0.063*		*0.028*	
Year 1: Average flux(kg CO_2-C ha^{-1} day^{-1})*	30.9 ± 3.6^{a}	33.5 ± 1.9^{a}	34.7 ± 2.0^{a}	38.8 ± 2.6^{a}	37.4 ± 3.5^{a}	46.7 ± 7.9^{a}	40.6 ± 3.7^{a}	42.2 ± 2.5^{a}
P value	0.557		0.254		0.341		0.742	
Year 2: Average flux(kg CO_2-C ha^{-1} day^{-1})*	35.5 ± 4.5^{a}	37.4 ± 4.9^{a}	30.7 ± 3.3^{a}	33.3 ± 4.8^{a}	27.7 ± 1.5^{a}	41.8 ± 5.8^{a}	28.3 ± 2.3^{a}	34.2 ± 2.9^{a}
P value	0.786		0.666		0.084		0.165	

4.2 India (ICRISAT)

Annual rainfall for the 2017-18 kharif/rabi seasons was 1126 mm, 730 mm fell over the July to January cropping period, 100% of which fell during the rice crop, with no rainfall at all recorded during the chickpea (rabi) crop (Figure 18). Mean minimum and maximum temperatures for the rice season were 22.0°C and 30.3°C respectively, with average minimum temperatures dropping to 13.4°C during the chickpea crop.

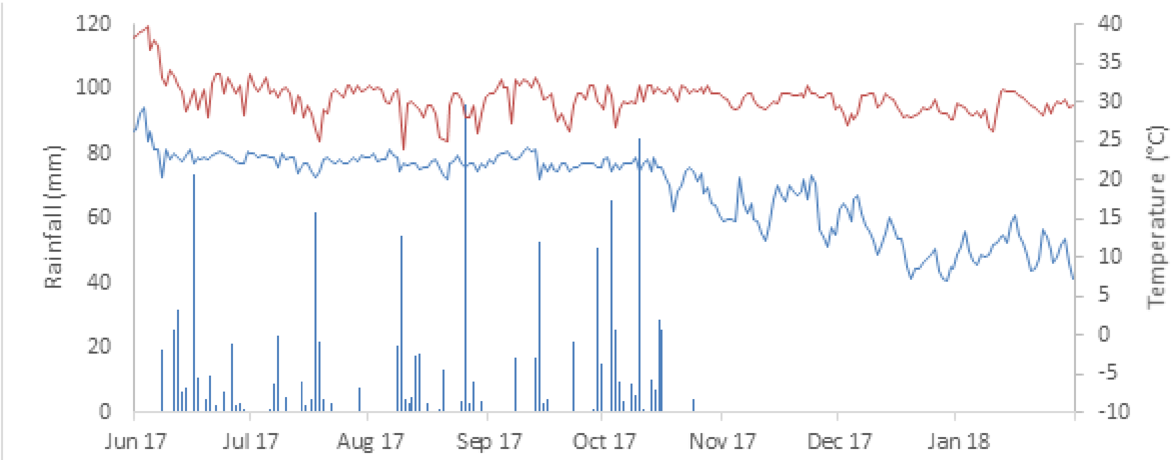

Figure 18. Daily rainfall, minimum and maximum temperature for the research site at ICRISAT, India during the 2017-18 rice and chickpea cropping seasons.

4.2.1 Rice and chickpea yields

No significant difference between rice stover yields was observed, though a 13% and 17% yield penalty ($P<0.05$) from farmer practice (FP) associated with the vermi-compost (VC) and poultry manure (PM) respectively was observed in the grain yield (Figure 19). There was no significant difference between FP and farm-yard manure in either grain or stover production. By contrast there was a striking increase in chickpea grain yields in all OA treatments compared to the FP which failed to set seed, with yields in the PM, VC and FYM increasing by a factor of 5, 10 and 19 respectively (Figure 20). This equated to a yield increase of 1,268 kg ha^{-1} in the FYM, 634 kg ha^{-1} VC and 286 kg ha^{-1} for the PM.

Yield results were also reflected in the crop N uptake (Figure 21) which in the rice was highest in the FP with 131 kg ha^{-1} total (grain + stover) N uptake, suggesting the majority of the 120 kg of N applied as urea made it into the crop. This was followed by the FYM, VC and PM with 126, 112 and 111 kg N ha^{-1} respectively. This was equivalent to a deficit in N uptake of between 6-21 kg N ha^{-1} in the treatments which received OA compared to the FP. In the chickpeas by comparison, FP had the lowest total crop N uptake with 8.1 kg N ha^{-1}, followed by the PM (13.7 kg N ha^{-1}), VC (21.8 kg N ha^{-1}) and FYM (50.0 kg N ha^{-1}). This led to significant positive N differentials between OA treatments and the FP, the largest being >40 kg N ha^{-1} in the FYM. As with plant N uptake, total P and K uptake in the rice showed no difference between treatments in the rice, while the higher yields from the FYM also resulted in significantly higher uptake in the chickpea (Figure 22). No significant difference ($P>0.05$)

was observed between FP and OA treatments in total organic carbon or total N, P or K in any of the treatments (Figure 23).

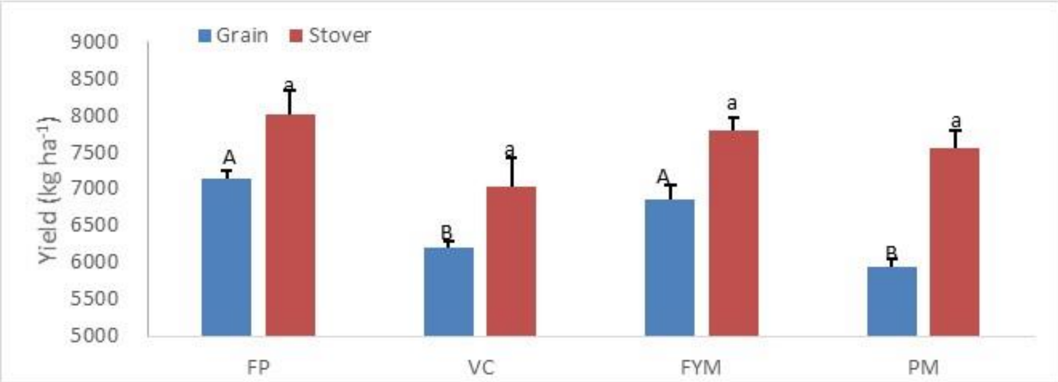

Figure 19. Rice stover and grain yields for the farmers practice (FP), vermi-compost (VC), farmyard manure (FYM) and poultry manure (PM) treatments at ICRISAT, India. Letters indicate significant differences between treatments (*P*<0.05).

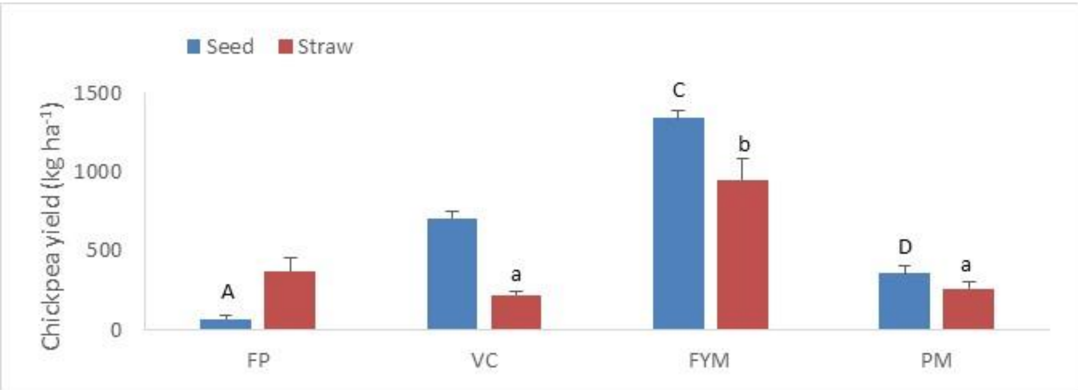

Figure 20. Chickpea seed and straw yields for the farmers practice (FP), vermi-compost (VC), farmyard manure (FYM) and poultry manure (PM) treatments at ICRISAT, India. Letters indicate significant differences between treatments (*P*<0.05).

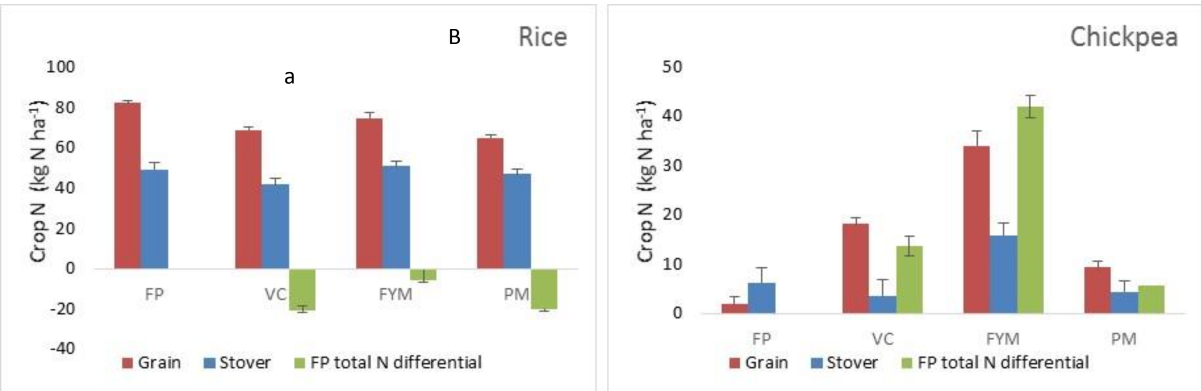

Figure 21. *Crop N uptake in the grain and stover and the difference in total N (grain + stover) compared to the farmer practice (FP) treatment for the rice and chickpea crops at ICRISAT, India.*

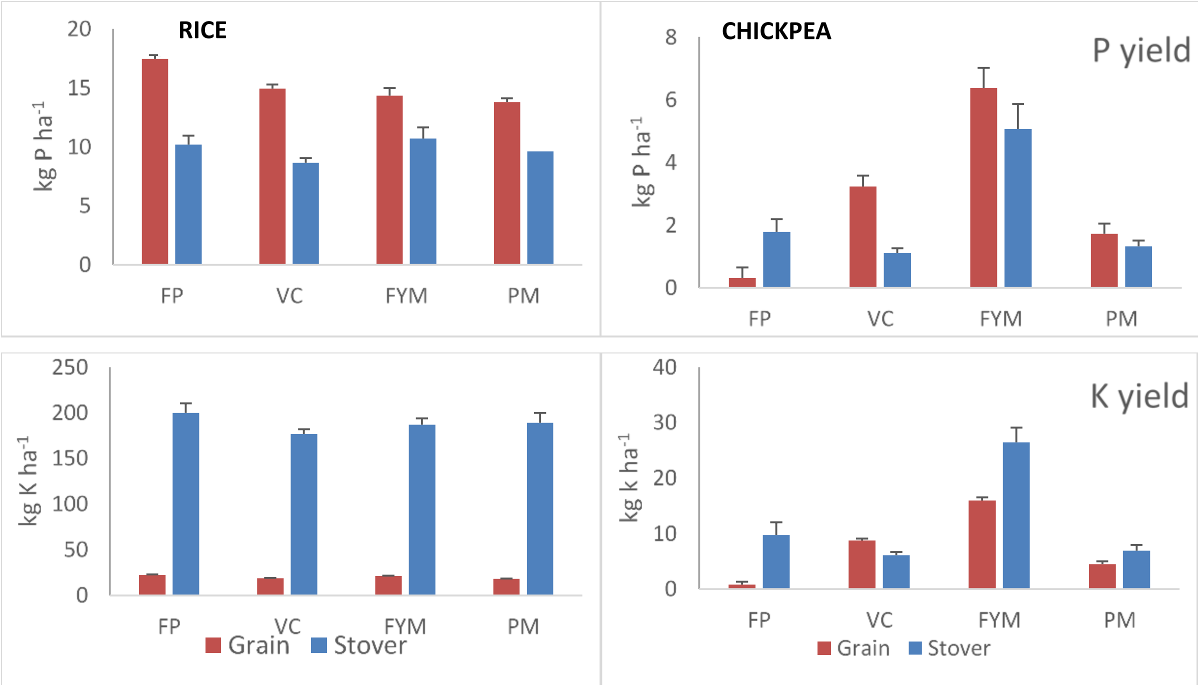

Figure 22. *Total phosphorus (P) and potassium (K) recovery (kg ha*$^{-1}$*) in the grain and stover for the rice and chickpea crops*

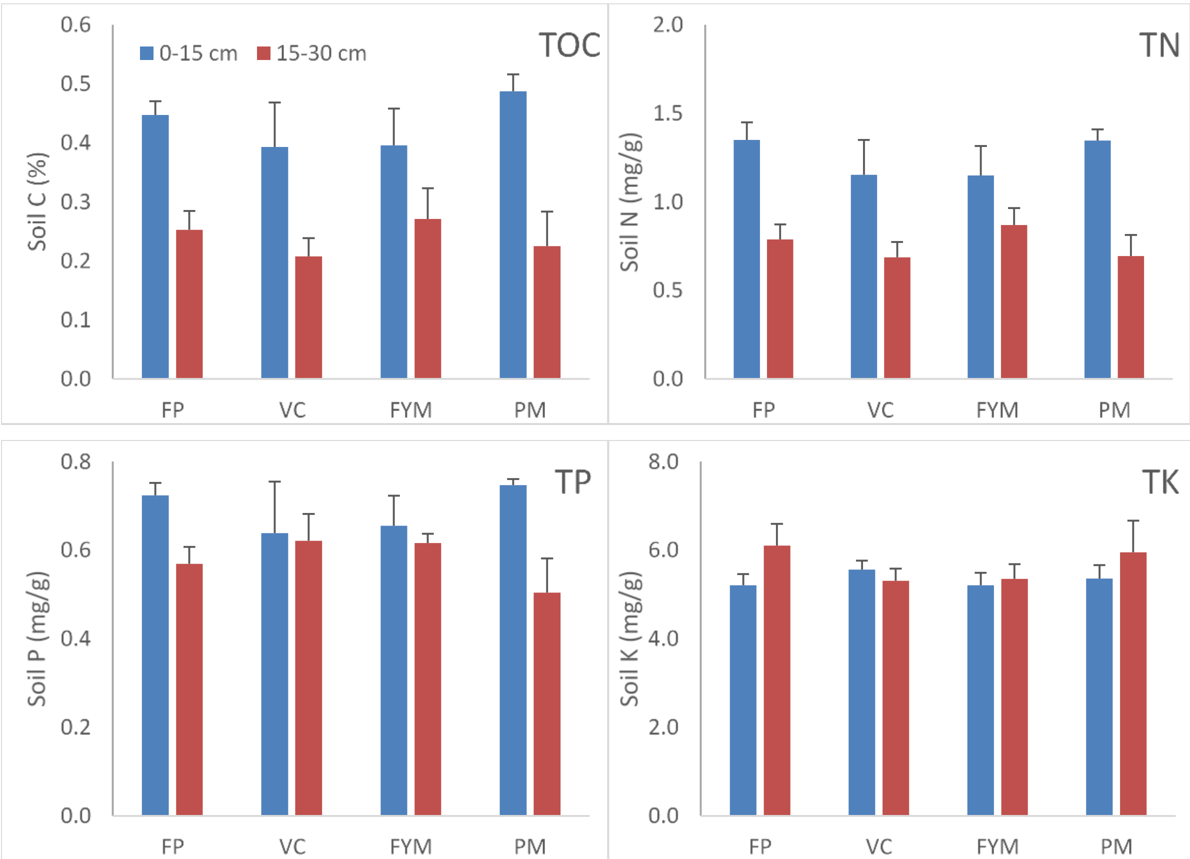

Figure 23. Total organic carbon (%TOC), total nitrogen (TN), total phosphorus (TP) and total potassium (TK) recovery (mg g^{-1}) in the top 0-15 and 15-30 cm at the end of the chickpea crop.

4.2.2 Influence of OA application on GHG emissions

Overall emissions of both N_2O and CH_4 were relatively low, with cumulative totals of just 11.8 g N_2O-N ha^{-1} and 2900 g CH_4-C ha^{-1} respectively for the farmer treatment. Over 98% of emissions occurred during the rice crop, with the majority being emitted after the first urea topdressing. Only the application of the PM amendment had any significant impact on emissions, reflecting its high N availability by increasing N_2O by a factor of ten. While both the VC and FYM showed slightly higher mean CH_4 emissions, high variability between plots prevented any treatment differences being significant.

Methane was by far the most important greenhouse gas contributor, accounting for >95% of global warming potential (GWP: N_2O + CH_4 expressed in CO_2-equivalents) in the farmers practice treatment (Table 7). A similar effect was seen across the OA treatments, with the exception of the PM where the high N_2O emissions, combined with non-significant but lower CH_4 fluxes, increased the contribution of N_2O to total GWP to over 50%. Overall, total GWP was lowest in the FP with 135 kg CO_2-eq ha^{-1} followed closely by PM, before increasing to almost 200 kg CO_2-eq ha^{-1} in the FYM and VC due to higher CH_4 emissions.

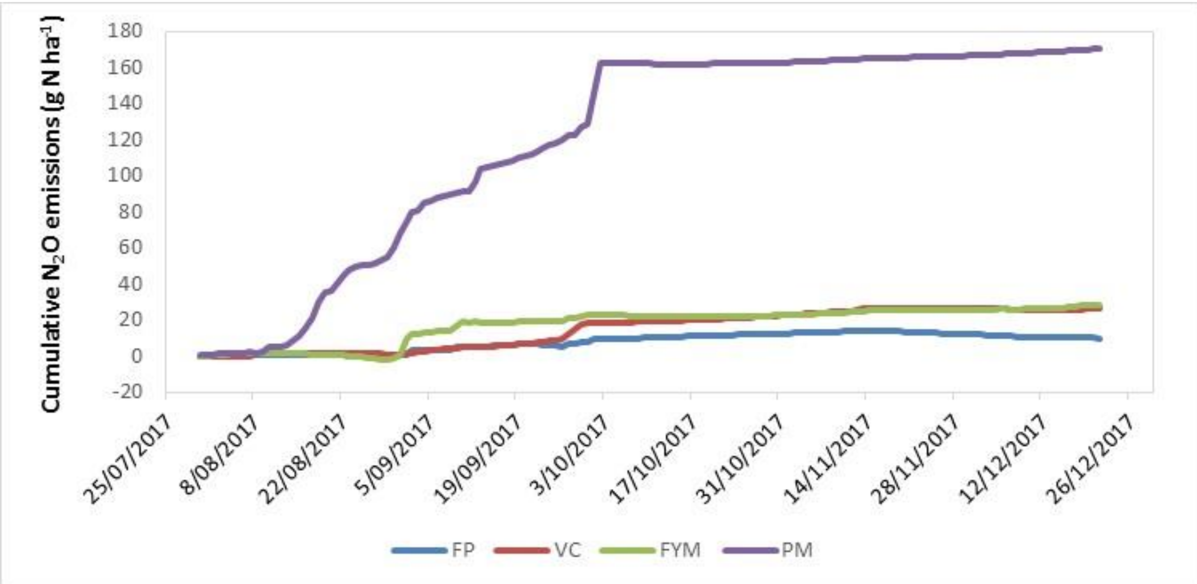

Figure 23. Cumulative N_2O (g N ha^{-1}) emissions from the Rice-chickpea rotation at ICRISAT 2017-18.

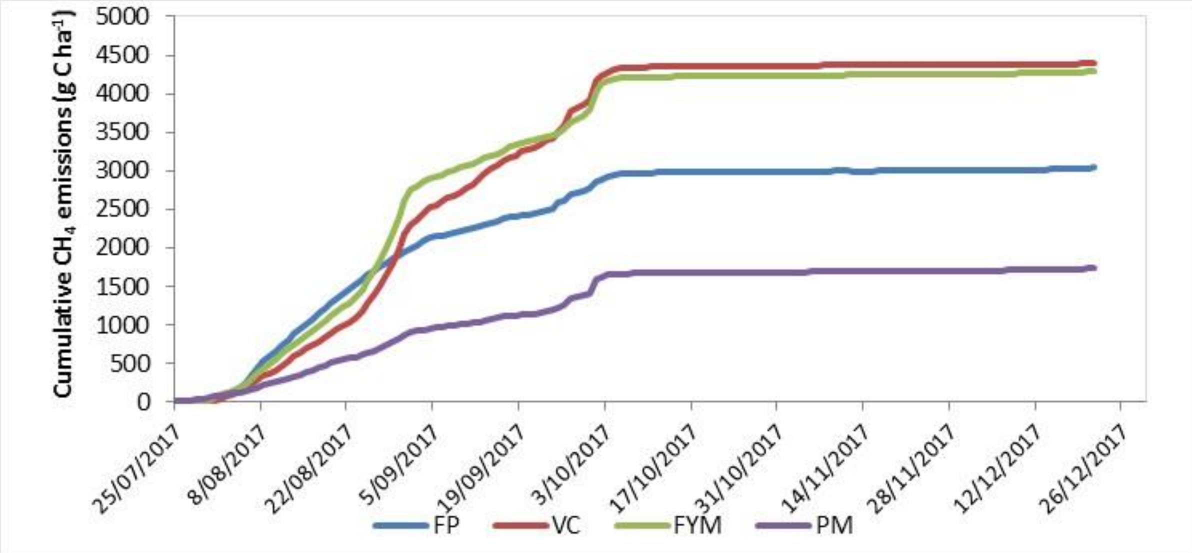

Figure 24. Cumulative CH_4 (g C ha^{-1}) emissions from the Rice-chickpea rotation at ICRISAT 2017-18.

Table 7. Average daily and cumulative emissions of N_2O and CH_4 for the control (FP) and organic amendment treatments, along with their respective and total global warming potentials (GWP) expressed in kg of CO_2 equivalents. Subscript letters indicate significance (P<0.05) between OA treatments via analysis of variance (ANOVA) and the post-hoc Tukey multiple-comparison test.

	Farmers Practice	**Vermi-Compost**	**Farmyard Manure**	**Poultry Manure**
Average daily N_2O (g N ha^{-1})	0.21 ± 0.13^a	0.29 ± 0.17^a	0.58 ± 0.33^a	2.71 ± 1.10^b
Cumulative N_2O (g N ha^{-1})	11.8 ± 9.7^a	21.2 ± 18^a	22.0 ± 18^a	162 ± 38^b
N_2O GWP (kg CO_2- eq)*	*5.5 ± 4.5^a*	*9.9 ± 8.4^a*	*10.3 ± 8.4^a*	*75.9 ± 17.8^b*
Average daily CH_4 (g C ha^{-1})	23.9 ± 11.6^a	39.6 ± 11.1^a	31.3 ± 12.9^a	14.9 ± 8.0^a
Cumulative CH_4 (kg C ha^{-1})	2.86 ± 1.30^a	4.17 ± 1.73^a	4.03 ± 2.04^a	1.60 ± 0.88^a
CH_4 GWP (kg CO_2- eq)*	*130.0 ± 63.6^a*	*189.5 ± 78.6^a*	*183.2 ± 92.7^a*	*72.7 ± 40.0^a*
Total GWP	**135.5 ± 63.6**	**199.4 ± 87.1**	**193.5 ± 101.1**	**148.6 ± 57.8**

*CO_2-eq were calculated using a GWP of 298 and 24 for N_2O and CH_4 respectively.

In the rice, the inability for the VC and PM products to supply the 25% reduction in synthetic is likely due to lower than expected total N concentrations, lower total N availability and slower mineralization rates from the VC and PM products. VC only contained 1.1% N (equivalent to 55.2 kg N ha^{-1}) and under the anaerobic rice paddy conditions the N stabilised during the composting process would have mineralized very slowly or even immobilized some of the urea N applied. The PM also failed to supply sufficient N to meet crop demand despite its relatively high N content (3.2%) and low CN ratio and therefore expected availability. One possible explanation for this is the high and consistent N_2O emissions from the PM during the paddy crop, which combined with the anaerobic conditions suggests high rates of N losses via microbial denitrification limited yields.

The high N content and apparent availability created significant N_2O production during the rice, despite the constant anaerobic conditions. While not possible to quantify, this most likely also increased total denitrification losses (N_2O+N_2), which were high enough to limit yield potentials in both the rice and the subsequent chickpea crop. In contrast it appears that only very limited amounts of N were either mineralised or lost from the FYM and VC during the anaerobic conditions, limiting plant uptake in the rice but also preserving N for the post-rice chickpea crop. While the most significant yields were observed in the FYM, both the VC and PM also increased yields compared to the FP, albeit at a much lesser degree. This increase in chickpea yield could be contributed to a number of things: 1) insufficient N or P being available in the FP at the end of the rice crop due to high uptake during the growing season limiting chickpea growth, 2) higher water use by the larger rice plants under the FP depleting soil moisture availability in the subsequent chickpea crop, 3) improved soil structure following OA application allowing the chickpeas to access soil moisture deeper in the profile, or 4) increased N and P availability though OA mineralisation. While all reasons most likely contributed to some extent, the dramatic increase in the FYM yields, which also had over double the total N input of the other OA's (128.5 kg N ha^{-1}) suggests increased N availability played an important role in increasing yields in post-rice crops.

4.2.3 Economics of organic amendment application in India

Local prices (Hyderabad, India) for the VC, PM and FYM are $70, $40 and $48 USD per Mg. In terms of relative value of the macro nutrients added, the PM represented greatest nutrient load at $46.33 Mg^{-1} ($3.2, $30.8 and $10.3 for N, P and K respectively), followed by FYM at $20.30 Mg^{-1} ($4.2, $8.2 and $7.9) and VC at $9.60 ($1.8, $4.3 and $3.5). The significant yield increase in the chickpea resulted in the marginal cost to produce 1 kg of chickpea of $0.19 USD for FYM, $0.21 for PM and $0.55 for VC. The FYM and PM also contains substantial carbon (24% and 19% respectively) which may provide additional long-term benefits that are difficult to quantify, while the VC appeared to have a large mineral (soil) component with only 10% carbon.

At a local commodity price of Rs 62 (0.87 USD) per kg of chickpea the return on investment (accounting for fertilizer costs only) for 1 kg of OA was $4.60 for FYM, $4.10 and $1.60 for VC. Some of this additional benefit would have been offset in the rice where the 25% reduction in urea application only reduced costs by $10.60 ha^{-1}. However, without a urea only comparison in the chickpea it's not possible to compare these returns to synthetic fertilizer costs.

5 Conclusions

This project had three major aims; (1) quantify N turnover and N_2O losses from a range of commonly used OA across India and Sri Lanka, (2) examine the potential for increasing NUE by better accounting for N in OA to provide recommendations for the use of OA by local farming communities and (3) enhance capacity of global change research in India and Sri Lanka.

In both Sri Lanka and India significant increases in yields could be demonstrated with both the medium (2.5 years) and short (1 year) term application of organic amendments. However, the high relative cost of OA's compared to synthetic bagged fertilizers requires substantial additional benefits above the value of the nutrients alone to make their use economical. This effect is exacerbated under fertilizer subsidies which skewer the economic benefits even further away from organic amendment use. Additionally, the use of these products in all cases increased GHG emissions through the application of additional N or through higher carbon inputs which can stimulate both the production of N_2O through denitrification and CH_4 through methanogenesis in low carbon soils. As such for environmental gains to be realised, their use has to be coupled with either reduced use of urea or ammonium based fertilizers, thus saving GHG's consumed in the production process, with decreased emission intensities (kg yield per kg GHG) or through increased carbon sequestration in soils.

An important mechanism for reducing the economic costs, optimising benefits and maximising farmer uptake of organic amendments is to understand the difference in inherent properties of individual products and the possible benefits/drawbacks of each. Organic amendments vary greatly in terms of nutritional load, carbon and nitrogen stability and price and ultimately it is a case of the right tool for the right job. For instance:

- green waste compost is rich in carbon, but low in available nutrients, and is most economical to apply to heavily cultivated soils (for instance green leafy vegetables) which have been depleted in carbon and subsequently has low structure, infiltration or water holding capacity. It is uneconomical to apply as a nutrient source.
- In rice the addition of a relatively available N source such as PM can lead to large N losses and increase N_2O emissions even under anaerobic conditions
- Composts are expensive and generally low in nutrients (total and available) and are often marketed as improving soil health with little evidence. In this study the commercial vermi-compost obtained was only 10% carbon so those additional benefits might not be available
- Organic amendments are extremely variable in terms of product quality depending on the original organic source material, storage conditions and age. Understanding this variability is critical for the integration of OAs into synthetic fertilizer budgets.

6. Future Directions

Longitudinal studies are required to demonstrate the long-term, cumulative soil benefits of repeated OA application across a range of management and amendment types. This would allow lower application rates to be examined, increasing the economic viability, as well as environmental sustainability of these products. Ultimately user friendly tools are required that help farmers navigate the complexity of using organic amendments, allow greater confidence in nutrient release predictions and allow farmers to reduce their GHG footprint while increasing agricultural sustainability. This is the current aim of a newly commenced national project across 12 sites and agricultural industries in Australia which will provide the scientific basis, quality predictions and farmer tools to assist farmers across the tropics better manage their organic amendments.

7. Appendix

Conferences:

1. International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", 4 – 8 December 2016, Melbourne, Australia. www.ini2016.com

   Attendees:

   Anuga Liyanage, University of Ruhuna, Sri Lanka (anugaliyanage@gmail.com).

   David Rowlings, QUT, Australia (d.rowlings@qut.edu.au).

Workshops:

1. "Expanding young researchers' knowledge on options for reducing agricultural emissions", Climate, Food and Farming Network (CLIFF) workshop, Cologne, Germany. 6-17 November 2017.

   Attendees:

   Kurku Mamatha, ICRISAT and Professor Jayashankar Telangana State Agricultural University, India (kurkumamatha@gmail.com).

2. High temporal resolution GHG data analysis workshop, ICRISAT, India. 27-28th February 2018.

   Presenter: David Rowlings, QUT, Australia (d.rowlings@qut.edu.au)

   Attendees:

   Kurku Mamatha, ICRISAT and Professor Jayashankar Telangana State Agricultural University, India (kurkumamatha@gmail.com)

   Shanthi, Jagadabhi, ICRISAT, India (J.Shanthi@cgiar.org)

   Mahender Kumar, ICRISAT, India (k.Mahender@cgiar.org)

   Jana Kholova, ICRISAT, India, (J.Kholova@cgiar.org)

   Gopi Nallagarla (gopinathnallagarla@gmail.com)

Seminar

1. Final PhD seminar – Anuga Lyanage, 7th March 2018, University of Colombo.
   Presenter: Anuga Lyanage anugaliyanage@gmail.com

   Attendees:

   David Rowlings, QUT, Australia (d.rowlings@qut.edu.au)

   G.K.L. Konasinghe/ Director International Division University of Colombo, Sri Lanka (kokila@law.cmb.ac.lk)

   Prof. Mahanama /Dean Faculty of Science UOC (maha@chem.cmb.ac.lk)

   Vice Chancellor, University of Ruhuna (vc@admin.ruh.ac.lk)

   Sudheera Ranwala, University of Colombo, Sri Lanka, Ranwala@pts.cmb.ac.lk

Funding sources outside the APN

ICRISAT's funding (5000 USD) obtained from CAAS (Chinese Academy of Agricultural Sciences) was provided to Research Fellow, Dr Padma Shanthi to visit Dr David Rowlings research group at Queensland University of Technology (QUT) for obtaining training in GHG quantification and analyses.

University Grants Commission (Sri Lanka). Automated GHG system training: 21 Oct – 3rd Nov 2017. Funding for Anuga Liyanage to travel to QUT (Australia) for training on data analysis and analytical equipment. ($5000 USD).

CCAFFS Climate, Food and Farming Network (CLIFF) workshop award. Funding for Kurku Mamatha to attend the 9 day workshop in Cologne, Germany in November 2017 ($3000 USD).

LKR 3.5 million - University Grants Commissions (Sri Lankan government) scholarship (Mrs Anuga Liyange), travel expenses and some operating costs and $7,100 from the University of Ruhuna to cover gas analysis.

Sample analysis costs, Central Analytical Research Facility, QUT - $10,000 USD.

In-kind:

QUT international fee-waiver (Mrs Anuga Liyange,) $57,000 USD

Equipment essential for collecting and analysing GHG samples will be provided to the project in-kind including a set of 12, fully automated GHG sampling system valued at $80,000 (ICRISAT).

$20,000 USD In-kind contribution of project lead Dr David Rowlings (0.1 FTE).

List of Young Scientists

Sri Lanka

1. Anuga Lyanage – PhD student QUT (Australia) and University of Colombo (Sri Lanka). anugaliyanage@gmail.com
2. Nishadi Liyanage (nishadi3652.liy@gmail.com). University undergraduate University of Ruhuna. Field and laboratory technician.

India

1. Shanthi, Jagadabhi (J.Shanthi@cgiar.org) – Research fellow
2. Mamatha Kurku (kurkumamatha@gmail.com) – PhD student
3. Mahender Kumar (k.Mahender@cgiar.org)- research field and laboratory technician.
4. Gopi Nallagarla (gopinathnallagarla@gmail.com) – environmental engineer and laboratory technician