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Finding the ways that work

Fair Climate Network

Climate smart farming in India

A pathway to poverty alleviation, food security, and climate adaptation and mitigation

Accion Fraterna Ecology Centre — sustainable . human . nature

PWDS Palmyrah Workers Development Society

the timbaktu collective — in celebration of life

sacred — Social Animation Center for Rural Education and Development (SACRED)

BEST Bharath Environment Seva Team

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Citation

Please cite this report as follows:

K. Kritee, Drishya Nair, Daniel Zavala-Araiza, Malla Reddy, Jeremy Proville and Richie Ahuja (2019). Climate smart farming in India: A pathway to poverty alleviation, food security, and climate adaptation and mitigation. An online report with greenhouse gas flux data from rice and non-rice cropping systems from four agro-ecological regions in India. Published by Environmental Defense Fund, New York, NY.

Acknowledgments

The authors thank, without implicating, Joseph Rudek, Tapan K. Adhya, Terrance Loecke, Steven Hamburg for their collaboration, ideas on experimental design or analysis. For help in conducting the surveys and experiments, we thank the entire Fair Climate Network team, especially Shalini Balireddygari and Obulapathi Dava from Accion Fratrena, Karthik Ram, Abhilash S. R, and D. Athiyaman, from Bharath Environment Seva Team, Murugan Madasamy and Daniel Anandaraj, from Palmyrah Workers Development Society, Ramakrishna V. Dokka, Vasanthkumar Jugga and V. Manikandan from the Timbaktu Collective and Somashekar Balakrishna and Leela Venkataiah from Social Animation Center for Rural Education & Development. Any remaining errors in this report are our own. We also acknowledge Tashina Esteves and Rakesh Tiwari for a few diagrams and photographs. This scientific dimension of these low-carbon (climate smart) farming initiatives in India was embedded in our over-arching low-carbon rural development strategy; and this report complements the results that are either already published and will soon be published in a peer-reviewed scientific journal.

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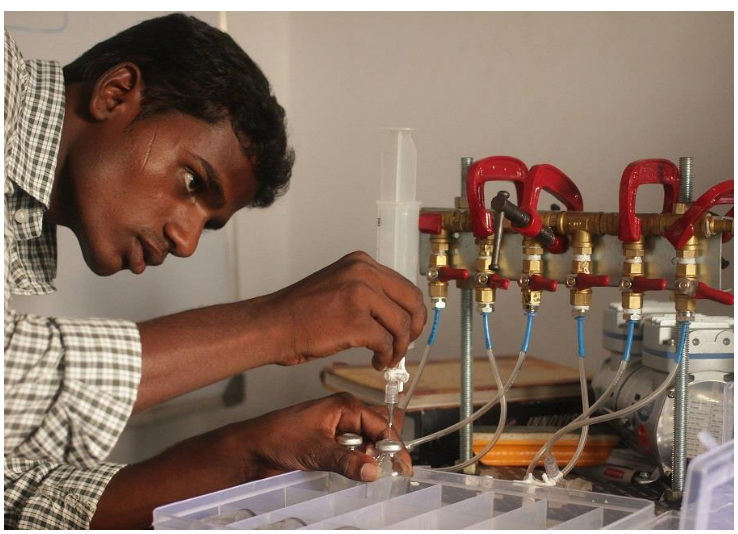
Executive summary

India's challenge is to combat poverty through a development pathway that enhances the nation's food and water security *and* builds climate resilience, while also minimizing GHG emissions. India's agricultural sector GHG emissions are estimated to be 350 million tons a year (18% of the country's total)[1]. But these emissions are poised to grow dramatically in the next several years, particularly if India emulates China's over use of nitrogen fertilizer (now 3.5 times that of India) in an effort to achieve higher yields[2]. Fertilizer and water over-use are forms of waste and hurt the economic bottom line of the farmer while also having deleterious effects on the regional environment and our climate. The over-applied (or excess) fertilizer stimulates soil microbes to release nitrous oxide, a gas whose heat-trapping effect is a staggering >260 times that of carbon dioxide. In addition to nitrous oxide, flooded rice farms release methane, another greenhouse gas whose heat trapping effect is ~80 times that of carbon dioxide over the short time frame. It is crucial to note that, for developing countries like India, minimizing future climate footprint by preparing to avoid GHG emissions is as important as reducing current GHG emissions now.

There are very limited number of academic or research organizations devoted to precise and accurate study of climate impacts of farming in India and all such organizations are focused on crops in irrigated and fertile Indo-gangetic belt in North and North-western India. To meet the needs of semi-arid dryland crops in peninsular India, we fostered a unique paradigm of establishing research laboratories within the official premises of our NGO partners in rural India. Based on inter-comparison of all existing international recommendations, we developed state-of-the-art protocols for tropical and developing parts of the world to determine both the business-as-usual GHG emissions from four Indian crops (rice, groundnut, finger- and foxtail-millet)[3]. We also developed methodologies for determining the extent of mitigation possible via several potential climate smart (or low carbon) farming practices.

A summary of our results in presented in Table 1 where we show that smart management of fertilizers and water can increase/maintain yields and economic profits while decreasing GHG emissions under several conditions. For upland crops[3-5], because of our use of more than three fertilizer application rates, we have been able to show for the first time for Indian crops that nitrous oxide emissions vary non-linearly with changing nitrogen use. For groundnut, N_2O-N (in kg ha^{-1}) = 2.18e-04$(N_{total})^2$ - 1.61e-3N_{total} + 0.668. For millets, N_2O-N (kg ha^{-1}) = 6.34e-05 $(N_{total})^2$ + 3.26e-03 (N_{total}) + constant. We also demonstrate that both the current IPCC and Indian regional linear emission factors of 1% and 0.58%, respectively, are too conservative for high N-input rates. For rice, through our regression and geospatial analysis, we highlight the previously under-appreciated role that nitrous oxide emissions from rice farms can have on increasing global warming[6-9]. We also show a direct correlation between cumulative extent of flooding at rice farms and nitrous oxide emissions, and demonstrate how both methane and nitrous oxide emissions can both be effectively managed through changing fertilizer and water use.

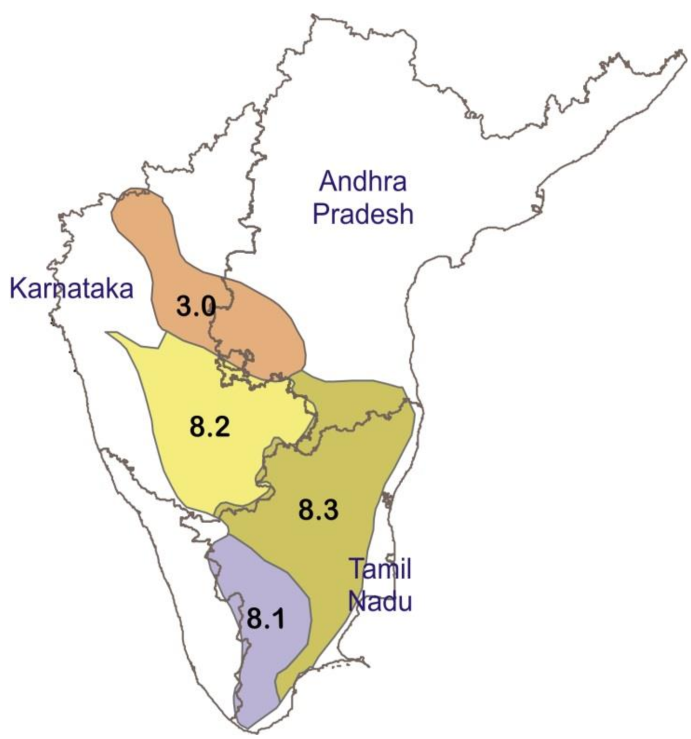


Introduction

Climate change is already imperiling the livelihoods of farmers around the globe by exacerbating droughts, heat waves, floods and other extreme-weather events, as well as creating an influx of new pests and diseases. Worldwide, 500 million small-holder farms produce about 80% of the food consumed in Asia and sub-Saharan Africa, and provide livelihoods for more than 2 billion people[10]. In arid and semi- arid regions – home to more than 40% percent of the world's population, including 650 million of the poorest, most food-insecure people – dryland agriculture is particularly vulnerable to drought. Unless business-as-usual emission trends are altered, additional warming will increasingly devastate these vulnerable agricultural communities, further exacerbating the immense challenges of poverty alleviation, food and water security, and energy access already facing developing countries. Understandably, developing countries want to address climate change through the development framework. Thus, there is an urgent need for strategies that provide a "triple win" by simultaneously:

1. enhancing farmers' economic development through maintenance of crop yields and reduction in input costs
2. making agriculture more resilient to the impacts of climate change, thus enhancing food security at the local, national and even global level
3. minimizing agriculture's future emissions of greenhouse gases (GHGs)

Fig. 1 Study areas: Four agro-ecological regions (AER) in peninsular India



Climate smart farming (CSF), also called Low-carbon farming (LCF) and often referred to locally as Sustainable Agriculture (SA) (and as referred to within the document), practices can deliver on all of these three counts. And as the world moves to implement market-based measures to promote GHG mitigation, markets can offer an additional incentive for small-holder farmers to adopt climate smart practices. The primary reason to adopt CSF should be common sense: the farmers should adopt CSF because they see the direct economic benefits that help promote the well-being of their families and communities. However, for small-holder farmers to find buyers for their carbon credits, the credits must be regarded as legitimate which means that the impact of specific farming practices on yields, farm-economics and climate must be measured and the credits must be certified using a science-based methodology approved by an internationally recognized standard-setting body.

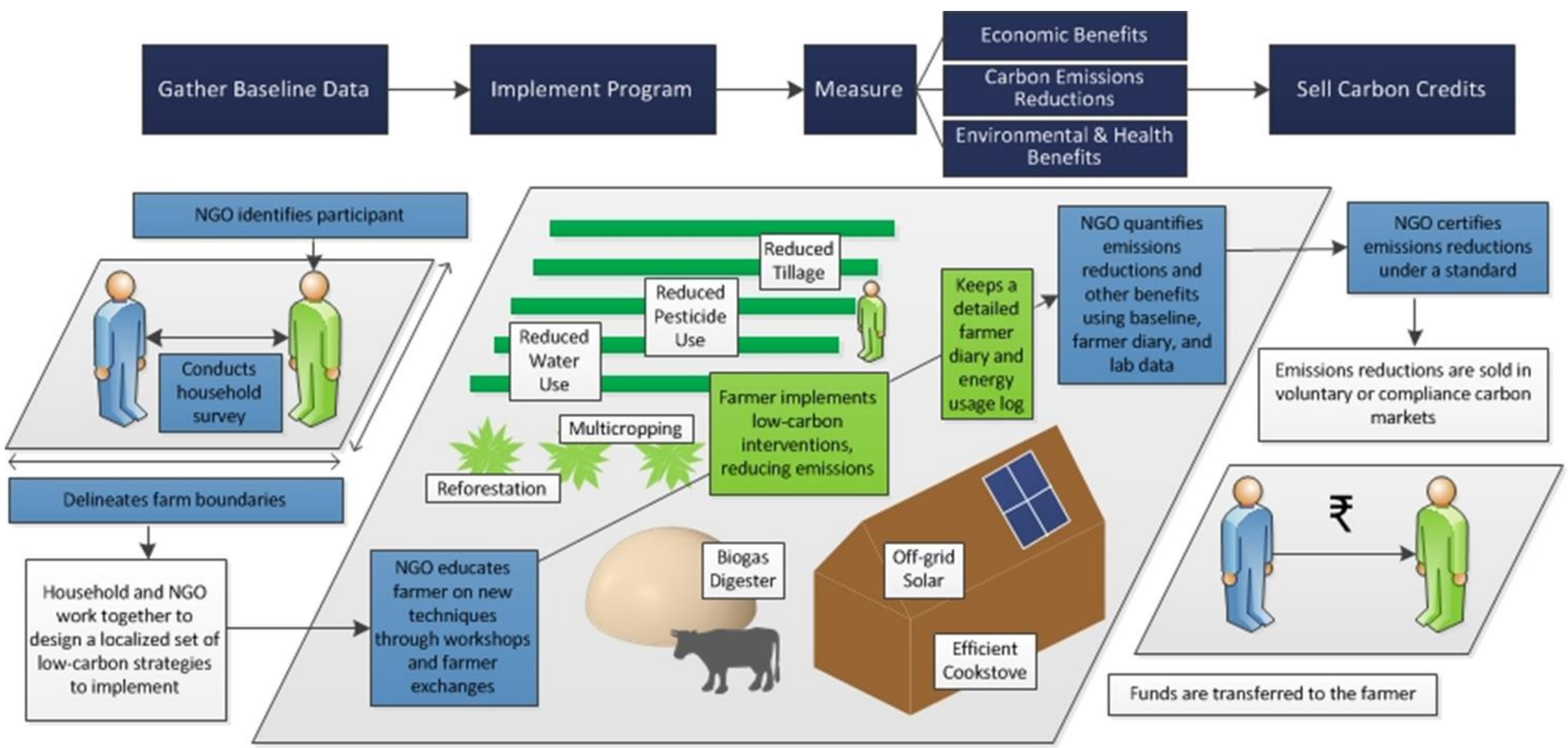
This report is based on work conducted to generate the high-resolution data needed for developing "emission factors" (the average emission rate of a given GHG as a function of given cropping practices) to allow existing and future domestic and international methodologies to be applied to:

1. Better account for emissions being generated from Indian landscapes and also to understand how these may best be managed while improving farm productivity and farmer livelihoods, especially given the national commitments under the Paris agreement,
2. Generate, over time, carbon credits from rice and three upland crops across four agro- ecological regions in peninsular India and assess its potential as an additional incentive for adoption of such CSF practices.

(A representative groundnut (peanut) farm for measuring nitrous oxide emissions)

Our work was done at five sites within four agro-ecological regions in peninsular India (Fig. 1) in partnership with Fair Climate Network, a pan-India coalition of non-governmental organizations (NGOs) that are promoting potential climate smart farming practices among small-holder farmers across for four different crops (i.e., groundnut, rice, finger-millet and foxtail millet). The measurement of yield, economic and climate impacts of different farming practices is routinely performed by academic institutions in developed countries. However, in India and other developing countries, there are limited number of academic or research organizations devoted to precise and accurate study of climate impacts of farming. In India, all such organizations are focused on irrigated and fertile Indo-gangetic belt in North and North-western India. To meet the needs of semi-arid dryland crops in peninsular India, we developed a unique program of establishing research laboratories within the official premises of our NGO partners in rural India. In each of the five research sites, the laboratories monitored N_2O and CH_4 emissions within 5-30 km radius of corresponding small-holder (< 1.5 acre or 0.6 hectares) experimental farms that represented various business-as-usual (i.e., mainstream) and alternate (or potential climate smart) farming practices for specific crops.

Fig. 2 Overall EDF-FCN strategy in peninsular India



Overall strategy

The scientific dimension of our low-carbon (climate smart) farming initiatives in India was embedded in our over-arching low-carbon rural development strategy (Fig. 2) and included the following series of activities:

1) *Collection of demographic data*: Local partner NGO staff collected detailed baseline data at the household level to understand basic financial, educational, land and livestock ownership data.
2) *Delineation of land-holdings and collection of farm data*: Using hand-held GPS systems, local NGOs surveyed each farmer's parcel of land, confirm land ownership through inspection of title deed, and create a digital geographic record that can be linked to the household's demographic data.
3) *Development of baseline agronomic and economic data*: With our NGO partners, EDF conducted desktop research to gather baseline information generated by other researchers, government and academic institutions. This information was supplemented with primary data on local crop-specific agronomic and economic factors using our standardized questionnaires and survey methodologies. All this data was then synthesized to identify main crops, their cropping calendar and determine farmers' mainstream (business-as-usual or baseline) farming practices and economic conditions (see Fig. 3 below).

(Over 30 weather stations were installed as a part of this initiative)

4) *Identification and application of potential low-carbon (climate smart or sustainable) farming practices*: Potential climate smart farming were identified in consultation with local farmers and agronomists to achieve the following inter-related goals: 1) improve or maintain yields; 2) improve soil/water quality; and eliminate or reduce the use of external fossil-fuel dependent inputs such as synthetic fertilizers and chemical pesticides (which in the long term lead to improved health and resilience of agricultural ecosystems; and reduce input costs); 3) decrease GHG emission intensity and 4) maintain/improve farm level profitability. These practices included alternate wetting and drying for paddy, efficient nutrient management, green and/or fermented manure application, integrated pest and weed management. Please see Fig. 4 below.

5) *Monitoring of emissions and agronomic indicators from representative fields*: Lab staff regularly collected air and soil samples from selected farms that remain under their constant supervision that utilize both mainstream (business-as-usual) and sustainable (i.e., potential climate-smart) practices. Collected over multiple growing seasons, these measurements helped us determine the regional emission factors.
6) *Modeling*: EDF conducted linear and multiple regression modelling to estimate emission factors or emission factor equations.
7) *Generation of carbon contracts and sale of credits*: Once we have compiled the requisite data from our field studies, determined emission factors and selected a statistical approach to consolidate our results, NGOs and aggregators can help generate carbon contracts with farmers and facilitate the sale of the emission reduction units. The funds generated through this sale flow back to the farmers as a new income stream.

This report covers results from steps 3 through 6.

(A farmer's daughter being trained to collect air samples using one of the older manual chamber designs)

We have already published our rigorous technical methodology and protocols for collecting air samples using transparent chambers and analyzing them using an optimized Gas Chromatograph in a peer-reviewed scientific journal (Step 5 above)[3]. In that publication, along with the sampling and analytical guidelines that are based on our experiments, we presented a meta-analysis of six leading internationally and regionally recommended approaches to monitor GHG emissions from cropland soils to put our work in perspective. Our methods do not replace but rather complement other existing recommendations, especially by focusing on sampling (e.g. transparent vs opaque chambers, stacked chambers for "in-row" placement, detachable lids, dead volume in chamber sampling lines) and data-processing issues (e.g., problematic integration of daily fluxes, relative importance of temperature and crop volume correction) that have not been discussed earlier. We also presented in detail a pathway to enhance a gas chromatograph (GC)'s precision, which has direct influence on the minimum detection limit (MDL) of the whole methodology. The conceptual approach underlying GC optimization (e.g., oxygen venting/bypass, baseline stabilization, moisture backflush and adequate separation of CO_2 from N_2O) was systematically presented, and will orient new research groups and/or GC manufacturers, especially in the developing regions of the world, to precisely measure GHG emission fluxes.

We have also published data for steps 3 through 5 for two groundnut cultivation seasons[4], all rice[6-9] seasons and are in the process of submitting one more manuscript that present our complete datasets for all groundnut and finger millet crops in the near future.

(Research staff collecting samples from deeper layers of soil)

Research findings

Regional business-as-usual (mainstream) practices for main crops in each Agro-ecological region (AER) were determined through farmer surveys and were used in mainstream agriculture (MA; business-as-usual) subplots at each farm (e.g. Fig 3). We have done a total of 2000 farmer surveys for all NGOs. We also tested two to three different sustainable agriculture (SA; potential climate smart) package of practices (PoPs) for each crop at each reference plot during different years. According to the Food and Agriculture Organization (FAO)), low carbon (or climate smart) farming practices are those that (a) sustainably increase productivity and income (b) help in adapting and building resilience to climate change (c) reduce or remove greenhouse gas emissions where possible. Hence, along with GHG measurements, sustainable agriculture practices were assessed for their potential to increase or maintain yield and farm profit. While finger-millet (*ragi*) and groundnut SA practices matched or surpassed MA yields and farm-level profits, we were unfortunately not able to meet the yields and profits of MA sub-plots for rice and foxtail millet (*korra*). Along with high-resolution GHG measurements, soil, temperature and water indicators with potential to influence GHG emissions were also studied in great detail in each agro-ecological region and/or site (Fig. 1).

Before beginning our measurements, we developed detailed protocols for designing of manual sampling chambers suitable for measuring GHG fluxes from upland rainfed crops and rice paddies on tropical semi-arid smallholder farms. We also optimized N_2O and CH_4 analysis for precisely processing of a large number of field samples everyday. Detailed infrastructural requirements for setting up a lab, general templates for recording lab safety information, instrument conditioning and maintenance and systematic recommendations for flux calculation sheets created by our team have provided in our published manuscript[3] and will assist new research/NGO groups in establishing labs in other parts of the world to record field and lab data necessary for safely and reliably calculating GHG emission fluxes and/or quantify GHG mitigation potential of potential climate farming practices.

(Laboratory staff from all five research sites undergoing training to operate Gas Chromatographs)

Rice multivariate regression model

Climate impacts of rice were investigated at five farms in operational areas of three different NGOs and a combined assessment of results from all these five farms yielded results explained below.

Our detailed datasets from all the rice seasons are available free of charge through the website of journal Proceedings of the National Academy of Sciences[7]. Following multivariate regression model explained which factors affected N_2O emissions from rice most significantly (p-value <0.001, adjusted $R^2 = 0.80$):

$N_2O\text{-}N = -0.01*(\text{water index}) - 0.91*(\text{flood events}>3\text{ days}) + 0.02*\text{Ninorganic} + \epsilon_1$

Where N_2O-N represents emissions in kg N ha^{-1}, water index is the sum of daily water levels in a field water tube (FWT) in a growing season. flood events>3 days is the number of times a plot had greater than 0 cm water level (above soil level) for more than 3 days, $N_{inorganic}$ is inorganic N input in kg ha^{-1} that is calculated on the basis of percentage N is each chemical fertilizer added to the plot and ϵ_1 is statistical residual error. Hence, N_2O emissions were positively correlated with added inorganic nitrogen and negatively correlated with water use and number of extended flooding periods and added organic matter. In continuously flooded fields, organic matter increases methane emissions but in fields which undergo alternate wetting and drying, addition of organic matter appears to decrease nitrous oxide emissions[7].

In contrast to N_2O, rice-CH_4 was found to be positively correlated with parameters reflecting the extent of flooding and water use and the amount of soil organic matter[7].

Generalized recommendations that could reduce net climate impacts of rice: Based on our in-depth analysis of GHG emissions at each farm, we offer the following general recommendations to farmers in the Indian study region.

- Keep water index for the whole season between -250 and 250 cm (mild intermittent flooding) such that flooding is shallow.
- Limit the number of times water stays above soil level for more than 3 days.
- Add as little inorganic N as really necessary to maintain crop yields. For regions that remain intermittently flooded, add inorganic N in split doses right before a flooding event.
- Don't let the fields drain too much and keep water levels above -5 to -7 cm during the growing season (except close to harvest)
- For farms where water index is high (sometimes because water does not percolate down quickly or water percolated down quickly but irrigation is very frequent), reduce organic matter use to reduce CH_4 emissions.
- For farms where water index is low likely because water percolates down quickly and there is low water use, higher amount of organic carbon can be added to reduce N_2O emissions.

The climate impacts for all the investigated upland crops were measured within operational areas of each NGO (Accion Fraterna for groundnut, Timabktu for foxtail millet, and SACRED for finger millet) and detailed findings are presented in the sections below. More details will be available in our soon-to-be-published peer-reviewed manuscript.

Fig. 3 Example of results from survey done to determine key crops and growing seasons

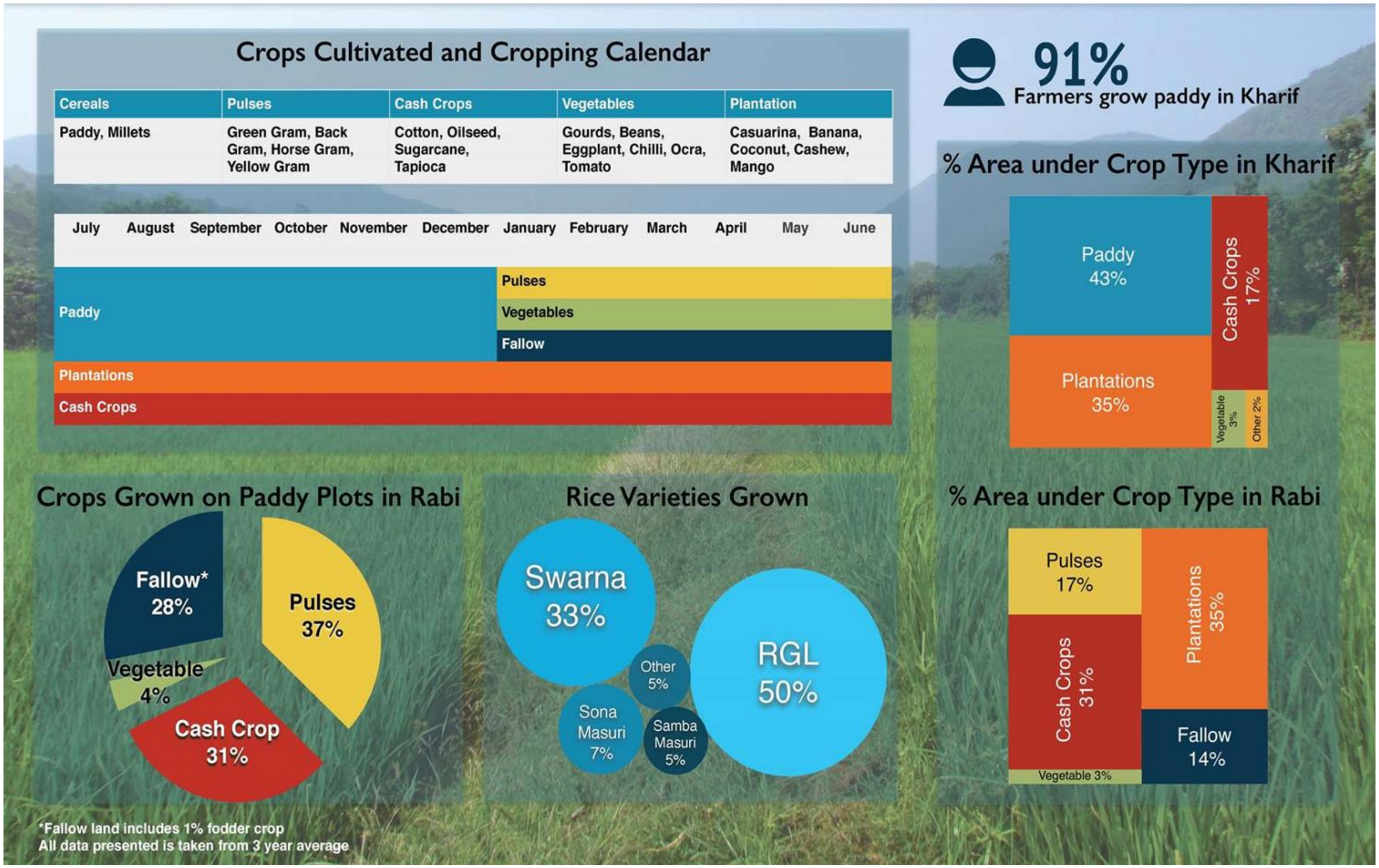
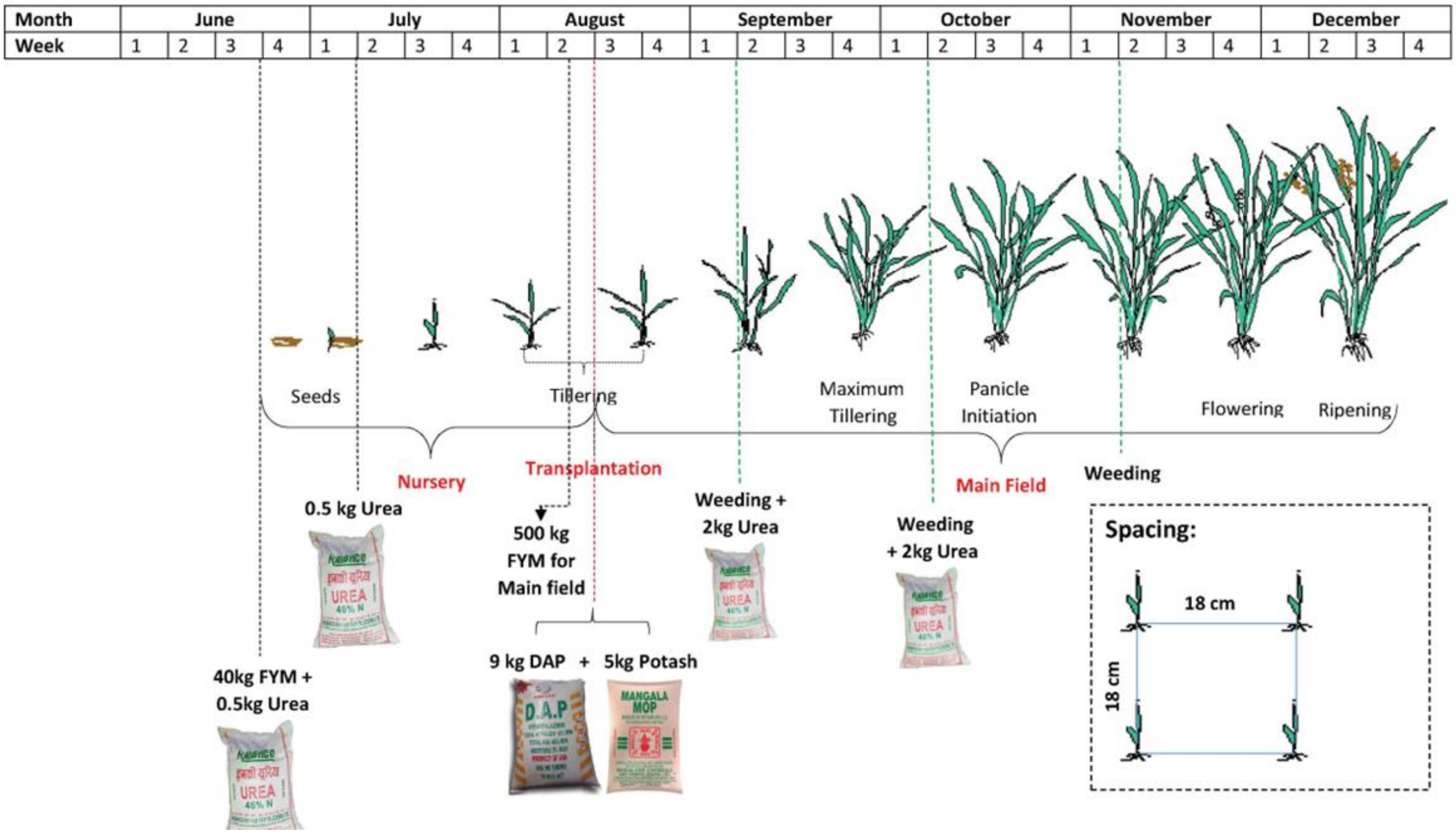


Fig. 4 Example of potential climate smart farming practice package for rice This example is from a very remote region where very small amount of inorganic N was applied to rice fields as a business-as-usual practice and our recommendation was to increase to balance the fertilizer use by adding non-nitrogenous fertilizers to increase rice yields.



Bharath Environment Seva Team (BEST) (AER 8.2)

Crop

Rice

Baseline Practices determination

Farmers were surveyed for Samba paddy season from 2012-2014. 60, 70 and 300 farmers were surveyed during 2012, 2013 and 2014 in BEST operational area for determining baseline-farming practices (Table 1, please see end of the document)

Greenhouse gas measurements

Mainstream agriculture (MA) practices determined through surveys and sustainable agriculture (SA) alternate package of practices developed by BEST were measured for GHG emissions, yield and farm profits. Since alternate wetting and drying (AWD) was practiced in SA plots, field water tubes levels were also monitored regularly from each replicate (Table 1)

(A farmer learning to do measure water levels in the field via field water tube measurements)

Results

Paddy GHG monitoring: Total emission reduction (CH_4+N_2O) from SA practices range from (1.6 to 6 tCO_2e ha^{-1} $season^{-1}$ based on a 100 year time scale as is commonly used for CO_2). Seasonal N_2O emission factors ranged from 0-15% instead of previously published very low values between 0.002 to 0.7%. Please see Fig. 5. For complete analysis, please see our peer reviewed manuscript[6,7].

- Measurements conducted in 2012 representative plots show that MA treatments had significantly higher N_2O emissions (14.5 kg N_2O ha^{-1}; maximum N_2O emissions among all 13 treatments) and very similar CH_4 emissions as that of SA. High N_2O emissions from MA plots can be attributed to high N input rates[7].
- For the year 2013, MA treatment had higher N_2O emission and similar CH_4 emissions. MA had a lower water index, higher inorganic N input and higher clay to sand ratio. The difference in water index was the main driver of N_2O emissions (Table 2, please see end of this document).
- In the year 2014, N_2O emissions for both SA and MA were close to the lower end of all treatments, although slightly higher for MA. CH_4 emissions are slightly higher in SA, high water index and an elevated number of continuous flooding events suppress N_2O emissions for both SA and MA. Conversely, these high flooding conditions trigger CH_4 emissions and in particular the relatively higher number of continuous flooding events in SA corresponds to the higher CH_4 emissions (Table 2)
- Please see the multivariate regression model and generalized recommendations for reducing net climate impacts of rice cultivation in the "Research Findings" section.

Yields were lower during all the years of measurement from SA plots in comparison to MA plots (Table 2)

Palmyrah Workers Development Society (PWDS) (AER 8.3)

Crop

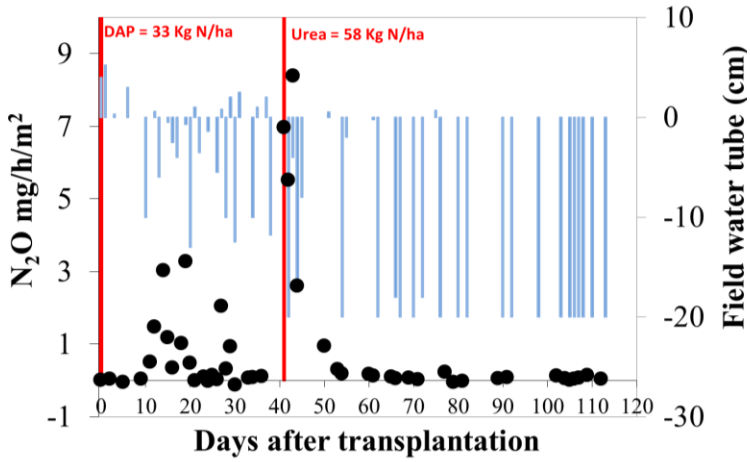
Rice

Baseline practices determination

About 80 farmers were surveyed for in 2013 to determine baseline practices in PWDS operational area (Table 1).

Fig. 5 Nitrous oxide emissions at rice farms can be very high

This figure shows N_2O fluxes observed in a manual chamber placed in a rice farm at BEST site in 2012. Red lines represent timing of the addition of N fertilizers. Blue lines represent water levels as measured in field water tubes.



Greenhouse gas measurements

Mainstream practices (MA) determined through surveys and sustainable alternate package (SA) of practices developed by PWDS were measured for GHG emissions, yield and farm profits. Since alternate wetting and drying (AWD) was practiced in SA plots, field water tubes levels were also monitored regularly from each replicate (Table 1)

Results

Total emission reduction ($CH_4 + N_2O$) from SA practices range from (0 to 2.1 $tCO_2e\ ha^{-1}$).

Both SA and MA had similar and low N_2O emissions. However, both treatments had significantly high CH_4 emissions, the maximum measured in this study (Table 2). These two treatments had similar inputs and soil characteristics (clay/sand ratio), but different flooding characteristics with overall high water index values. The soil organic C from both SA and MA treatments were at the maximum observed, this high soil organic C content supports the high CH_4 emissions.

Both SA and MA yields were found to be similar.

While several preliminary measurements were done prior to 2013, there was only rice cropping season within the PWDS operational area where GHG emissions were made for the entire season. This region is characterized by relatively higher water availability as compared to AF and BEST operational areas and has soils with higher soil organic carbon. Among the five rice farms investigated during our work, the farm in the PWDS operational area had the highest water indices (cumulative water levels) (Table 2) and among the highest CH_4 emissions and the lowest N_2O emissions. Please see the multivariate regression model and generalized recommendations for reducing net climate impacts of rice cultivation in the "Research Findings" section.

(Women harvesting seedlings for rice nursery)

Social Animation Center for Rural Education & Development (SACRED) (AER 8.1)

Crop

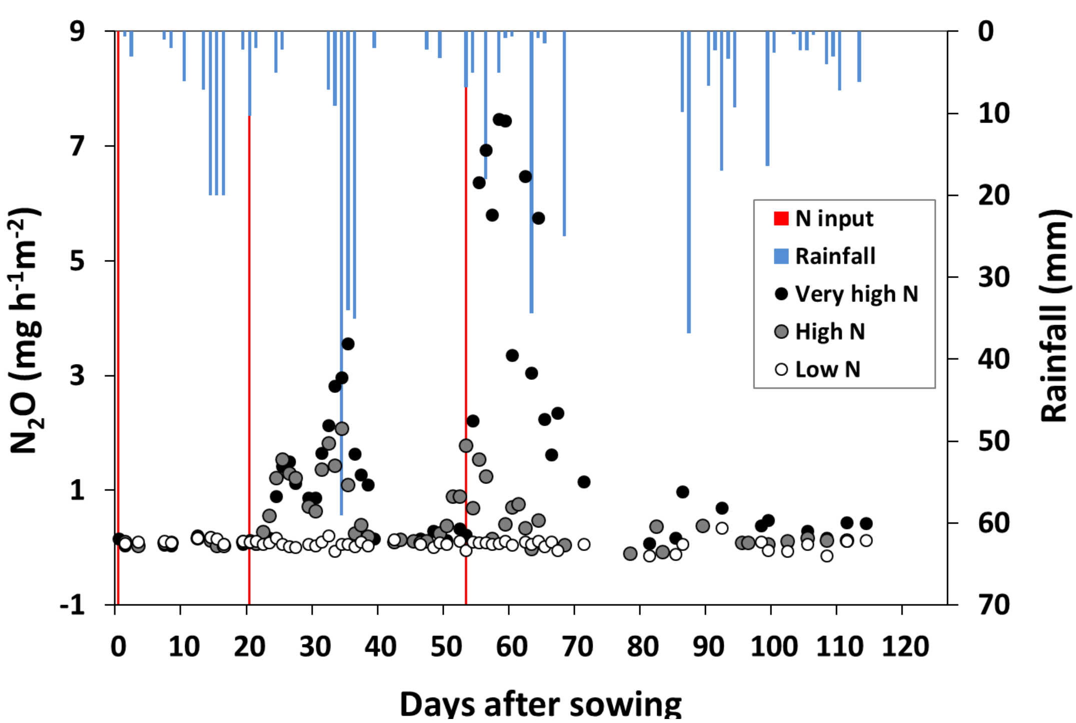
Finger Millet (*Ragi*)

Baseline practices determination

For upland crops, we had three non-zero N input treatments: Low N, High N and Very High N. The "Very high N" treatment included addition of N input that was way beyond the range of fertilizers normally applied to *ragi* fields. We have used farmer surveys as well as data on N fertilizer application rates from the Government of India Input survey tables to determine baseline framing practices. Please see Tables 1,3 and Supporting Tables 1-2 for details.

Fig. 6 Nitrous oxide emissions from finger-millet farms

This figure shows N_2O fluxes recorded at three sub-plots with three different rates of nitrogen fertilizer use at a finger millet farm in a high rainfall site in 2015. Red lines represent timing of the addition of N fertilizers. Blue lines represent rainfall recorded in the weather station next to the farm.



Greenhouse gas measurements

Nitrous oxide emissions were measured from the year 2012-2015 during rainfed (locally called *kharif*) seasons. Years 2012-2014 comparatively received much less rainfall (204 ± 120 mm) than 2015 (480 mm). Measurements for each rainfall category were done from four different treatments: Very high N, High N, Low N (SA) and control (N = 0) plots (Table 3). Please see Fig. 6 above for a representative N_2O flux profile during a given season. Please see Tables 1,3 and Supporting Tables 1-2.

Multiple regression

Each finger-millet, foxtail millet or groundnut farm every year with a different treatment was considered an independent observation in the regression analysis. To select our multivariate regression model(s) for N_2O, we consecutively added/removed parameters like rainfall, amounts of organic and inorganic N, soil pH and organic content looking to minimize the Akaike Information Criterion and checking for model significance after adding or removing parameters.

Results

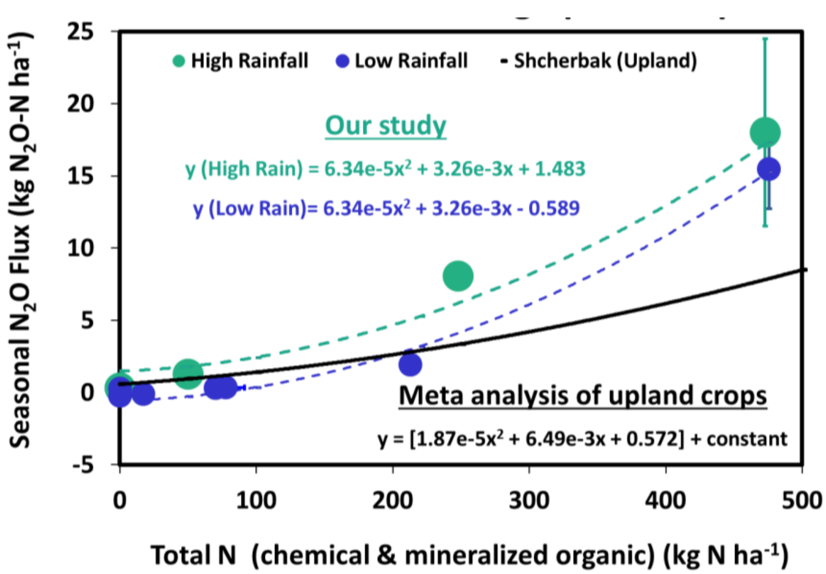
Nitrous oxide mitigation potential of SA practices ranges from 0.24 to 2.9 $tCO_2e\ ha^{-1}$ for high rainfall region and 0.07 to 0.9 $tCO_2e\ ha^{-1}$ for the low rainfall region. Nitrous oxide emissions increased non-linearly in a quadratic manner with increasing nitrogen input for both low and high rainfall region. When considering finger-millet datasets by itself, there was not a statistically significant difference between high and low rainfall regions. However, when we combined finger-millet datasets from foxtail-millet (see below, the other non N-fixing crop investigated as a part of this study), there was significant difference between behavior of N_2O emissions from high and low rainfall regions with respect to intercept of the quadratic equation . For non N-fixing upland crops, the following equation best describes nitrous oxide emissions:

N_2O-N (kg ha^{-1}) = 6.34e-05 $(N_{total})^2$ + 3.26e-03 (N_{total}) + 1.48 (High Rainfall)
N_2O-N (kg ha^{-1}) = 6.34e-05 $(N_{total})^2$ + 3.26e-03 (N_{total}) – 0.589 (if rainfall is lower than the crop requirement)

where N_{total} is the amount of total N (mineralized organic and inorganic) added in kg ha^{-1}. Please see Fig. 7. As explained earlier[7], the range of mineralization rates of organic N over three years was obtained from literature.

Fig. 7 Millets: Non-linear response to added nitrogen

This figure compares non-linear response of N_2O to changing N_{total} rate for finger- and foxtail millet (non N-fixing upland crops) with the average non-linear response seen for over 221 non N-fixing upland cropping seasons included in meta-analysis by Shcherbak et al, 2014). Please see section on foxtail-millet in AER 3.0 as well.

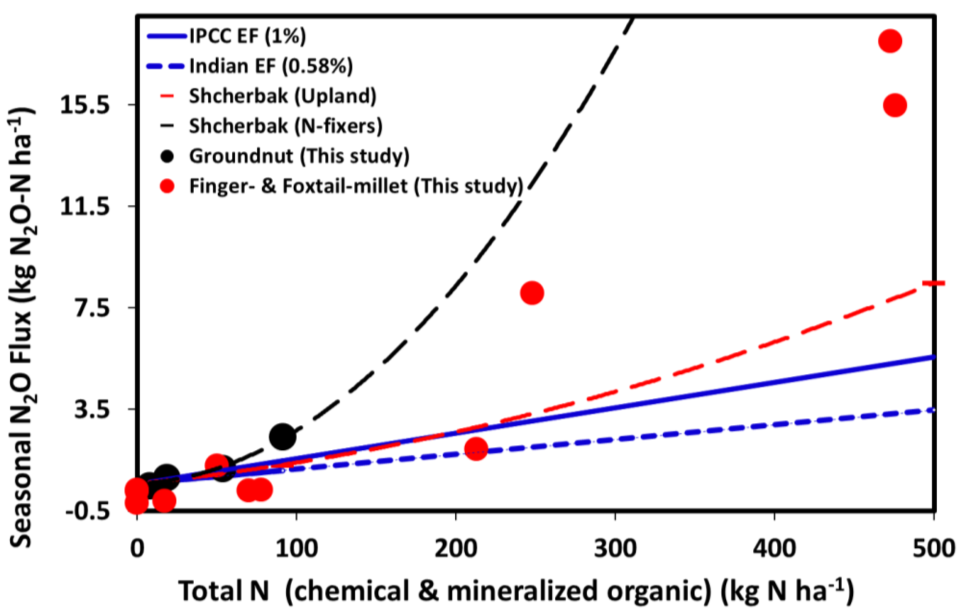


Discussion

Emission factors were found to be much higher than IPCC and Indian government's estimates of 1% and 0.58% respectively. We compared our emission factor equations with previously published global or national emission factors as well as emission factor equations published recently. As shown in Figs. 7 and 8, IPCC and Indian government indicate that N_2O emissions respond to changing nitrogen use in a linear manner with ~1% or 0.58% of added nitrogen converted to N_2O-N in each cropping season (or year). However, a recent meta-analysis of over 230 cropping seasons compiled by Shcherbak et al (2014)[11] shows that N_2O emissions increase non-linearly with increasing N application and the extent of this non-linearity depends on the crop under consideration. Our emission factor equation for non N-fixing upland crops (finger-millet (*ragi*) and foxtail-millet (*korra*)) is significantly differently from the quadratic equation for upland crops derived by Shcherbak et al (Fig. 8) with higher response to changing N input at high N rates than suggested by Shcherbak et al. Our results further support the growing consensus that for low N input systems typical of rain-fed crops in Africa and Asia, increase in fertilizer use to enhance productivity will lead to relatively small increase on N_2O emissions as compared to the impact of equivalent additions (or reductions) in systems fertilized far beyond crop N needs.

Fig. 8 Non-linear response: N_2O emissions from upland crops

This figure compares non-linear response of N_2O to changing N_{total} rate as seen in our research with the linear responses (the global emission factor of 1% adopted by IPCC and Indian Government's linear emission factor of 0.58%) as well as the average non-linear response seen for over 230 N-fixing and non N-fixing upland crops (meta-analysis by Shcherbak et al, 2014). Please see also the section on finger-millet above (AER 8.1) and sections (below) on groundnut and foxtail-millet (AER 3.0).



Accion Fraterna (AER 3.0)

Crops

Groundnut (peanut) and Rice

Mainstream agriculture (MA) baseline determination

Baseline surveys were conducted in AF working area during 2012-2013 to capture Kharif groundnut farming practices and separate surveys were conducted amongst Rabi farmers for the year 2012 (Table 1). For the year 2014, surveys were conducted in three neighboring operational areas that are served by three different non-governmental organizations in Anantapur district (The Social Education and Development Society (SEDS), Accion Fraterna and Timbaktu Collective). Data collected included basic information on the farmers, ploughing period and method, organic and inorganic manure/fertilizer input details, pest management, cost and labor investment, harvest and yield etc. Paddy farmers were surveyed in 2012 and 2013 (Table 1). Please see our peer reviewed manuscript[4], Tables 1 and 3 as well as Supporting Tables 1-2 for details of crop management practices.

Greenhouse gas measurements

Groundnut- Kharif Mainstream practices (MA) determined through surveys and sustainable alternate package (SA) of practices developed by SEDS were measured for nitrous oxide emissions, crop yield and farm profit for the years 2012. For the year 2013, SA practices used at the reference plot were developed by AF. In the year 2012, measurements were done from rabi (irrigated) practices as well. In 2014, measurements were done from baseline practice, high nitrogen input practice and a control plot with zero input to capture range of N_2O emissions and to help coming up with an emission factor equation.

Paddy- GHG emissions, yield and farm profits were measured from three replicates of MA and SA practices in the years 2012 and 2013 for irrigated paddy. Since alternate wetting and drying (AWD) was practiced in AP plots, field water tubes levels were also monitored as regularly as possible (Table 1).

Results & Discussion

Groundnut

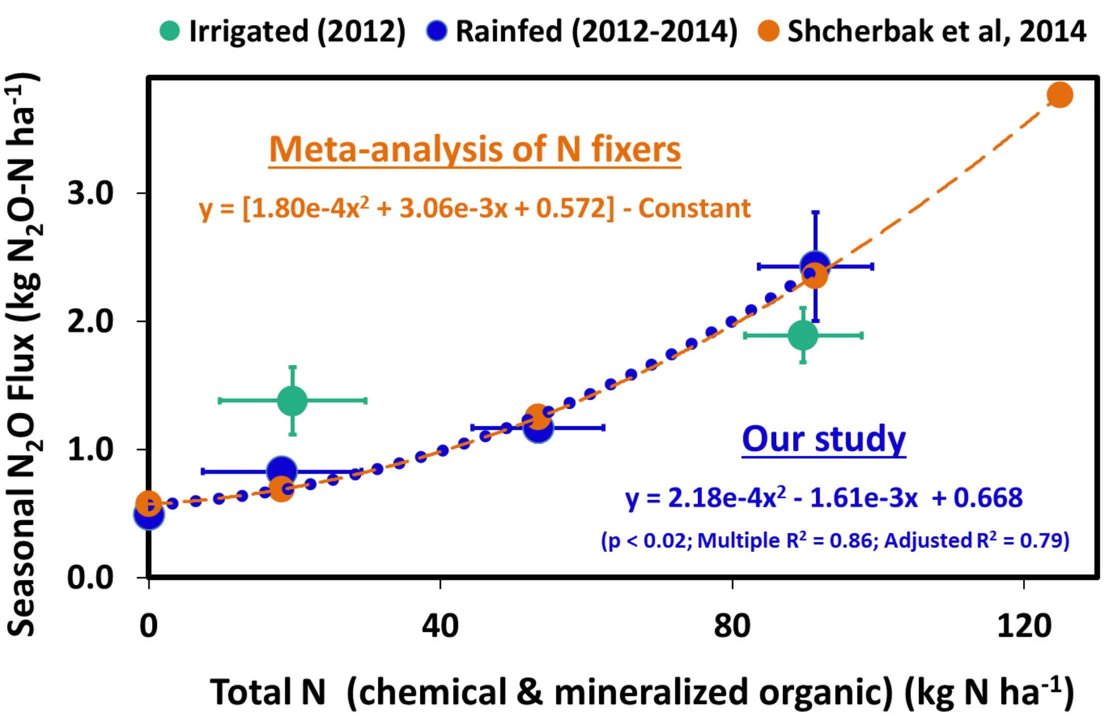
Based on measurements done in all three years, it was found that N_2O responds to N input in a non-linear quadratic manner.

$N_2O\text{-}N$ (kg ha^{-1}) = 2.18e-04$(N_{total})^2$ - 1.61e-3N_{total} + 0.668

where N_{total} is the amount of total N (mineralized organic and inorganic) added in kg ha^{-1}. Please see Fig. 9. As explained earlier[7], the range of mineralization rates of organic N over three years was obtained from literature. Forced linear emission factor was found to be 2.2% instead of United Nations' IPCC average estimate of 1%. (a forced linear emission factor is obtained when the data is forced to follow a linear path instead of non-linear path in the N_2O emission *vs* N input graph). The range of direct emission reduction for groundnut depends on the exact amount of nitrogen used in MA and SA plots. Using the exponential equation described above, nitrous oxide mitigation potential of SA practices ranges from 0.24-0.64 tCO_2e ha^{-1}

Fig. 9 Nitrogen fixing groundnut: Non-linear response to nitrogen

This figure compares non-linear response of N_2O to changing N_{total} rate for groundnut (a N-fixing upland crop investigated in our research) with the average non-linear response seen for seven N-fixing upland cropping seasons included meta-analysis by Shcherbak et al, 2014).



For the year 2012, 40–60 % reduction in application of total N increased pod yield by 50 and 35 % and net profit by ~120 and ~70 % in a drought-hit rainfed (*kharif*) and an irrigated (*rabi*), respectively. Yield and farm profit were not significantly different for MA vs SA for the year 2013. Over all the years SA treatments resulted in lower nitrous oxide emissions, leading to a reduction of (0.24-0.64 tCO_2e ha^{-1}), hence the SA practices were proven to be climate smart. Using our non-linear equation, N_2O emissions resulting from any rate of N input can be calculated. The forced linear emission factor (2.2%, see above) found through this study is much higher than the IPCC and Indian emission factors of 1% and 0.58% respectively. Hence, even without non-linear emission factor equation using emission factor of 2.2% would give higher reduction to the farmers (Fig. 9, Tables 1 and 3). Our study[5] also suggests that SA practices lead to improvement in eco-system services which include decreased N run off, lower indirect N_2O emissions and lesser GHG emissions associated with fertilizer production and fertilizer transportation.

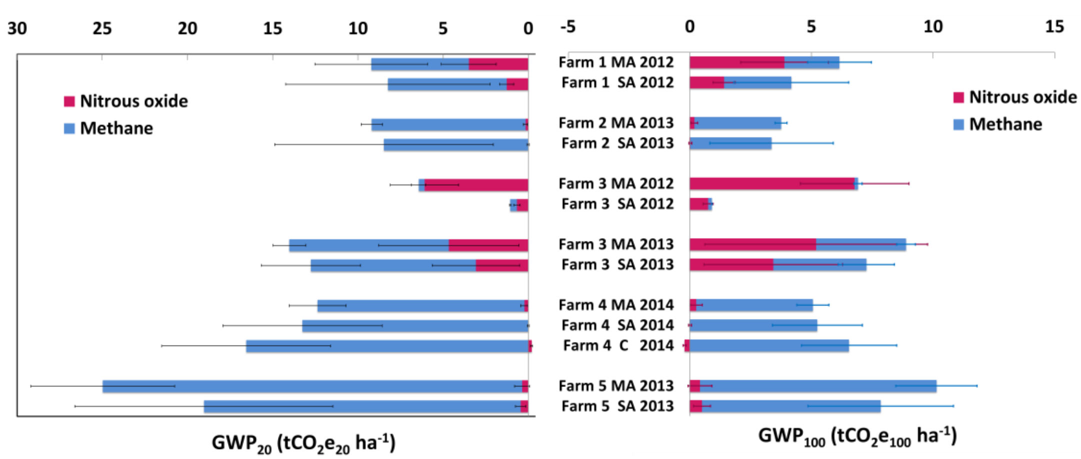
To put our results for upland crops in perspective, we compared them with previously published global or national emission factors (N_2O emission rate as a function of given nitrogen use) as well as emission factor equations published recently. As shown in Fig. 8, IPCC and Indian government indicate that N_2O emissions respond to changing nitrogen use in a linear manner with ~1% or 0.58% of added nitrogen converted to N_2O-N in each cropping season (or year). However, a recent meta-analysis by Shcherbak et al (2014) shows that N_2O emissions increase non-linearly with increasing N application and the extent of this non-linearity depends on the crop under consideration. We find that our results for groundnut, a N-fixer are much similar to the EF equation for N-fixers presented by Shcherbak et al (See Fig. 8) as compared to their EF equation for non N-fixing upland crops.

Paddy

Total emission reduction ($CH_4 + N_2O$) from SA practices range from (0.4 to 2 $tCO_2e\ ha^{-1}$ on a 100 year time scale). N_2O emission factors ranged from 0-15%. For the measurements done in 2012, MA treatments had higher N_2O emissions (SA = 3.0 kg $N_2O\ ha^{-1}$, MA = 8.3 kg $N_2O\ ha^{-1}$). We see the inverse relationship with CH_4 emissions, where SA had slightly higher emissions (SA = 81.1 kg $CH_4\ ha^{-1}$, MA= 66.5 kg $CH_4\ ha^{-1}$). Please see Fig. 10 as well as the multivariate regression model and generalized recommendations for reducing net climate impacts of rice cultivation in the "Research Findings" section. All results pertaining to rice systems have been published as a peer reviewed study[7]. Our compiled results from all of our rice reference plots indicate that measuring N_2O emissions from rice fields is as important as measuring CH_4 emissions.

Fig. 10 Short- and long-term climate impacts of rice cultivation

The global warming potential of N_2O is 3 and 9 times higher than CH_4 over 20 and 100 years, respectively. Therefore, the climate impacts of N_2O dominate those of CH_4 in the longer term (e.g., 100 years). The error bars for GWP_{20} tCO_2e_{20} and GWP_{100} tCO_2e_{100} represent the ± 95% confidence interval. Farms 1 and 2 are in AER 3.0, Farms 3 and 4 are in AER 8.2 and Farm 5 is in AER 8.3. MA represents mainstream (baseline) agricultural practices and SA represents sustainable (or potential climate-smart) agricultural practices.



The Timbaktu Collective (AER 3.0)

Crops

Foxtail-millet (*Korra*)

Baseline Practices determination

Baseline surveys were conducted in Koppal district in same AER 3.0. A total of 50 farmers were surveyed for the year 2013 (Table 1). Please see Tables 1 and 3 as well as Supporting Tables 1-2 for details.

Greenhouse gas measurements

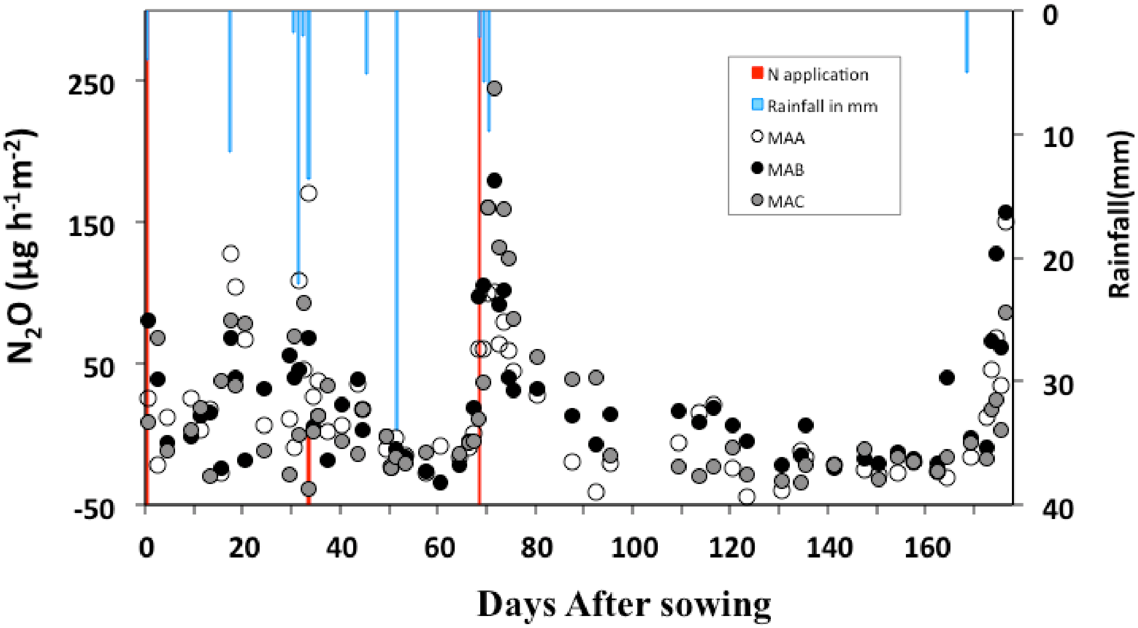
Kharif baseline practices (MA) determined through surveys and sustainable alternate package (SA) of practices developed by Timbaktu were measured for nitrous oxide emissions, crop yield and farm profit for the years 2013. Two replicates for both the treatments and a control plot with zero input were also maintained.

Results

For the year 2014 where rainfall and crop yields were low (see discussion below), nitrous oxide mitigation potential from SA practices was found to be 0.19 tCO_2e ha^{-}in 2014. Nitrous oxide emissions increased non-linearly ($R^2 = 1$) with nitrogen input where Y is N_2O emission in kg N_2O-N and X is the amount of total N added in kg ha^{-1}. Forcing linear relationship between N application rate and N_2O emissions from low rainfall region had a lower R^2 value than the non-linear equation but this forced (or implied) linear emission factor for low-rainfed region was 0.8%. Please see Fig. 11.

Fig. 11 Nitrous oxide emissions from foxtail-millet farm

This figure shows N_2O fluxes recorded at three mainstream agriculture sub-plots with same nitrogen fertilizer use at a foxtail-millet farm in 2014. Red lines represent timing of the addition of N fertilizers. Blue lines represent rainfall recorded in the weather station next to the farm. N_2O emission peak 30 days after harvest (DAS 135) likely because of inorganic nitrogen left in the soil.



Discussion

Fig.11 above shows daily emissions from 2014 Foxtail millet and highlights the response of N_2O to nitrogen input (indicated by two solid red lines) and rainfall (indicated by inverted blue lines). The harvest occurred on Day 135. White, black and grey dots represent results from three different replicate chambers in MA plot. The figure also shows N_2O emissions after rain event during fallow period after the crop was harvested emphasizing that when the applied nitrogen is not taken up by the crop or converted into N_2 or N_2O gas or leached as nitrate during the season, it is still available to be converted to N_2O after the harvest.

Even though yields recorded at the SA reference plot in 2014 was lower than of the MA plot, average yields from other SA farmers in the region for the year 2015 were similar to MA yields, which indicates that SA practices have the potential to match MA yields. SA plots recorded lower N_2O emissions in comparison to MA plots, with a reduction potential of 0.19 $tCO_2e\ ha^{-1}$ (Table 3). The forced linear emission factor was found through this study is lower than the IPCC estimate of 1% but higher than Indian emission factors of 0.58%. Because we have GHG emission rate measurements from only one year for this crop, we are not as confident about their general applicability as for other crops. However, it is very significant that our results support the observations from others parts of the world (Shcherbak et al, 2014) and both the non N-fixing crops (finger- and foxtail-millet) investigated as a part of our study show much lower emissions that N-fixing crop (groundnut) at similar N applicate rates.

Conclusions

Ensuring Indian farmers recognize the tradeoffs associated with excess fertilizer applications and understand the long term implications of sustainable practices, rather than re-educating farmers retroactively – is a key step in minimizing India's future carbon footprint. Though focused in India, this initiative should have far broader ramifications because smallholder communities have important similarities even across global regions.

Pathway for rigorous measurement of GHG emissions from rice and upland crops in tropical and developing parts of the world Our peer-reviewed methodology[3] offers detailed considerations for designing of manual sampling chambers and guidelines for optimizing N_2O and CH_4 analysis for precisely processing of a large number of field samples. This manuscript presents a detailed list of infrastructural requirements for setting up a new lab in rural settings, general templates for recording lab operations information, instrument conditioning and maintenance and systematic recommendations for flux calculation sheets. This piece of work will assist new research/NGO groups in establishing labs in other parts of the world to record field and lab data necessary for safely and reliably calculating GHG emission fluxes and/or quantify GHG mitigation potential of potential climate farming practices.

Importance of managing both nitrous oxide and methane emissions from rice cultivation: In our previous publications[6-8], based on this body of work, we highlight the hitherto under-appreciated role that nitrous oxide emissions from rice farms can have on increasing global warming, and the opportunity to mitigate those emissions if effectively managed. Based on the untested assumption that almost all irrigated rice fields are continuously flooded and most of the climate impact of rice production is due to methane emissions, the global climate mitigation community has been focused on water management (i.e., intermittent flooding) without accounting for the potential adverse impact on N_2O emissions. Through our large empirical dataset from five intermittently flooded rice farms in India, we find that N_2O seasonal emissions can be three times higher than previously reported, and that N_2O emissions increase as the degree to which fields are flooded decreases. It is relevant to note that intermittent flooding at rice farms is likely much more common (especially in South-Asia, Africa and South America) than acknowledged in existing studies as well as in UNFCCC reports. In other words, N_2O emissions from rice cultivation could be much higher than previously reported, with the net effect of increasing net radiative forcing from rice production. As water stress due to increasing temperatures and droughts in the tropics becomes more common, intermittent flooding practices are likely to be an increasingly more prevalent component of rice cultivation. We quantify the potential scale of the net climate impact, including N_2O emissions, from rice paddies through a geospatial extrapolation. The results suggest that the current global climate impact of rice cultivation could be 1.5-3 times current estimates if intermittent flooding regimes, such as those being currently being advocated, are adopted. There is a positive path forward. Our analysis of potential climate smart practices shows that co-management of water with inorganic nitrogen and/or organic inputs, as opposed to water managed independent of nitrogen or organic inputs, can decrease climate impacts by 60%. Elsewhere in this report, we have presented rice management recommendations that are likely to minimize both methane and nitrous oxide emissions from rice cultivation. Our work suggests that region-specific studies that map water use and measure effects of multiple co-managed variables on CH_4 and N_2O emissions are necessary to determine and lower the climate impacts of rice cultivation over both the long- and short-term. An improved understanding of the implications of GHG mitigation strategies currently being advocated must be integrated into our thinking as soon as possible.

Differential impact of increasing fertilizer use in low vs high N input upland crops: Our measurements for three upland crops, groundnut, *korra* and *ragi* show that the current Indian and global N_2O EF of 0.58% and 1%, respectively, are too conservative, especially for high N-input rates (Fig. 7). These IPCC or Indian emission factors imply that there is a linear relationship between N application rate and nitrous oxide emissions. In contrast, our data shows a faster than linear N_2O emission increase with increasing N inputs. We were able to detect this faster than linear response to changing N inputs because our study employed more than three nitrogen application rates at each farm and also because our sampling frequency was very high. To our knowledge, our work is the first body of work that measured nitrous oxide emissions from four different N application rates in India. It suggests that Indian budgets might be significantly altered by replacing the constant Indian

0.58% EF with an N-rate–dependent EF. In particular, this change would likely lower emission estimates from regions predominantly fertilized at low N inputs while increasing emission estimates from highly fertilized areas.

Our data for upland crops supports the conclusion of several International studies that N_2O emissions are accelerated in soils fertilized in excess of crop requirements. Thus, as concluded earlier (Shcherbak et al, 2014), when the impact of N fertilizer reductions on N_2O emissions is estimated, it is important to avoid overestimating the impact of reductions where N is applied at rates close to crop N needs and to avoid underestimating the impact of reductions where N is over-applied. This means that the largest mitigation gains are to be made where fertilizer N is applied in excess, such as in many areas of Indo-gangetic plain. In areas which currently have low GHG emissions due to lower nitrogen or water use, e.g., in rainfed cropping systems, future emission increases may be contained by optimizing nitrogen and water application to sustainably maximize yields and profits. It is possible that India is underestimating emission reductions due to lowered N application rates because economical N application reductions (with respect to yield) can be safely made only in fields where N is currently being applied in excess (i.e., at higher N rates).

Capacity building: While there were many logistical, infrastructural, linguistical, cultural and education-level barriers, we have created tremendous institutional capacity within our local Indian NGO partners to undertake rigorous scientific projects in the future. Between 2012-2015, we surveyed 2000 farmers with help of Indian NGO staff members and analyzed ~35000 air samples across three Indian states and fourteen cropping seasons. To enable such highly precise measurement of GHG emission rates and to be able to correlate these emissions with multiple soil and management parameters, we trained >25 personnel in highly specialized scientific instrument operations and rigorous lab maintenance as well as >50 personnel in field operations including soil, water and crop sampling.

TABLES

TABLE 1

Summary of results from all EDF-FCN research sites in peninsular India

	Accion Fraterna			Timbaktu	PWDS	SACRED		BEST
Crop and Season								
AEZ	3	3	3	3	8.1	8.2	8.2	8.3
Crop	Groundnut	Groundnut	Rice	Foxtail Millet	Rice	Finger millet	Finger millet	Rice
Season	Kharif (Rainfed)	Rabi (Irrigated)	Kharif (Rainfed)	Kharif (Rainfed)	Kharif (Rainfed)	Kharif (low rainfall)	Kharif (high rainfall)	Kharif (Rainfed)
Monsoon pattern	Southwest	Northeast	Southwest	Southwest	Northeast	Southwest	Southwest	Southwest
Time period of measurement	2012-2014	2012	2012-2013	2014	2013	2012-2014	2015	2012-2014
Number of cropping seasons measured	3	1	2	1	1	3	1	3
Mainstream and Sustainable practices								
Seed variety	Kadiri 6	Kadiri 6	BPT 5204	Local	ASD 16	MR1	MR1	ADT 39
Number of baseline surveys	3	1	2	1	1	0*	0*	3
Baseline survey size: number of farmers	92-150	84	90-150	51	78	0*	0*	60-300
PoP's tested in reference plot	2	1	2	1	1	2	1	3
Range of N use in MA plots (kg ha^{-1})	55-95	105	205-400	60-80	120	470-220	470-250	200-220
Range of N use in SA plots (kg ha^{-1})	40-75	40	25-105	8-25	100	65-90	45-55	40-120
Analytical details								
Gases measured	N_2O	N_2O	N_2O and CH_4	N_2O	N_2O and CH_4	N_2O	N_2O	N_2O and CH_4
Number of samples analysed	~6000	~2000	~4000	~1800	~2000	~5000	~1500	~6000
GHG sampling intensity (%)	41-53	47	44-49	45	60	34-56	34-56	33-64
Water level sampling intensity (%)	-	-	55-73	-	86	-	-	94-100
Results								
Yield increase range (%)	0 to 50	35	-45 to -5	-16	0	-10	25	-35 to -10
Reduction in inorganic fertilizer use (%)	100	100	100	100	18	75	82	71
GHG reduction range (tCO_2e ha^{-1})	0.24-0.64	0.24	0.4-2	0.19	0-2.1	0.07-1	0.2-3	1.6-6
Forced Linear Emission factor(%)**	2.2	1.7	0-6.9	0.8	0.1-2.2	3.3	4	0.0-15.4

*Surveys were conducted in 2012 and 2013 but due to calculation errors, we decided to use Indian government data for calculation of emission reduction. ** As mentioned in the text, for upland crops, N_2O fluxes responds to N input in a quadratic manner. A forced linear emission factor (EF) is obtained when instead of an exponential trend, when a linear trend is forced on the data in an emission vs N input graph. In most cases, the forced linear EF doesn't explain our data as well as the quadratic emission factor equation but the forced EFs allows direct comparison of our data with IPCC-EF of 1%.

TABLE 2

Summary of climate impacts of rice cultivation in peninsular India

	N input (kg ha^{-1}) Inorganic	N input (kg ha^{-1}) Organic[1] (Min - Max)	C input[2] (t ha^{-1}) (Min - Max)	Water index[3] (cm)	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	Yield (t ha^{-1})	N_2O EF (%)[4]
Agro-ecological region[5] 3.0 (Seed variety BPT 5204)								
Farm 1 2012								
Mainstream (MA)	91	21 - 67	3.9 - 4.5	-555 ± 85	13.1 ± 6.03	66.5 ± 38.4	4.8	2.8 - 6.9
Sustainable (SA)	0	24 - 75	4.1 - 4.8	-580 ± 144	4.70 ± 1.53	81.1 ± 69.7	4.6	3.2 - 5.3
Farm 2 2013								
Mainstream (MA)	243	15 - 69	5.6 - 6.8	-1 ± 33	0.62 ± 0.47	105 ± 7.23	4.8	0.07 - 0.22
Sustainable (SA)	0	23 - 106	8.4 - 10.0	-152 ± 16	0.10 ± 0.20	98.3 ± 74.5	2.7	0.0 - 0.2
Agro-ecological Region[5] 8.3 (Seed variety ADT 39)								
Farm 3 2012[8]								
Mainstream (MA)	219	2 - 10	0.0 - 0.0	-486 ± 10	22.7 ± 7.47	3.98 ± 4.89	4.2	4.6 - 8.3
Sustainable (SA)	61	17 - 56	2.7 - 3.7	-416 ± 81	2.51 ± 0.69	4.60 ± 0.39	2.7	1.0 - 1.7
Farm 3 2013								
Mainstream (MA)	202	4 - 10	0.6 - 0.8	-1036 ± 16	17.4 ± 15.4	108 ± 11.2	5.6	2.2 - 10
Sustainable (SA)	20	19 - 59	2.5 - 3.0	-858 ± 52	11.5 ± 9.55	112 ± 33.9	4.0	2.0 - 15.4
Farm 4 2014								
Mainstream (MA)	174	5 - 15	1.0 - 1.2	-212 ± 63	0.88 ± 0.83	141 ± 19.3	3.5	0.0 - 0.46
Sustainable (SA)	91	5 - 17	1.1 - 1.4	-316 ± 147	0.02 ± 0.2	154 ± 54.3	3.2	0.0 - 0.13
Agro-ecological Region[5] 8.1 (Seed variety ASD 16)								
Farm 5 2013								
Mainstream (MA)	121	0 - 0	0.00 - 0.00	15 ± 65	1.39 ± 1.66	286 ± 49.1	6.5	0.1 - 1.6
Sustainable (SA)	99	0.2 - 1	0.01 - 0.02	-156 ± 91	2.47 ± 1.16	216 ± 88.1	6.5	1.0 - 2.2

Please see Kritee et al (PNAS, 2018) for details. [1]Estimate of mineralised organic N available in each season were based on literature; [2]Organic C content estimated via literature review; [3]Cumulative water use calculated by adding field water tube level data; [4]Range of minimum emission factors for individual replicate plots based on inorganic N and maximum organic N input; [5]See Fig. 1

TABLE 3

Summary of climate impacts of upland crops in peninsular India

Treatment	Inorganic N (kg ha^{-1})	(Min - Max) Organic N# (kg ha^{-1})	Total N (kg ha^{-1})	Grain yield* (kg ha^{-1})	N_2O flux (kg N_2O-N ha^{-1})	GHGI (Flux/yield) (tCO_2et^{-1})
Groundnut (Dry rainfed site; 163 ± 17 mm rain) 2012-2014						
Very High N	77	7 - 22	91 ± 8	240 ± 0	2.43 ± 0.43[a]	4.73 ± 0.83
High N	37±9[#]	7 - 25	53 ± 9	376 ± 53[a]	1.17 ± 0.11[b]	1.45 ± 0.16
Low N (SA)	0	7 - 29	18 ± 11	514 ± 94[a]	0.83 ± 0.09[c]	0.75 ± 0.11
Control	0	0 - 0	0 ± 0	254 ± 0	0.49 ± 0.03[d]	0.90 ± 0.05
Groundnut (Wet irrigated site-370 mm water use) 2012 (Data from Kritee et al, 2015)						
High N	75	8 - 23	90 ± 8	1021 ± 0	1.89 ± 0.21[a]	0.87 ± 0.10
Low N (SA)	0	10 - 30	20 ± 10	1379 ± 0	1.38 ± 0.26[a]	0.47 ± 0.09
Finger-millet (Dry low rainfall region - 204 ± 120 mm) 2012-2014						
Very High N	470	3 - 9	476 ± 3	1135 ± 156[a]	15.47 ± 2.75[a]	6.38 ± 1.25
High N	206	3 - 10	213 ± 3	1469 ± 105[a]	1.94 ± 0.55[b]	0.62 ± 0.18
Low N (SA)	50	14 - 42	78 ± 14	1284 ± 248[a]	0.34 ± 0.08[c]	0.13 ± 0.03
Control	0	0 - 0	0 ± 0	623 ± 17[b]	0.27 ± 0.05[c]	0.20 ± 0.04
Finger-millet (Wet high rainfall region - 480 mm) 2015						
Very High N	463	5 - 14	473 ± 5	2095 ± 452[a]	18.01 ± 6.48[a]	4.03 ± 1.69
High N	238	5 - 14	248 ± 5	2307 ± 178[a]	8.08 ± 0.63[ab]	1.64 ± 0.18
Low N (SA)	41	5 - 14	50 ± 5	2929 ± 338[b]	1.27 ± 0.03[ac]	0.20 ± 0.02
Control	0	0 - 0	0 ± 0	1869 ± 197[a]	0.33 ± 0.22[ac]	0.08 ± 0.06
Foxtail-millet (Rainfed - 121 mm) 2014						
High N	49	10 - 32	70 ± 11	208 ± 19[a]	0.30 ± 0.09[a]	0.7 ± 0.20
Low N (SA)	0	8 - 26	17 ± 9	140 ± 18[a]	-0.10 ± 0.16[b]	-0.3 ± 0.08
Control	0	0 - 0	0 ± 0	26 ± 0[b]	-0.2 ± 0.00[b]	-1.3 ± 0.20

All uncertainties are 1 SE. For each of the five categories, different superscripted letters (a-d) next to yield and N_2O flux columns denote statistical difference ($p < 0.1$). p values are lower than 0.01 is several cases. [#]Estimate of mineralised organic N available during the season. [##]Variations existed from year to year because farmers change the amounts of fertilizer added in response to rainfall

Supporting TABLE 1

Upland crops: Site description, soil quality, weather and other details

	Groundnut (2012)	Groundnut (2012)	Groundnut (2013)	Groundnut (2014)	Foxtail-millet (2014)	Finger-millet (2012)	Finger-millet (2013)	Finger-millet (2014)	Finger-millet (2015)
Agro-ecological region (AER)	3	3	3	3	3	8.2	8.2	8.2	8.2
Measured SOM (0-15 cm) (%)	0.67	0.67	0.32	0.32	0.48	0.72	0.72	0.72	1.43
Water holding capacity (0-15) (% v/v)	53	53	52	52	54	52	52	52	56
Measured Sand, Silt, Clay (0-15 cm) (w	75, 12, 13	75, 12, 13	72, 15, 13	72, 15, 13	See note*	68, 17, 15	68, 17, 15	68, 17, 15	68, 16, 17
Season description (w.r.t monsoon)	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest
Local name of the season	*Kharif*	*Rabi*	*Kharif*	*Kharif*	*Kharif*	*Kharif*	*Kharif*	*Kharif*	*Kharif*
Season duration (Days)	113 (Jul 19-Nov 9)	110 (Dec 14 - Apr 3)	16 (Jul 10 - Nov 3)	112 (Sep 4 - Dec 25)	100 (Oct 12 - Jan 19)	129 (Aug 25 - Jan 1)	128 (Aug 5 - Dec 11)	130 (Aug 21 - Dec 29)	114 (Aug 3 - Nov 25)
Measured Seasonal Rainfall (mm)	196	370	188	107	101	92	185	337	480.4
Measured Seasonal Temp (Max/min)	20°C/37°C	15°C/40°C	21°C/35°C	20°C/36°C	21°C/36°C	11°C/35°C	10°C/35°C	14°C/33°C	14°C/37°C
Farm size (ha)	0.42	0.42	0.28	0.28	0.31	0.1	0.1	0.1	0.16
Altitude (m)	610	610	356	356	436	787	787	787	737
Latitude and Longitude	14.655031 N 77.641203 E	14.655031 N 77.641203 E	14.654511 N 77.641670 E	14.654511 N 77.641670 E	14.27289 N 77.611878 E	12.78549 N 77.21779 E	12.78549 N 77.21779 E	12.78549 N 77.21779 E	12.77355 N 77.20298 E
Location (Village, District)	Upparapalli, Anantapur	Upparapalli, Anantapur	Upparapalli, Anantapur	Upparapalli, Anantapur	Chennekothapalli, Anantapur	Nijayapanadoddi, Ramnagara	Nijayapanadoddi, Ramnagara	Nijayapanadoddi, Ramnagara	Channegowdanadoddi, Ramnagar
Seed variety	K6	K6	K6	K6	Local	MR1	MR1	MR1	MR1
Seed quantity BP|AP (kg/ha)	173 | 173	222 | 222	124 | 124	143 | 143	12 | 7	24.7	22	22	24
GHG Sampling Intensity (% days)	40	46	59	42	34	36	51	44	53
% readings below MDL (N_2O)	21	11	20	19	32	42	47	36	4
% Negative values	22%	8%	10%	5%	38%	32%	28%	17%	10%

* We could not measure the soil texture (w/w) at this farm but expect it to be similar to that of groundnut farms which are only ~45 km (28 miles) away based on previous research.

Supporting TABLE 2

Upland crops: Timing of addition of fertilizers

DAS	Inputs	Very High N (VHN) (kg ha^{-1})	High N (HN) (kg ha^{-1})	Low N (LN) (kg ha^{-1})
Groundnut 2012-2014 (*Kharif* - Low Rainfall)				
-15±0	Farm Yard Manure	4944 ± 0	7165 ± 1446	8275 ± 1605
-15	Neem cake***			247 ± 247
0	DAP*	180 ± 0	176 ± 7	
0	*Ghanajeewamrutha****			494 ± 0
39±1	Gypsum		494 ± 0	494 ± 0
42±7	*Ghanajeewamrutha****			494 ± 0
44±8	Urea*	99 ± 0	14 ± 14	
71	Muriate of Potash		99 ± 0	
Groundnut- 2012 (*Rabi* - Irrigated)				
-15	Castor cake		741 ± 0	741 ± 0
-15	Neem cake			247 ± 0
0	DAP		136 ± 0	
0	*Ghanajeewamrutha****			49 ± 0
30	Urea		111 ± 0	
30	*Jeewamrutha****			5**
36	Gypsum		494 ± 0	494 ± 0
52	*Jeewamrutha****			10**
71	*Jeewamrutha****			20**
Finger-millet (*Ragi*) 2012-2014 (*Kharif* - Low Rainfall Region)				
-22±7	Farm Yard Manure	1529 ± 0	1804 ± 0	7412 ± 0
0	Urea			54 ± 0
0	Single Super Phosphate			99 ± 0
0	Muriate of potash			62 ± 0
0	Diammonium phosphate	99 ± 0	104 ± 0	
37	Urea	593 ± 0	410 ± 0	27 ± 0
72±11	Urea	395 ± 0	0 ± 0	27 ± 0
Finger-millet (*Ragi*) 2015 (*Kharif* - High Rainfall Region)				
-15	Farm yard manure	2471 ± 0	2471 ± 0	2471 ± 0
0	Urea			
0	Single Super Phosphate			
0	Muriate of Potash			
0	Diammonium Phosphate	62 ± 0	69 ± 0	40 ± 0
20	Urea	593 ± 0	297 ± 0	37 ± 0
45	Urea	395 ± 0	198 ± 0	37 ± 0
Foxtail-millet (*Korra*) 2015 (*Kharif*)				
-15	Farm Yard Manure		9880 ± 0	6175# ± 0
0	Diammonium Phosphate		47 ± 0	
0	*Ghanajeewamrutha****			247 ± 0
25	*Ghanajeewamrutha****			247 ± 0
34	Urea		87 ± 0	

DAS stands for days after sowing. *Variation in DAP/Urea amounts exist because farmers change the amounts of fertilizer added in response to rainfall ** Values expressed in litres. ****Ghanajeevamrutha* and *jeevamrutha* are fermented manures. Neem cake is Indian organic manure made from seeds of *Azadirachta indica*. See Kritee et al (2015) for details. # The Low N package originally recommended by partner NGO included addition of 1500 Kg ha^{-1} enriched (NADEP) compost whose N content can be as high as 1.2%. This product was, however, not available, as is true for most farmers in the region. If NADEP was added, it would have added 13-18 kg N ha^{-1} amount of N.

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