Greenhouse gas emissions from rice

RGTW Working Paper Number 5 , 2013

Alfred Gathorne-Hardy[1] alfred.gathorne-hardy@area.ox.ac.uk

Globally rice is a crucial crop: it has a central role in providing food, it has a central role in providing employment, and it has substantial environmental impacts. This paper looks at the environmental impacts from rice farming, specifically greenhouse gas emissions.

Rice provides the staple food for over 60% of the world's population. Globally 80% of rice is grown by small farmers in low income and developing nations, and in India rice farming is a key source of employment for the 60% of Indian workers still dependent on agriculture for work. Yet rice production is also an important source of greenhouse gas emissions, for example responsible for between 3 and 8 times the emissions of wheat, due largely to the methane emitted from flooded paddy fields, and the energy needed for pumping water.

Understanding how these emissions arise, and potential mitigating steps, is important not only for environmental scientists, but also for social and political scientists who wish to understand the interactions between the social and environmental aspects of agriculture.

This paper is aimed at scientists and non-scientists alike - while covering all the science associated with rice farming greenhouse gas emissions, it aims to do so in a manner understandable by all.

---

[1] Prepared in dialogue with Barbara Harriss-White and Rebecca White

CONTENTS

1. Introduction

It is notoriously difficult to mitigate greenhouse gas (GHG) emissions from agriculture, in part dueto the lack of end product substitution. While transport can shift from fossil fuels to electricity, and electricity can shift from fossil fuels to renewables, no such substitutions are available for agriculture. Farmers can use nutrients more efficiently but nutrients are still required, more milk can be milked from each cow, but cows still produce methane. In essence, most GHG mitigation options in agriculture are at best incremental rather than revolutionary.

At present agriculture represents a relatively small fraction of total GHG emissions from developed counties, for example about 9.2% for the UK (DECC 2013), but this proportion is likely to increase as other sectors reduce their emissions. In contrast agricultural GHG emissions from many developing countries are reducing in relative importance – not because agriculture is becoming more GHG efficient, but because the emissions from the rest of the economy are growing. In India, for example, agricultural emissions in 2007 were 17% of total emissions (MoEF 2010), down almost 40% of the nation’s total over 13 years (MoEF 2004).

Yet the lack of simple technological fixes for agriculture should not be taken as a reason to ignore the sector. In contrast it is even more important to understand every source of emissions, as the route to emission reductions is likely to be a wide ranging set of salami cuts rather than a few large technological changes (Prins et al, 2010).

The aim of this paper is to try and understand the main sources of emissions from Indian rice production, and then understand some of the potential methods to reduce emissions. A separate paper is dedicated to the production stage of the rice production/distribution system due to the complicated and unique forms of emissions from this stage.

A major elephant trampling in the room is *demand*. If there is any single activity that would reduce emissions from agriculture it is a reduction in unnecessary demand, specifically from land hungry end products such as cereal-fed meat or first generation biofuels. But unlike the shifts available from the power sector, for instance, demand is a socio-political rather than technological factor, and is more complicated to manipulate. Demand is a solution mostly independent of the measures discussed below, and partly for this reason, and partly due to its overriding complexity, it will not be covered here.

On farm GHG emissions for rice production fall into four main categories:

1. Methane emissions
2. Nitrous oxide emissions (from microbial action in soils)
3. Carbon storage in the soil - soil organic carbon (SOC)
4. Direct and Indirect CO_2 emissions associated with on and off farm energy production and use, as well as the production of farm equipment. These are covered in depth in another paper from this series..

2. Methane production from rice

Methane (CH_4) is the primary GHG from irrigated rice farming systems, so understanding methane production is important for understanding the overall GHG burden of rice production. The total methane emissions from a paddy field are determined by methane *production, oxidation* and *transport* (Frenzel et al. 1999). These in turn are affected by the physical, chemical and biological properties of the soil, quantity of organic residues, temperature, plant physiology, and water regime (Minami 1995).

2.1.Production

Methanogenesis, methane production, is a microbial process strictly limited to anaerobic conditions[2] (Ma et al. 2010). While oxygen can diffuse in water, the rate of diffusion is 10,000 times slower than through air, so paddy soil is anoxic within hours of flooding (Chanton et al. 1997, Bodelier 2003). Although not all rice is grown in flooded conditions, globally 90% of rice land is at least temporarily flooded (Wassmann et al. 2009)[3].

Respiration and methane production

Respiration is the conversion of chemical energy (for example sugars) into useful energy. It is most efficient in the presence of oxygen (oxygen is used as an *electron acceptor*, or an *oxidising agent*).

When oxygen is in short supply alternative *electron accepters* are used by soil microbes (oxides of nitrogen, magnesium, iron and sulphur, used in that order (Frenzel et al. 1999, Xu et al. 2003)) but once these are all 'used up' (*reduced*), anaerobic respiration will occur, including the use of CO_2, with methane produced as a by-product:

$$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3\ CH_4 + \text{energy}$$

The production of methane from organic matter is a complicated process, and requires at least four sets of micro-organisms, each progressively degrading complex organic compounds into simpler molecules such as H_2, CO_2 and $CH_3CO^-_2$ that methanogens can use. Different populations of methanogens use different compounds for energy generation (Le Mer and Roger 2001)

2.1.1.Drivers of field CH_4 production.

Water regime. As discussed above, methanogenesis occurs only in anaerobic conditions, and flooding is the key driver of soil anaerobic conditions, so the flooding regime is critical to

---

[2] Although there is some debate about aerobic methanogenesis, see claims by (Keppler et al. 2006), these have been largely discounted (Beerling et al. 2008)

[3] The GHG emissions from dryland rice, grown in aerobic soils, are closer to that of other cereals such as wheat. Dryland rice is a net sink of methane, and nitrous oxide is likely to be a more important GHG. It is discussed specifically in section 5.3 below.

methanogenesis (Adhya et al. 2000, Yan et al. 2005, Ma et al. 2010). Yet flooding a field doesn't immediately result in significant methane production due initially to the reserves of trapped molecular oxygen in soil pores and then to the existence of alternative electron acceptors that allow aerobic respiration. These reserves take time both to build up and to be used, so the length of flooding and drying periods are critical, both during and prior to the crop. Thus a short drainage prior to transplanting reduces total CH_4 emissions, but not as much as a whole aerobic season (such as a preceding aerobic wheat crop, for example). Similarly during rice growth, a single drainage will reduce methane emissions (Wang et al. 2000), but two drainages will reduce emissions even further (Yan et al. 2005). It is suggested that the impact of drainage could impact CH_4 production not only through the levels of electron acceptors in the soil, but also through the toxic impacts of molecular oxygen on methanogenic bacteria during drainage (Xu et al. 2003). In summary, longer and more frequent field drainage results in lower CH_4 emissions.

Importantly, while intermittent drainage reduces methane emissions, drainage increase N_2O emissions (another important greenhouse gas), as discussed in section 3.1 below.

The use of midseason drainage was developed as a method for increasing rice yields (for example reducing sulphide toxicity (Stępniewski and Stępniewska 2009)) and conserving water, rather than for climate change mitigation (Tyagi et al. 2010). This has important implications for the success of introducing such a practice, as in principle its spread could be limited to knowledge of its potential – no additional incentive should be needed. Wang et al (2000), found the use of midseason drainage resulted in a small, although not significant, decrease in yields, but such findings are not common.

Organic amendments

Methane is produced from the respiration of organic matter in anaerobic conditions. Given the existence of abiotic conditions in a paddy soil, the supply of methanogen substrate - soil organic matter – is the commonest limiting factor for methanogenesis (Yao et al. 1999, Wang et al. 2000).

Organic matter typically arise from four sources – three imported or easily controllable sources: animal manure, green manure and crop residues (straw, stubble, roots), and one by-product of rice production – this year's root exudates, sloughed off root cells, root turnover. The addition of 5t rice straw ha^{-1} increased CH_4 emissions tenfold compared to the use of urea alone (Neue et al. 1996), and the CH_4 reductions associated with alternate irrigation was lost when rice straw was added compared to continuously flooded paddy, measured per tonne of paddy (Adhya et al. 2000).

Root exudates.

Root exudates consist of a wide range of compounds, from sugars to complex proteins, which are released from the roots into the surrounding soil (the rhizosphere). They have a variety of purposes, including allelopathy (the chemical inhibition of one species by another, for example to reduce competition), antifungal and feeding symbionts. Root exudates commonly comprise up to 20%, and exceptionally as much as 50%, of the total carbon fixed by the plant, in rice this figure is assumed to equal about 15% of harvest biomass (Bronson et al. 1998)Nguyen, 2003; Rees et al., 2005). Root exudates can – depending on the biotic and abiotic soil conditions – become recalcitrant soil organic carbon (SOC) and increase the overall C storage; or can prime other biological molecules, encouraging SOC breakdown (Hagedorn et al., 2001).

This organic amendment associated increase in CH_4 emissions decreases over the growing season to insignificance, suggesting the rice plant becomes increasingly important for both mediating CH_4 emissions (see 'transport' below), and also providing substrate for CH_4 production through root exudates and sloughing off of root cells (Neue et al. 1996). In one study 'this years'' C was responsible for 50% of methane production compared to methane sourced from previous fixed C stocks by the later stages of growth (although notably no organic amendments where applied in that study) (Tokida et al. 2011). Importantly, while there will always be a degree of root exudation and turnover, the extent may vary according to the rice variety.

Unsurprisingly bio-fertilisers such as Azolla tend to increase CH_4 ha^{-1} , presumably through increasing methanogenic substrate, but the emissions on a weight basis can be reduced due to the yield gains associated with N fixation (Adhya et al. 2000).

In summary – high rates of organic amendments such as manure, straw or green manures are likely to lead to a higher level of methane production in flooded soils.

Temperature

Higher soil temperatures have been widely cited to increase CH_4 emissions (Adhya et al. 1994, Neue et al. 1996, Aggarwal 2008).

Other factors such as hours of sunshine and water levels appear to indirectly impact soil temperature, rather than having direct impacts.

2.2.Oxidation

Methanogenesis *produces* CO_2 and CH_4 in equal quantities (see 'Respiration and methane production text box above), but from the climate perspective it is the quantity of CH_4 that reaches the atmosphere that matters, and this is often substantially less than that originally produced. Significant quantities of methane are oxidised before release. Kögel-Knabner et al (2010) give a full review of soil biochemistry under paddy rice systems.

This provides an apparent contradiction: how CH_4 can be both created and oxidised in a paddy field – methane can only be produced in an anaerobic environment, so how can it be oxidised in the same place? The answer is heterogeneity within paddy soils: areas of soil will be anoxic, and in other zones oxidising agents will be available. There are three main areas within paddy system where oxidation of methane occurs: at the soil/water surface, where the limited oxygen that does diffuse through the water column is oxidised to CO_2 and H_2O; around the root zone where oxygen leaks out of the roots (Gilbert and Frenzel 1998, Bodelier 2003); and finally in the rice aerenchyma (see text box for description), which are critical for the survival of rice (and other aquatic plants) in anoxic soils, but also a key mode of methane emissions.

Subsequently a range of methano*trophic* micro-organisms exist in the rhizosphere and surface soil, reducing the amount of methane that reaches the atmosphere by as much as 90% (Kögel-Knabner et al. 2010, Ma et al. 2010). I

Oxidation at the soil /water surface layer is inhibited by ammonium, which is likely to be oxidised in preference to $CH_{4.}$ This cannot be extrapolated to assume increased CH_4 emissions from fields fertilised with ammonium as nitrate – the product of ammonium nitrification – can inhibit methanogenesis

There is an apparent correlation between the rate of methanogenesis and the rate of methane oxidation, for example Xu et al. (2003) found that although CH_4 production increased if soil had been flooded in the previous season, so did oxidation, so that although CH_4 production increased by 13.3 times, CH_4 flux increased by only 6.1 times. Similarly Adhya et al. (2000) found that increased organic amendment also increased methane oxidation potential, and although organic amendment

Aerenchyma

Plant roots need oxygen to grow, repair themselves and to actively transport sugars and nutrients, yet roots in standing water exist in an anoxic environment. Rice plants have a system of air filled intercellular spaces called aerenchyma, which allow oxygen diffusion from leaves to the roots. Some of this oxygen then leaks into the soil surrounding the roots (the rhizosphere), where it has important properties – mainly the oxidising of various reducing substances in the root proximity (Flessa and Fischer 1992). This protects the plant against reducing substances such as ferrous iron and hydrogen sulphide and to some level the productivity of rice is influenced by the oxidising potential of its roots (Raskin and Kende 1985).

consistently increased CH_4 emissions per hectare, the use of Azolla decreased CH_4 emissions t^{-1}. Presumably the suitable conditions for methanogenesis previously stimulated growth in the methanotrophic bacteria population, priming them to consume more CH_4 while it is produced.

Other minor factors.

Puddling, the mixing of soil and water to create a soil easy to transplant into and to produce a layer impervious to water, occurs through the destruction of soil texture[4]. The reduced percolation can increase methanogenesis by reducing the flow of oxygen containing water (Sharma and DeDatta 1985)

2.3.Transport

Methane is made in the soil, and emitted to the atmosphere through one of three mechanisms: ebullition (bubbles), after diffusing through the paddy water column or transported through rice plants (typically about 10% : 90% respectively) (Le Mer and Roger 2001, Cheng et al. 2006, Das and Baruah 2008). But how does methane get into, and then move through, the rice plant? Modes of plant methane emission are not fully understood. Nouchi et al (1990) suggest stomata are not an important plant emissions site (there is no correlation with transpiration rates, and the addition of abscisic acid (which is known to close stomata) did not slow the release of methane). Instead they suggest that methane emissions occur from the culm (an aggregation of leaf sheaths). Yet others found the opposite – a link between emissions and transpiration, and a correlation with stomata density and methane emissions rates (Chanton et al. 1997, Das and Baruah 2008). As methane emission is likely to be diffusion dominated, any plant: atmosphere openings result in methane diffusion from the plant.

Varietal choice and other factors impacting emissions.

---

[4] This destruction of soil structure will be discussed RE the impact of organic matter on rice yield later – one of the traditional advantages of manure application is the improvement of soil structure, but if this is deliberately destroyed one key benefit of manure is lost.

The role of traditional versus improved varieties and methane emissions is not clear but evidence suggests traditional varieties emit more methane on an area basis (also see the discussion under oxidation above – it is important to realise that when measuring flux we are looking at a combination of production, oxidation and transport). Gogoi et al. (2008) found a two-times difference in emissions between varieties. Both Das and Baruah (2008) and Gogoi et al. (2008) found correlations between physical factors including the leaf area index, the number of leaves, tiller number and medullary cavity size with methane emission rates, and these where typically higher with traditional rather than improved varieties. Neue et al (1996) found increased emissions with traditional varieties, but also quoted reduced emissions from traditional varieties from an Indonesian study.

But - can this be generalised to all traditional and modern varieties and what happens to the methane not transmitted? Large portions of methane produced during anaerobic phases of rice production can become trapped in the soil, and although drainage allows oxidation, much methane is released during drainage as macropores become aerated, allowing the methane to reach the atmosphere (Neue et al. 1996). If reduced transport potential is associated with different varieties, is there a corresponding build-up of soil methane that is released on drainage, or are total methane emission rates also reduced? These details have not been research, according to our knowledge.

Methane – a few background points

Methane is the second most important (long life) GHG after CO_2, responsible for ≈ 20% of anthropogenic global warming (IPCC 2007). Typical ranges over the last 650kyr are 400ppb in glacials, and 700ppb during interglacials (with one measurement 770ppb). In contrast, 2005 levels were 1774ppb, so the atmospheric concentration has more than doubled. The rate of growth has substantially slowed from a peak of 1%yr in the 1970s to close to zero.

Most CH_4 is destroyed in the atmosphere by OH radicals (and NO_3 radicals at night) resulting in a life expectancy of approximately 12 years.

The role of CH_4 in mitigation climate change is contentious, one side suggest effort focused on reducing CH_4 emissions can provide dramatic cuts quickly, effectively buying us time to 'sort everything out' with the added benefits of air quality improvements (Shindell et al. 2012). The alternative argument suggests that climate focing is ultimately determined by atmospheric stock of $CO_{2,}$ CH_4 only lasts for circa 12 years in the atmosphere (IPCC 2001), so is less important as a GHG than longer lasting gases, for example Allen et al (2009).

Sources (total 596)		Quantity
Natural (total 168)	Wetlands	145
	Termites	23
Anthropogenic (total 428)	Coal mining	48
	Gas and oil	36
	Ruminants	189
	Rice agriculture	112
	Biomass burning	43
Sinks (from AR4) (total 581)	Soil	30
	Tropospheric OH	511
	Stratospheric loss	40

Table 1. Sources and sinks of CH_4 ($Tg(CH_4)\ yr^{-1}$) 1996 – 2001. This is the most recent data. There is considerable variation in figures, by a factor of 2.

2.4.Mitigating rice methane emissions

Many different mechanisms for controlling methane emissions have been proposed, including varietal choice and fertiliser use, but water management and modifying quantities of organic amendment dominate. Yan et al. (2005) assumes that a single drainage reduces emissions by ≈40%, although it is likely that this figure has high uncertainty (for example a study from Orissa showed methane emissions of 16,19, 27 and 36kg ha^{-1} per season from alternately flooded, continuously flooded, alternately flooded with 2t straw and continuously flooded with 2t straw, fields respectively (Adhya et al. 2000)).

The premise is that reduced flooding results in reduced methane emissions through both reduced methanogenesis and increased methanotrophic activity. Pot trials with intermittent drying periods show significant reductions in CH_4 emissions with intermittent drying, more shorter periods providing greater savings than fewer longer (Ma et al 2011). The uptake of different drainage activities is likely to partially determined by how fewer longer or more shorter drainage periods on weed growth.

There is also a suggestion that the drop in redox potential associated with CH_4 planting occurs faster if the field had been flooded the previous season, so alternate wet and dry season cropping could further reduce methane emissions, see Table 2.

Preseason water status	Relative flux
Short drainage	1
Long drainage	0.68
Two drainages	0.12
Flooded	1.90

Table 2. Relative fluxes for different preseason water statuses (Supposing the flux of 'short drainage' to be 1). Taken from (Yan et al. 2005)

The timing of organic amendment is also important; if it occurs immediately before rice production then CH_4 production can be considerably increased (for example 6t straw ha^{-1} resulted in x3.1 CH_4 emissions) while if it occurs at the beginning of the previous season this increase is reduced (to only 1.8 in this example) (Yan et al. 2005). This is presumably due to rapid aerobic breakdown of labile carbon over the previous season, in which case this benefit only offers genuinely benefits from the climate change perspective if the previous season was farmer aerobically.

Fertiliser use.

Nitrogen fertiliser is commonly the limiting factor in rice production, so, to maximise yields, some form of N is commonly applied – whether synthetic or organic. The impact on CH_4 emissions is unclear – studies have shown that urea ($CO(NH_2)_2$) and ammonium sulphate($(NH_4)_2SO_4$) can decrease emissions – potentially though inhibiting methanogenesis, for example Xie et al (2010) reported 28-30% lower emissions over the season when 150-250kgN (urea) ha^{-1} was applied. Application between these two levels did not seem to impact CH_4 emissions, but lower levels do seem to result in increased CH_4 emissions. A long term study by Dong et al. (2011) also suggests that increased use of urea and ammonium phosphate – the two main N fertilisers used in India – significantly reduced CH_4 emissions, and significantly increased yield. Neither of these studies measured nitrous oxide (N_2O) emissions, which are likely to be higher in total with higher N fertiliser rates – even if the increases are not from on-site (as is discussed later, N_2O emissions from flooded fields are typically low, but leaching of N could lead to significant off-site N_2O emissions from high N application rates – see section 3.2).

The implication of these results suggests that CH_4 emissions from farmers not using urea could be higher than IPCC default factors suggests, as these are generated from conventional farms where urea use will have suppressed CH_4 emissions, thus emissions from organic farms specifically could be higher than 2^o data suggests.

Other studies have shown increases in emissions associated with urea or ammonium phosphate ($(NH_4)_2HPO_4$) applications – potentially through increasing plant growth and so both providing additional feedstock for methanogenic bacteria, and additional transport. For example Cai et al. (1997) found ammonium sulphate reduced CH_4 emissions by 42 and 60%, and urea by 7 and 14% at 100kgN ha^{-1} and 300kg N ha^{-1} respectively. But they found a strong inverse correlation between CH_4 and N_2O, driven by the water regime – very little N_2O emissions during field flooding, but rapidly increasing N_2O emissions during drainage.

In summary, CH_4 emissions are highly variable, and until a large enough body of research is developed to untangle the impact of different N fertilisers from other variables, the importance of N on methane emissions remains a matter for further research. It cannot yet be used in life cycle assessment.

2.5. Important caveat for all these discussions.

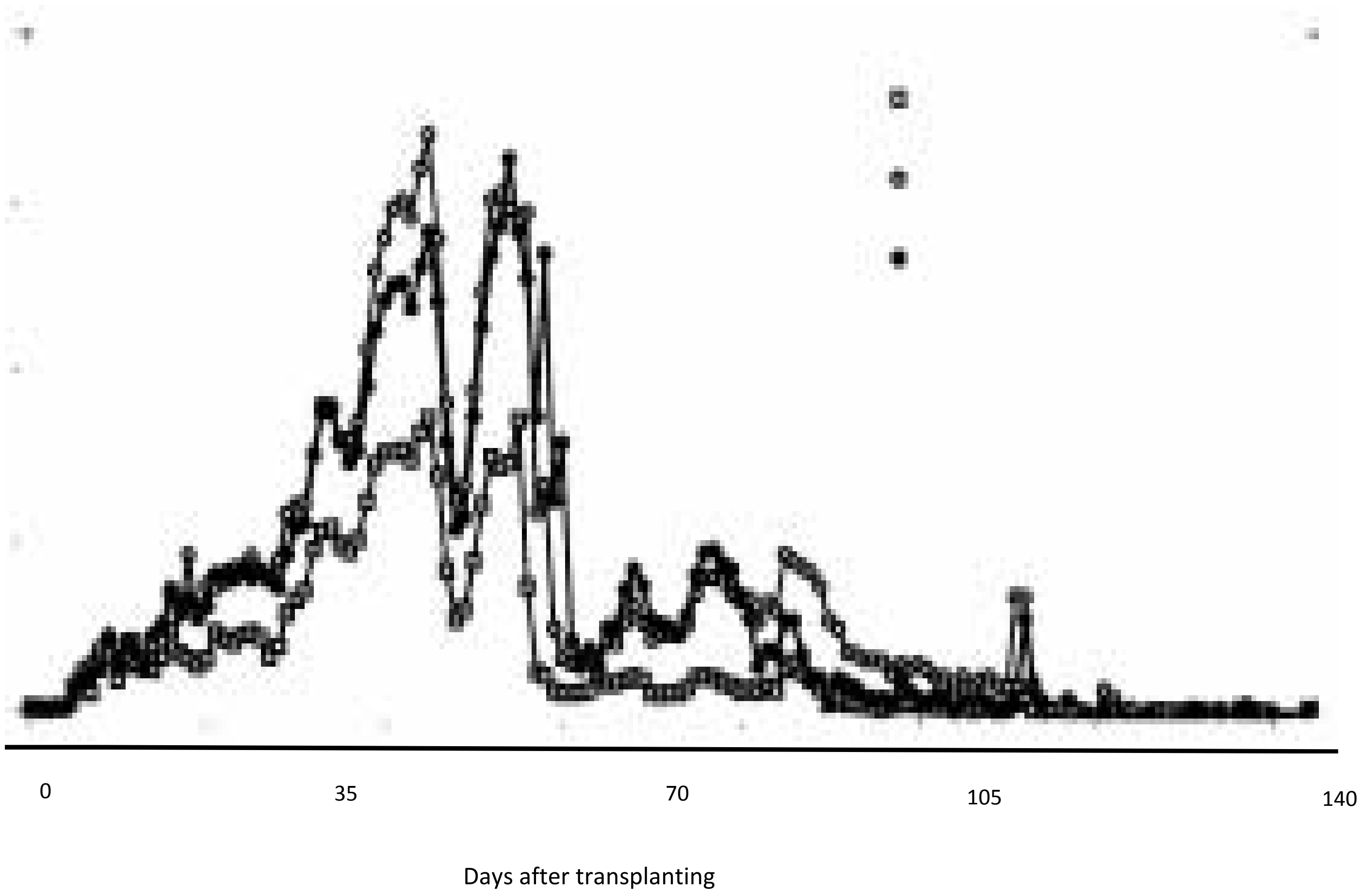

Figure 1. Seasonal pattern of CH_4 emissions after transplanting. Drainage occurred from days 55-75. This illustrates the non-linear nature of CH_4 emissions from paddy rice. From (Wang et al. 2000)

The quantity of methane produced is highly variable over space and time. Within a particular site patterns of emission such as depicted below in Figure 1 are common (see also (Adhya et al. 2000), while methods of calculating usually amortise differences over the season, reducing accuracy considerably, depending on many factors, and a long term study in China showed that under the same treatment (except for depth in continuously flooded fields) CH_4 emissions varied by 68% over three years (Dong et al. 2011). Thus although it is important to identify trends associated with CH_4 emissions, it should be recognised that predicting the actual numbers from a specific site is dangerous!

3. The Nitrogen Cycle and production of N_2O.

Nitrogen (N) is essential for plant growth, and is the most commonly limiting plant nutrient worldwide, as such the addition of N– as manure or synthetic fertiliser – often increases plant growth.

Plants can absorb nitrogen in a variety of forms, recent evidence showing even whole amino acids can be absorbed; but is most commonly absorbed as nitrate through the roots.

N fertiliser is important from the climate change perspective due to energy intensive production, and the release of N_2O from soils. N fertiliser production uses the Haber-Bosch process to convert atmospheric N2 into ammonia. Although this is now extremely energy efficient process, it is also highly energy intensive, using approximately 1% of the global primary energy supply (Erisman et al. 2008). Additionally during the production of ammonium (for example for making Di-ammonium phosphate) some N_2O is released, although the proportion of N_2O release per kg of fertiliser has reduced signficantly in modern European plants.

3.1.Nitrous Oxide 1. Direct emissions

N_2O is estimated to be responsible for 13% of Indian agricultural GHG emissions (MoEF 2010). It is produced from de-nitification and nitrification by soil bacteria, and during the production of ammonium nitrate.

In most arable agriculture N_2O is the dominant GHG. In UK wheat production for example N_2O is responsible for 80% of on-field GHG emissions (Woods et al. 2008).

Nitrous oxide emissions from traditional flooded paddy fields, with 100% water filled pore space (WFPS) are minimal, as nitrification, producing NO_3^- from NH_4^+ cannot occur due to anaerobic conditions, and consequentially neither can de-nitrification due to lack of NO_3^- in the soil[5] (Qin et al. 2010). Any N_2O that already exists in the soil, like NO_3^-, is used as an electron acceptor, and so further reduced to N_2, a gas that is transparent to infra-red (a non GHG, it has no radiative forcing, GWP=0) (Granli and Bockman (1994) quoted in (Ghosh et al. 2003)). This is demonstrated in Hou et al. (2000) , where N_2O emissions are close to zero outside the midseason drainage[6]. In conditions of very little soil moisture, N_2O emissions are equally low, presumably due to minimal bacterial activity. Between these two extremes nitrous oxide emissions are dominated by nitrification at low levels of water filled pore space (WFPS), and de-nitrification at higher moisture levels – the actual % WFPS

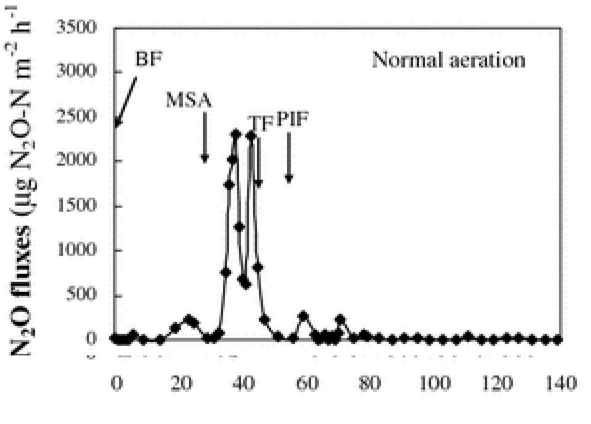

Figure 2. Nitrous oxide emissions from paddy rice with one midseason drainage (MSA). Note how the emissions are close to zero except during drainage period.

x axis relates to days after transplanting. Arrows relate to N fertiliser applications. BF, TF, and PIF equate to basal fertilizer, tillering fertilizer, and panicle initiation fertilizer, respectively. taken from Li et al. (2011)

---

[5] This is because all the NO3- has already been reduced (used as an electron donor) to NH4+ when the soil became anaerobic

[6] One reason they were not absolute zero is the aerated zone around paddy roots, allowing nitrification of NH4+ to occur in this localised environment (Duan et al. 2007)

corresponding to maximum N_2O emissions varies according to a range of factors, but is typically found between 45-80% (Hansen et al. 1993, Yan et al. 2000, Zheng et al. 2000).

The trade-off between methane and nitrous oxide emissions is shown clearly in Figure 3 – there is almost no overlap in the production of the two gases. It is also interesting to note that as well as producing methane, agricultural soils can sequester it (see RHS of the graph) – the situation in most aerobic soils

When the soil is neither too wet nor too dry the N application rate is the main driver of N_2O production, and the easy access N from mineral fertilisers produces higher levels of N_2O than the typically more bound, organic N (Qin et al. 2010).

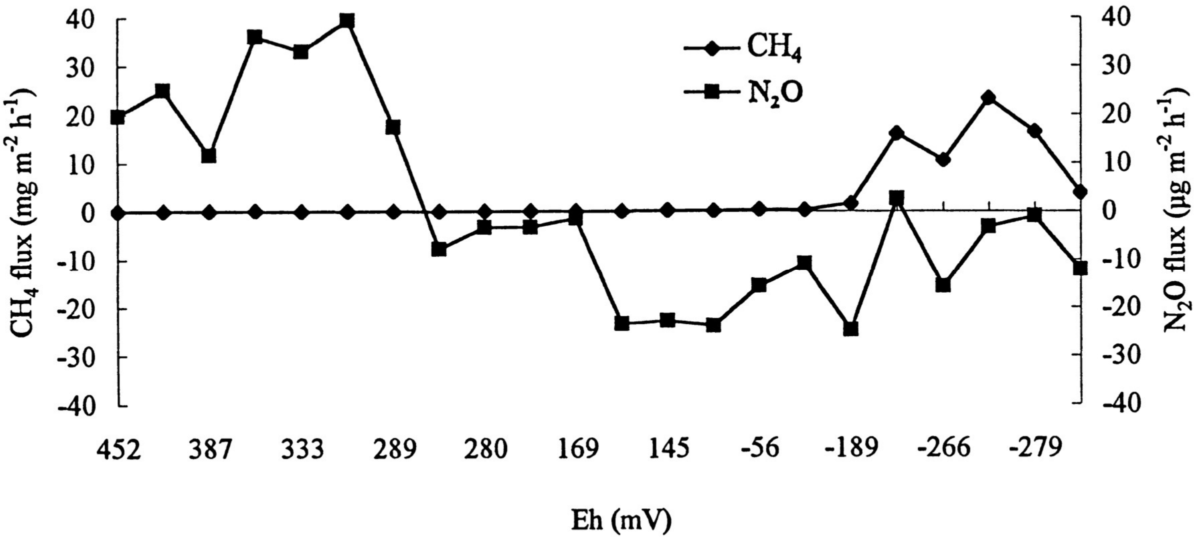

Figure 3 Relationship between CH4 and N2O emissions and redox potential in rice field throughout the season (1996) from Hou et al (2000).

3.2.Nitrous oxide 2. Indirect emissions.

Nitrogen use efficiency, measured as the uptake of N, is typcically low, for example Haefele et al (2008) 13-17% for irrigated rice, and 9-23% for rainfed, and Pathak et al (2002) found in some sites >50% of applied N emitted as N_2O. NH_4 volatilisation can be very high, especially during warm, windy weather. For example DNDC modelling suggested several cases where over 50% of available N is volatalised (Babu et al. 2006), Minamikawa et al (2010) found N_2O emissions from just the leached fraction of N where higher in irrigated rice than direct N_2O emissions. Yet in their most recent GHG accounting, the GOI used a standard emissions/ha for rice of 0.76kg N_2O-N ha^{-1}, quoting Pathak et al (2002). Interestingly this equals 0.003% of total applied N – approximately the direct emission factor from the IPCC – and substantially less than the 0.38% suggested by Pathak et al from urea used in rice. What the overall emission factor should be is unclear, Nitrous oxide emissions associated with fertiliser use are based on field measurements, but these ignore the fate of nitrogen lost from the field. While very little N_2O may be produced in the flooded paddy field, some nitrogen will be retained in the field to the following season – potentially with aerobic fields with associated N_2O release. Similarly if reactive nitrogen is removed from the field with drainage, then significant emissions could occur offsite that should be attributed to the onsite application of N. (Crutzen et al. 2007). Crutzen has suggested that at a global level the real N_2O emissions associated with N fertiliser are 3 - 5 times the emission factor commonly used. Previous analysis by others had suggested lower figures (x2 (Nevison et al. 2007) or x2.5 (Galloway et al. 2004)) but still substantially above the 1% recommended by the IPCC.

4. Soil organic carbon

Soil organic carbon is determined by the rate of soil C input (root exudates, roots, leaves, straw, manure etc), and soil C loss (typically dominated by mineralisation, but also includes erosion and leaching and mechanical removal, eg via machinery).

As flooded soils have very poor conditions for carbon oxidation (anaerobic), there is likely to be a build of SOC, comparable to the build-up of peat in natural wetlands, depending on the length of time the fields are kept flooded. This has been confirmed in China, where SOC in paddy soils is higher than in corresponding dry cropland (Pan et al. 2004).

This build up is dominated by the lack of SOC degradation, and there is no significant difference in SOC between organic and conventional continuously flooded rice (Qin et al. 2010). In addition although organic is likely to receive additional C input through organic manures, conventional rice typically generates higher yields, and thus increased crop derived C. This is especially important if the straw is returned, as straw has a far high C:N ratio than manure.

So far there is no data about the impact of mid-season drainage on soil organic carbon, but it could be hypothesised that such aerobic events would encourage the breakdown of SOM, resulting in a pulse of CO_2. The breakdown of SOM releases nutrients, so should not be seen as a purely negative feature of mid-season drainage/SRI production.

5. Impact of different rice production systems

So far this document has described irrigated rice systems. These are the most important system in India, accounting for 61% of India's production (although only 45% of its rice area) (Vittal et al. 2004).

5.1.SRI

This is only covered briefly as the topic covered in depth by Reddy et al (forthcoming in this working paper series)

Methane emissions

Emissions of CH_4 from SRI are hard to pin down. In an aerobic system there would be a net sequestration of methane, but in a partially anaerobic system we would still expect methane production, but at a lower level than in fully anaerobic systems. Controlled irrigation trials can be used as a surrogate. These do not include the other aspects of SRI techniques such as wider spacing and earlier transplanting, but methane emissions are dominated by the water regime, so these are likely to be less important. From these studies (Peng et al. 2011a, Peng et al. 2011b, Hou et al. 2012, Suryavanshi et al. 2013) there is a considerable range in methane emissions compared to conventional irrigation, but with a mean proportion of 0.58 methane emitted per area (SE of 0.19).

Nitrous oxide emissions

Nitrous oxide emissions are likely to be higher in SRI compared to flooded rice production due to the availability of oxygen, but like CH_4 emissions there is minimal data looking specifically at N_2O emissions from SRI compared to conventionally irrigated rice. The conditions in shallow water are often favourable for intense denitrification (Ross S.M. 1995). Using data from controlled irrigation as a proxy, suggests that N_2O emissions are 1.5x greater in SRI studies (Peng et al. 2011a, Peng et al. 2011b, Hou et al. 2012, Suryavanshi et al. 2013). Emissions were maximised at 80% WFPS, and started decreasing above 83% (identified as a potential mechanism to reduce CH_4 emissions) (Peng et al. 2011a).

A further complicating factor in understanding the emissions of both N_2O and CH_4 is what is defined as SRI? Strict SRI has a set of criteria in technologies and practices of production, but farmers often choose to follow only certain aspects of these. For example farmers in Tamil Nadu defined themselves as following SRI techniques if they used wider spaced planting (in that case planted with a planter) while all other agronomic factors were maintained as before – i.e. transplanted beyond the two leaf stage, multiple plants per hill and continual irrigation.

5.2.Organic rice production

One reason for rice field flooding is weed control. Dryland rice systems around the world often use herbicides to control for weeds, but such an option is not available for organic systems. Thus it *may* be more difficult to introduce periods of drainage under organic systems compared to conventional production techniques, or additional costs may be incurred for weeding. Yet the adoption of SRI organic systems suggest that aerobic paddy management using mechanical weeders may be successful.

The second key difference is that the N fertiliser addition will be organic N – carrying organic matter with the nitrogen – organic material being a key driver of CH_4 emissions. In addition to these factors, some pesticides used in conventional rice agriculture have been shown to inhibit methanogenesis.

The impacts of these factors in a Chinese study resulted in significantly higher (20%) CH_4 emissions from organic rice compared to conventional on an area basis. The impact was made even worse by reduced yield (Qin et al. 2010).

The picture is less clear for nitrous oxide emissions, where the dominating factor was drainage. Mid season drainage substantially increased N_2O emissions in both conventional and organic rice production systems.

Some herbicides increase N_2O emissions, a potential 'climate plus' for organic production (Das et al. 2011). Such a benefit could be further improved with the use of neem, a common addition to organic crops, which has been reported to decrease N_2O emissions when applied with urea (Majumdar et al. 2000).

5.3.Rainfed Rice production

Rainfed rice can be seen as more comparable to other, non-rice, arable crops rather than rice – the emissions are likely to be dominated by N_2O emissions followed by traction (diesel/bullock) emissions rather than methane. Figures for Indian dryland rice suggest between 77 to 150 mg N_2O-N m^{-2} /season from dryland rice (Baruah et al. 2010), but this is likely to depend upon the N application rate.

6. The importance of yield

Yield is a key numerator when it comes to measuring the GHG intensity of rice. It may be that using practices/products that increase GHG emissions on an area base actually reduce the GHG emissions associated with every unit of rice. For example rainfed rice is likely to have very low GHG emissions per hectare, but this does not translate into very low GHG emissions per kg, due to the lower yields of rice compared to conventional irrigated methods.

7. Conclusion

Globally rice is estimated to be responsible for 19% of anthropogenic methane emissions, second only to ruminants (Chen and Prinn 2006). This is in contrast to all other major food crops, which are grown in aerobic soils, sequester CH_4, and whose emissions are dominated by nitrous oxide. Methane emissions are determined by the rates of production, oxidation and transportation of methane, but from the management perspective the two key options can modify the amount of methane emitted. Firstly the quantity of organic matter (FYM, green manure, compost, straw) added to the field – the greater the inputs the greater the methane emissions. Yet while external inputs can be important, the plants themselves are a major source of methanogenic feedstock, so reducing organic matter input can only reduce CH_4 emissions by a limited amount.

Secondly water management. Methane emissions can be reduced by over 100% by changing the water management, but at the expense of increased emissions of nitrous oxide. Understanding the trade-offs between these two gases is important before different methods of rice production are advocated on grounds of climate mitigation.

While methane rightly dominates discussions of rice GHG emissions, nitrous oxide is also important, especially in rainfed and to a lesser extent SRI production systems.

Yield is also critical; it may be more effective to have high yields of rice from high area based GHG emitting farming systems, rather than lower yields from less GHG intensive systems. SRI offers the potential to increase yields while decreasing GHG emissions, a win-win.

Finally it is important to note that while GHG emissions are of great importance they must be put within the wider picture of sustainable development. For example how do GHG emissions interact with other measures of sustainability (food security, the quality and quantity of jobs, biodiversity, water quality etc)? This is one of the questions this research project is answering.

8. Glossary

Methanogenesis	The production of methane
Nitrification	The biological conversion of ammonia to nitrate via nitrite.
Denitrification	The biological reduction of nitrate to N_2 during which N_2O is leaked. It typically occurs in wet but not long term waterlogged soils.
Stomata	Pores on plant leaves that allow CO_2 to enter the plant, and also allowing O_2 and H_2O to escape. Importantly the size of the stomatal opening is regulated by two guard cells, allowing plants to reduce the opening size, for example when excessive water loss is likely to be a problem
Culm	An aggregation of leaf sheaths
Methanotrophs	Organisms, typically bacteria, that consume methane as an energy source.
Mineralisation	Mineralisation is the process of converting organic carbon to carbon dioxide – typically occurring through respiration/oxidation.
Redox potential	Redox potential is the measure of tendancy for a species to aquire electrons, and thus be reduced. So high redox potentials occur in environemnts where oxidation is likely, for example with plenty of oxygen. Conversely methane is likely to be released in environments with low redox potential, where there are fewer strong oxidisers such as oxygen around.

Oxidation	Oxidisation is one half of a redox equation, made up of OXidation and REduction. Oxidation is the loss of electrons to an oxidising agent, which is itself reduced. Reduction is the opposite reaction. Neither can occur without the other. The important point is that some redox reactions result in the release of energy, for example of conversion of glucose in the body to CO_2 and H_2O, while others are net sinks of energy, for example the production of urea fertiliser.
Rhizosphere	The rhizosphere is the soil region directly influenced by plant roots

9. Acronyms

WFPS	Water Filled Pore Space
N_2O	Nitrous Oxide
CH_4	Methane
FYM	Farmyard Manure
O_2	Molecular oxygen
NO_3^-	Nitrate
NH_4^+	Ammonium

10. References

Adhya, T. K., K. Bharati, S. R. Mohanty, B. Ramakrishnan, V. R. Rao, N. Sethunathan, and R. Wassmann. 2000. Methane Emission from Rice Fields at Cuttack, India. Nutrient Cycling in Agroecosystems **58**:95-105.

Adhya, T. K., A. K. Rath, P. K. Gupta, V. R. Rao, S. N. Das, K. M. Parida, D. C. Parashar, and N. Sethunathan. 1994. Methane emission from flooded rice fields under irrigated conditions. Biology and Fertility of Soils **18**:245-248.

Aggarwal, P. K. 2008. Global climate change and Indian agriculture: impacts, adaptation and mitigation. Indian Journal of Agricultural Sciences **78**:911-919.

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen. 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature **458**:1163-1166.

Baruah, K. K., B. Gogoi, P. Gogoi, and P. K. Gupta. 2010. N2O emission in relation to plant and soil properties and yield of rice varieties. Agron. Sustain. Dev. **30**:733-742.

Beerling, D. J., T. O. M. Gardiner, G. Leggett, A. McLeod, and W. P. Quick. 2008. Missing methane emissions from leaves of terrestrial plants. Global Change Biology **14**:1821-1826.

Bodelier, P. L. E. 2003. Interactions between oxygen releasing roots and microbial processes in flooded soils and sediments.*in* H. de Kroon and E. J. W. Visser, editors. Root ecology. Springer, Berlin, Germany.

Bronson, K. F., K. G. Cassman, R. Wassmann, D. C. Olk, M. van. Noordwijk, and D. P. Garrity. 1998. Soilcarbon dynamics in different cropping systems in principal eco-regions of Asia. Pages 35-57 *in* R. Lal, J.M. Kimble, R.F. Follett, and B. A. Stewart, editors. Management of Carbon Sequestration in Soil,. CRC Press, Boca Raton, New York,.

Cai, Z., G. Xing, X. Yan, H. Xu, H. Tsuruta, K. Yagi, and K. Minami. 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant and Soil **196**:7-14.

Chanton, J. P., G. J. Whiting, N. E. Blair, C. W. Lindau, and P. K. Bollich. 1997. Methane emission from rice: Stable isotopes, diurnal variations, and CO2 exchange. Global Biogeochem. Cycles **11**:15-27.

Chen, Y.-H. and R. G. Prinn. 2006. Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. Journal of Geophysical Research: Atmospheres **111**:D10307.

Cheng, W., K. Yagi, H. Sakai, and K. Kobayashi. 2006. Effects of Elevated Atmospheric CO2 Concentrations on CH4 and N2O Emission from Rice Soil: An Experiment in Controlled-environment Chambers. Biogeochemistry **77**:351-373.

Crutzen, P. J., A. R. Mosier, K. A. Smith, and W. Winiwarter. 2007. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry Physical Discussions:11191-11205.

Das, K. and K. K. Baruah. 2008. Methane emission associated with anatomical and morphophysiological characteristics of rice (Oryza sativa) plant. Physiologia Plantarum **134**:303-312.

Das, S., A. Ghosh, and T. K. Adhya. 2011. Nitrous oxide and methane emission from a flooded rice field as influenced by separate and combined application of herbicides bensulfuron methyl and pretilachlor. Chemosphere **84**:54-62.

DECC. 2013. 2011 UK greenhouse gas emissions, final figures. Department of Energy and Climate Change, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/73148/050213_Ghg_National_Statistics_release__2011_final_results_.pdf.

Dong, H., Z. Yao, X. Zheng, B. Mei, B. Xie, R. Wang, J. Deng, F. Cui, and J. Zhu. 2011. Effect of ammonium-based, non-sulfate fertilizers on CH4 emissions from a paddy field with a typical Chinese water management regime. Atmospheric Environment **45**:1095-1101.

Duan, Y. H., Y. L. Zhang, L. T. Ye, X. R. Fan, G. H. Xu, and Q. R. Shen. 2007. Responses of Rice Cultivars with Different Nitrogen Use Efficiency to Partial Nitrate Nutrition. Annals of Botany **99**:1153-1160.

Erisman, J. W., M. A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a century of ammonia synthesis changed the world. Nature Geosci **1**:636-639.

Flessa, H. and W. Fischer. 1992. Plant-induced changes in the redox potentials of rice rhizospheres. Plant and Soil **143**:55-60.

Frenzel, P., U. Bosse, and P. H. Janssen. 1999. Rice roots and methanogenesis in a paddy soil: ferric iron as an alternative electron acceptor in the rooted soil. Soil Biology and Biochemistry **31**:421-430.

Galloway, J. N., F. J. Dentener, D. G. Capone, E. W. Boyer, R. W. Howarth, S. P. Seitzinger, G. P. Asner, C. C. Cleveland, P. A. Green, E. A. Holland, D. M. Karl, A. F. Michaels, J. H. Porter, A. R. Townsend, and C. J. Vörösmarty. 2004. Nitrogen Cycles: Past, Present, and Future. Biogeochemistry **70**:153-226.

Ghosh, S., D. Majumdar, and M. C. Jain. 2003. Methane and nitrous oxide emissions from an irrigated rice of North India. Chemosphere **51**:181-195.

Gilbert, B. and P. Frenzel. 1998. Rice roots and CH4 oxidation: the activity of bacteria, their distribution and the microenvironment. Soil Biology and Biochemistry **30**:1903-1916.

Gogoi, N., K. Baruah, K., and P. Gupta, K. 2008. Selection of rice genotypes for lower methane emission. Agron. Sustain. Dev. **28**:181-186.

Granli, T. and O. C. Bockman. 1994. Nitrous oxide from agriculture. Norwegian Journal of Agricultural Sciences 128.

Hansen, S., J. E. Mæhlum, and L. R. Bakken. 1993. N2O and CH4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biology and Biochemistry **25**:621-630.

Hou, A. X., G. X. Chen, Z. P. Wang, O. Van Cleemput, and W. H. Patrick. 2000. Methane and Nitrous Oxide Emissions from a Rice Field in Relation to Soil Redox and Microbiological Processes. Soil Sci. Soc. Am. J. **64**:2180-2186.

Hou, H., S. Peng, J. Xu, S. Yang, and Z. Mao. 2012. Seasonal variations of CH4 and N2O emissions in response to water management of paddy fields located in Southeast China. Chemosphere **89**:884-892.

IPCC. 2001. Climate Change 2001: The physical science basis. Contribution of workgroup I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Section 7.4. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007. Climate Change 2007: The physical science basis. Contribution of workgroup I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keppler, F., J. T. G. Hamilton, M. Braß, and T. Rockmann. 2006. Methane emissions from terrestrial plants under aerobic conditions. Nature **439**:187-191.

Kögel-Knabner, I., W. Amelung, Z. Cao, S. Fiedler, P. Frenzel, R. Jahn, K. Kalbitz, A. Kölbl, and M. Schloter. 2010. Biogeochemistry of paddy soils. Geoderma **157**:1-14.

Le Mer, J. and P. Roger. 2001. Production, oxidation, emission and consumption of methane by soils: A review. European Journal of Soil Biology **37**:25-50.

Li, X., W. Yuan, H. Xu, Z. Cai, and K. Yagi. 2011. Effect of timing and duration of midseason aeration on CH4 and N2O emissions from irrigated lowland rice paddies in China. Nutrient Cycling in Agroecosystems **91**:293-305.

Ma, K., Q. F. Qiu, and Y. H. Lu. 2010. Microbial mechanism for rice variety control on methane emission from rice field soil. Global Change Biology **16**:3085-3095.

Majumdar, D., S. Kumar, H. Pathak, M. C. Jain, and U. Kumar. 2000. Reducing nitrous oxide emission from an irrigated rice field of North India with nitrification inhibitors. Agriculture Ecosystems & Environment **81**:163-169.

Minami, K. 1995. The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice. Fertilizer Research **40**:71-84.

MoEF. 2004. India’s Initial National Communication to the UNFCCC. Ministry of Environment and Forests, Government of India.

MoEF. 2010. India: Greenhouse Gas Emissions 2007. Ministry of Environment and Forests, Government of India, India.

Neue, H. U., R. Wassmann, R. S. Lantin, M. C. R. Alberto, J. B. Aduna, and A. M. Javellana. 1996. Factors affecting methane emission from rice fields. Atmospheric Environment **30**:1751-1754.

Nevison, C. D., N. M. Mahowald, R. F. Weiss, and R. G. Prinn. 2007. Interannual and seasonal variability in atmospheric N2O. Global Biogeochemical Cycles **21**.

Nouchi, I., S. Mariko, and K. Aoki. 1990. Mechanism of Methane Transport from the Rhizosphere to the Atmosphere through Rice Plants. Plant Physiology **94**:59-66.

Pan, G., L. Li, L. Wu, and X. Zhang. 2004. Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Global Change Biology **10**:79-92.

Peng, S., H. Hou, J. Xu, Z. Mao, S. Abudu, and Y. Luo. 2011a. Nitrous oxide emissions from paddy fields under different water managements in southeast China. Paddy and Water Environment **9**:403-411.

Peng, S., S. Yang, J. Xu, and H. Gao. 2011b. Field experiments on greenhouse gas emissions and nitrogen and phosphorus losses from rice paddy with efficient irrigation and drainage management. SCIENCE CHINA Technological Sciences **54**:1581-1587.

Qin, Y., S. Liu, Y. Guo, Q. Liu, and J. Zou. 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. Biology and Fertility of Soils **46**:825-834.

Raskin, I. and H. Kende. 1985. Mechanism of Aeration in Rice. Science **228**:327-329.

Ross S.M. 1995. Overview of the hydrochemistry and solute processes in British wetlands. Pages 133-182 *in* Hughes J.M.R. and Heathwaite A.L., editors. Hydrology and Hydrochemistry of British Wetlands,. Wiley, New York.

Sharma, P. K. and S. K. DeDatta. 1985. Effects of puddling on soil phuysical properties and processes. Pages 217-234 Soil physics and rice. International Rice Research Institute, Los Banos, Phillippines.

Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler. 2012. Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. Science **335**:183-189.

Stępniewski, W. and Z. Stępniewska. 2009. Selected oxygen-dependent process—Response to soil management and tillage. Soil and Tillage Research **102**:193-200.

Suryavanshi, P., Y. V. Singh, R. Prasanna, A. Bhatia, and Y. S. Shivay. 2013. Pattern of methane emission and water productivity under different methods of rice crop establishment. Paddy and Water Environment **11**:321-329.

Tokida, T., M. Adachi, W. Cheng, Y. Nakajima, T. Fumoto, M. Matsushima, H. Nakamura, M. Okada, R. Sameshima, and T. Hasegawa. 2011. Methane and soil CO2 production from current-season photosynthates in a rice paddy exposed to elevated CO2 concentration and soil temperature. Global Change Biology **17**:3327-3337.

Tyagi, L., B. Kumari, and S. N. Singh. 2010. Water management — A tool for methane mitigation from irrigated paddy fields. Science of The Total Environment **408**:1085-1090.

Vittal, K. P. R., P. K. Sinha, G. Ravindra Chary, G. R. Maruthi Sankar, T. Srijaya, Y. S. Ramakrishna, J. S. Samra, and S. G. Eds. 2004. Districtwise Promising Technologies for Rainfed Rice based

Production System in India. Central Research Institute for Dryland Agriculture, Indian Council of Agricultural Research, Hyderabad, India.

Wang, Z. Y., Y. C. Xu, Z. Li, Y. X. Guo, R. Wassmann, H. U. Neue, R. S. Lantin, L. V. Buendia, Y. P. Ding, and Z. Z. Wang. 2000. A Four-Year Record of Methane Emissions from Irrigated Rice Fields in the Beijing Region of China. Nutrient Cycling in Agroecosystems **58**:55-63.

Wassmann, R., Y. Hosen, and S. K. 2009. Reducing Methane Emissions from Irrigated Rice. IFPRI.

Woods, J., G. Brown, A. Gathorne-Hardy, R. Sylvester-Bradley, D. Kindred, and N. Mortimer. 2008. Facilitating carbon (GHG) accreditation schemes for biofuels, feedstock production HGCA.

Xie, B. H., X. H. Zheng, Z. X. Zhou, J. X. Gu, B. Zhu, X. Chen, Y. Shi, Y. Y. Wang, Z. C. Zhao, C. Y. Liu, Z. S. Yao, and J. G. Zhu. 2010. Effects of nitrogen fertilizer on CH4 emission from rice fields: multi-site field observations. Plant and Soil **326**:393-401.

Xu, H., Z. C. Cai, and H. Tsuruta. 2003. Soil Moisture between Rice-Growing Seasons Affects Methane Emission, Production, and Oxidation. Soil Science Society of America Journal **67**:1147-1157.

Yan, X., S. Shi, L. Du, and G. Xing. 2000. Pathways of N2O emission from rice paddy soil. Soil Biology and Biochemistry **32**:437-440.

Yan, X., K. Yagi, H. Akiyama, and H. Akimoto. 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Global Change Biology **11**:1131-1141.

Yao, H., R. Conrad, R. Wassmann, and H. U. Neue. 1999. Effect of soil characteristics on sequential reduction and methane production in sixteen rice paddy soils from China, the Philippines, and Italy. Biogeochemistry **47**:269-295.

Zheng, X., M. Wang, Y. Wang, R. Shen, J. Gou, J. Li, J. Jin, and L. Li. 2000. Impacts of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. Chemosphere - Global Change Science **2**:207-224.