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Mitigating Greenhouse Gas Emissions from Rice Production through Water-saving Techniques: Potential, Adoption and Empirical Evidence

Bjoern Ole Sander,* Reiner Wassmann and Joel D.L.C. Siopongco

Crop and Environmental Sciences Division, International Rice Research Institute (IRRI), Los Baños, Philippines

Abstract

Flooded rice fields are a large anthropogenic source of the greenhouse gas (GHG) methane (CH_4). Aeration of the paddy field can reduce methane emissions and at the same time save water. Different forms of water saving techniques (WST), e.g. alternate wetting and drying (AWD) and midseason drainage (MSD), have been developed and disseminated. This article gives an overview on adoption of AWD in the Philippines and assesses prospects and constraints. It also explains the Clean Development Mechanism (CDM) methodology for rice production and analyses the mitigation potential of WST in the form of a literature review.

The adoption rate of AWD strongly depends on the incentive for the farmer. While direct monetary incentives are limited to areas where saving water is directly linked to reduced costs (e.g. pump irrigation systems), indirect incentives (e.g. improved crop development) have not yet been scientifically assessed. The literature meta-analysis proves the great mitigation potential of WST. Methane emissions can be reduced by an average of 36.5% with a single drainage and by 43% with multiple aerations. Nitrous oxide emissions increase under all WST but this increase does not offset the reduction in CH_4 emissions. This study also shows that the amount of GHG emissions can vary drastically between different regions. This poses a challenge for the transfer of mitigation strategies from one region to another.

12.1 Water-saving Strategies

12.1.1 Principles of alternate wetting and drying and midseason drainage

Producing rice with less irrigation water requirements has been one of the core research objectives of natural resource management at IRRI and other research institutions. Midseason drainage is one strategy that has been widely adopted in China and Japan over the past decades. The principle is to expose the rice field to a dry period of about 7 days towards the end of the vegetative stage. Although water saving might be low under this strategy, grain yield tends to increase (Thompson, 2006) due to suppression of unproductive tillers, which translates to a higher water use efficiency.

While previous in-depth research focused on the identification of thresholds for reducing water use without compromising

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* Corresponding author, e-mail: b.sander@irri.org

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rice yield, this work has developed into a concise water-saving technology for rice farmers in irrigated lowlands called 'alternate wetting and drying' (AWD) starting in the early 2000s (Bouman *et al.*, 2007). The term AWD has been coined at IRRI and is synonymous with a variety of terms, such as controlled or intermitted irrigation as well as multiple aeration, that are used to describe alternatives to farmers' conventional practice of continuous flooding (CF). The intervals of non-flooded conditions from 1 day to more than 10 days depend on soil type and weather. In this technology, the farmers are taught to monitor the depth of the water table in the field using a perforated water tube that is inserted into the soil (Lampayan *et al.*, 2013). The practice which commences at 1 to 2 weeks after transplanting involves draining the field until the water level reaches 15 cm below the soil surface after which the field is re-flooded to a depth of around 5 cm. This irrigation scheme is done throughout the cropping season except during the flowering stage. The threshold of water at a 15 cm level below soil surface is called 'safe AWD', as this will not cause any yield decline because the roots of the rice plant will still be able to capture water from the saturated soils (Lampayan *et al.*, 2009). The AWD technology can reduce the number of irrigations significantly compared to farmer's practice, thereby lowering irrigation water consumption by 15–30%.

Adoption of alternate wetting and drying

Estimating the number of adopters of AWD is difficult. For the Philippines, the best estimation based on survey responses from national institutions is that around 100,000 farmers have adopted AWD (Lampayan, 2013). This number is based on the number of trainings and demonstration trials in different regions and the level of involvement of farmers and promotion of the technology. However, response may vary from those who practised AWD in the Philippines, e.g. in Canarem (Tarlac Province) the majority of the farmer-cooperators had positive feedback about the effectiveness of AWD as a water-saving technology as follows: (i) no yield difference with farmer's practice of continuous flooding; (ii) saves water; (iii) saves time and labour, thus, less expensive; (iv) heavier and bigger grains, and good shape; (v) more tillers; and (vi) less insect pests and diseases (Palis *et al.*, 2004).

Another example of AWD practised in the Philippines was in Bohol Island. In the face of declining rice production due to insufficient water supply and unequal water distribution, NIA (the National Irrigation Association of the Philippines) established the Bohol Integrated Irrigation System (BIIS) with: (i) the construction of a new dam (Bayongan Dam); and (ii) the implementation of AWD, which was imposed on the whole island by periodic water supply. The adoption of AWD facilitated an optimum use of irrigation water, so that the cropping intensity increased from ca. 119% to ca. 160% (related to the maximum of 200% in these double-cropping systems) (UNFAO, 2010).

The adoption of AWD strongly depends on the incentive for the farmer. In many parts of the Philippines, this incentive is directly linked to the irrigation system. In a pump system where farmers can achieve direct financial savings due to reduced diesel use for pumping under AWD, it is easily adopted and properly implemented. In irrigation systems where farmers pay seasonal fees independent of the actual water usage as currently employed in most of NIA-serviced areas, farmers were found to be reluctant to use water-saving techniques and AWD was not carried out properly.

With the development and improvement of irrigation canals by NIA as part of their nationwide medium-term plan, the use of pumps would become gradually less important. In turn, this – genuinely positive development – may decrease the incentive to adopt AWD as long as there are no policies from the local government units on water savings to support the practice of AWD by other means. As one example, adoption of meter-based (volumetric consumption-based) water rates instead of fixed area-based rates would promote practices of water saving. Volumetric pricing of irrigation water should induce incentive for better collective action toward saving water resources, than does area-based pricing in which marginal cost of using water is zero (Tsusaka *et al*., 2012).

Potential and constraints

In the perception of farmers, AWD means inadequate soil-water during the dry period, thus carries the risk of drought stress to the crop. However, studies have shown that thoroughly implemented AWD, specifically 'safe AWD', does not lead to any yield declines because the roots of the rice plant can still capture enough water. Flooding of soils over many years triggers the development of a hardpan at 15–30 cm depth which acts as a mechanical barrier for roots and water. Although this sealing may not be complete in terms of percolation losses, it reduces seepage so that roots can acquire enough water even after several days without surface water. It is difficult to convince farmers that the absence of standing water does not automatically imply absence of soil water. Thus, the perforated tube serves a dual purpose: (i) measuring the water table below the soil surface; and (ii) acting as visual assurance to the farmer that the roots still have access to water at the subsurface. One requirement for successful dissemination of AWD, however, is a reliable irrigation source to enable farmers to irrigate whenever it is needed. If irrigation water is scarce sometimes and farmers cannot be sure to have sufficient water, they would prefer to irrigate soon and not wait for a recommended level of drainage to avoid possible drought stress.

Another barrier for adoption of any water-saving strategy by farmers within a wider irrigation system is the physical separation of adopter and benefiter. Farmers near the source of irrigation water ('upstream farmers') who have the potential of saving water have no need to save water. It is the farmers who are far from the irrigation source ('downstream farmers') who would benefit from water saving because those farmers potentially face water scarcity but, as a result, have not much potential to save water themselves.

On the positive side, there is anecdotal evidence through farmers' claims that practising AWD not only saves water but also increases rice yields. This observation may be the exception rather than the rule but it should be followed up for further improving the attractiveness of AWD. Several potential mechanisms have been reported as a means to increase yields under AWD but this needs further investigation:

- lodging resistant culms;
- profuse tillering;
- reduced pests and diseases; and
- better soil conditions at harvest.

Even if the practised AWD management is 'slightly unsafe', i.e. the water level drops below 15 cm below soil surface and yields slightly decrease, the economic yield tends to be higher in AWD (Sibayan *et al*., 2010) because the cost of irrigation has decreased (in pump systems).

Water savings and greenhouse gas emission

Moreover, AWD technology has a proven potential to mitigate CH_4 emission. Methane is a potent GHG with a global warming potential (GWP) of 25 (IPCC, 2006), which means that it is 25 times more effective in trapping heat inside the Earth's atmosphere than CO_2. Cultivated wetland rice soils emit significant quantities of CH_4 (Smith *et al*., 2008). Methane is produced anaerobically by methanogenic bacteria, which thrive well in paddy rice fields. Hence, flooded rice fields are a large source of CH_4 emissions contributing about 10–14% of total global anthropogenic CH_4 emissions. Because periodic aeration of the soil inhibits CH_4-producing bacteria, AWD can reduce CH_4 emissions. Various studies on GHG emissions under AWD and other water-saving strategies have been conducted to quantify the mitigation potential of those water management strategies. The results will be further discussed in Section 12.3.

The capability of AWD to reduce CH_4 emissions is also reflected in the IPCC methodology (IPCC, 2006) which is used for computing GHG emissions in the 'National Communications' submitted by countries to the UNFCCC. 'Multiple aeration', the category AWD falls in, is presumed to reduce CH_4 emissions by 48% compared to continuous flooding of rice fields (IPCC, 2006). A single aeration of the field, commonly referred to as 'midseason drainage', reduces CH_4 emissions by 40%, as IPCC guidelines suggest.

However, AWD adoption may also have pitfalls in terms of higher emissions of nitrous oxide (N_2O), a GHG even more potent than CH_4 with a GWP of 298 (IPCC, 2006). Nitrous oxide emissions are generally very low to negligible in continuously flooded systems, so that the IPCC guidelines assign a lower emission factor to rice as compared to non-flooded crops. Under water-saving strategies, N_2O emissions tend to increase due to increased nitrification and denitrification activities with the soil conditions constantly changing between anaerobic and aerobic and related changes in the redox potential. Data on N_2O emissions under different water management regimes is limited and varies drastically as discussed in Section 12.3. The available data, however, suggest that the incremental N_2O emission through AWD is insignificant as long as the N fertilization remains within a reasonable range. Thus, the combination of AWD with efficient fertilization techniques, such as Site-Specific Nutrient Management, is the best way to avoid excessive N levels in the soil and thus, negative trade-offs in terms of mitigation potentials.

12.2 Clean Development Mechanisms

12.2.1 Definition and criteria

The CDM is one of the flexibility mechanisms introduced by the Kyoto Protocol (KP) in 1997. It is a project-based mechanism of emissions trading involving non-Annex 1 parties (developing countries) that do not have any stipulated obligation to reduce their GHG emissions. The idea behind this cooperative mechanism is that reduced GHG emissions will slow global warming – irrespective of the location of the savings. Annex 1 (industrialized) countries can take advantage of a CDM project implemented in a developing country by purchasing Certified Emission Reduction Units (CERs) to meet their targets or emission caps. This mechanism adds more choices and flexibility to comply with the targets and offers economically sound solutions. The non-Annex 1 countries in turn receive capital for investments in projects and clean technologies to reduce their emissions and enhance socio-economic well-being.

Thus, the CDM has two key goals: (i) to promote sustainable development (SD) objectives in the host country (i.e. non-Annex 1 countries); and (ii) to assist Annex 1 parties to meet their GHG reduction targets. A CDM project activity in a non-Annex 1 country produces certified emission reductions that can be used towards partial compliance of their emission reduction targets.

According to Section 12.5 of the KP, a CDM project has to satisfy the following criteria: (i) parties involved in the project activity do so voluntarily and both approve the project; (ii) the project must produce real, measurable and long-term benefits to the mitigation of climate change; and (iii) the emission reductions should be additional to any that would occur without the project activity (commonly known as the 'additionality' criterion).

Moreover, article 12.2 of the KP states that the purpose of the CDM is to assist non-Annex 1 parties in achieving SD. This is interpreted to suggest that the project activities should be compatible with the SD requirements of the host country. However, neither the KP nor the subsequent Conference of Parties (COPs) have provided guidance on defining sustainability, leaving the decision to the host countries. COP 7 in Marrakech in 2001 stipulated that all participating countries have to establish a 'Designated National Authority' (DNA) to assess if any CDM proposal complies with their own sustainability criteria (Bhattacharyya, 2011). Figure 12.1 gives an overview over the application and approval process of a CDM project.

However, applying CDM projects in rice production faces many challenges. The Bohol case (see 'Adoption of alternate wetting and drying' above) is an example of water

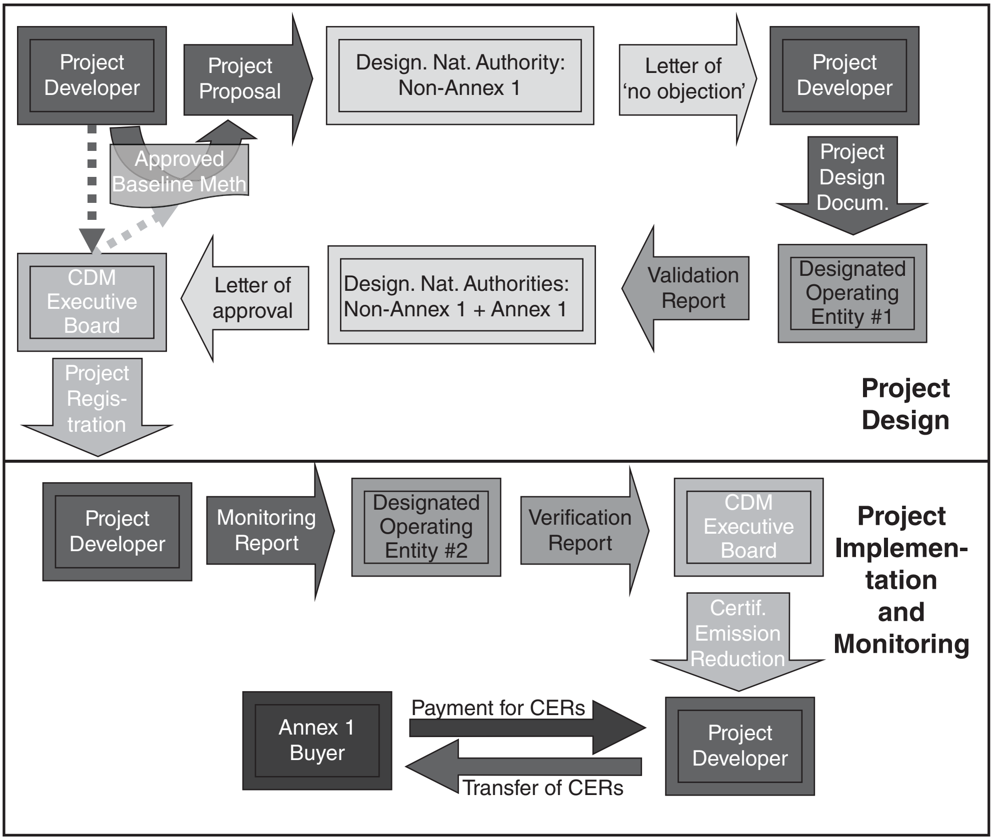

Fig. 12.1. Schematic presentation of the CDM Pipeline (Meth, methodology; Design. Nat. Authority, Designated National Authority; Docum., document).

savings possessing new technologies that increase the income of poor farmers while decreasing GHG emissions. Yet, it is not eligible for CDM because of missing additionality, i.e. AWD was introduced for the purpose of water saving without the incentive of CER generation and would have been introduced even if no GHG saving would have been achieved.

12.2.2 The rice clean development mechanism methodology

The eligibility of projects reducing *in situ* emissions from land use such as CH_4 emissions from rice remains intricate (Wassmann, 2010). However, in 2011 a CDM methodology for 'Methane emission reduction by adjusted water management practice in rice cultivation' was approved by the UNFCCC (2012). The methodology has been modified and is in its third version since August 2012. It now defines default CH_4 emission reduction values for different management practices in rice production. For applying AWD, for example, a reduction of 1.8 kg CH_4 ha^{-1} day^{-1} can be claimed under a certified CDM project. This translates to a saving of 4.5 t CO_2-eq ha^{-1} season^{-1} assuming a 100-day growing period (GWP (CH_4) = 25) or 4.5 CERs.

12.3 Literature Review

For this study we have surveyed peer-reviewed articles on CH_4 and N_2O emissions under different water management techniques in rice fields. The objective was a proof of concept as to what extent water management can be used to mitigate GHG emissions from rice fields. Using an online search engine for scientific literature, ISI Web of Knowledge, we identified 24 articles on field measurements encompassing GHG emission changes as a function of water management of a rice field. The initial number of results of the search was much higher, but many articles on this topic reported mechanistic studies without comparative emission rates under different water management strategies. These 24 articles compiled a total number of 96 experimental comparisons, i.e. one comparison corresponds to one season with adjacent field plots of CF and WST, which can be either multiple aeration (MA) or single aeration (SA). These two WST include AWD and mid-season drainage, respectively, as their most common forms. Moreover, we also included three articles on pot experiments that emulated different water management practices; these articles encompassed four comparisons between CF and WST. For comparing relative emission differences between CF and WST, the pot experiments were included in the analysis. For a comparison of absolute emission differences, however, pot experiments were excluded because of the different environmental effects of 'field' and 'greenhouse'. To assess the effect of different kinds of WST, these 106 comparisons were further classified according to two types of WST: SA and MA.

12.3.1 Results

The emission rates obtained from the different publications are shown in Tables 12.1–12.4 separated by countries/regions (for field measurements) and in Table 12.5 for the pot experiments. In these tables – as well as in the narrative – percentages given are relative GHG emissions of an applied WST as compared to a continuously flooded (CF) field (e.g. a relative emission of 60% shown in these tables translates into a reduction effect of 40%). We recognize that many readers will primarily be interested in the reduction effect, but we felt that the consistent use of relative emission rates will provide a more comprehensive presentation. In some instances in the text, we have given absolute values for reduction in units of kilograms per hectare per day.

These tables list emission rates per day as well as per season. Typically, the articles provided only one of these values, but we computed the corresponding value by using the number of days for one season, which was also obtained from the article. In some articles, emission rates were given as hourly rates and we multiplied it with a factor of 24 for daily emissions (assuming that hourly values provide daily averages).

The articles on field comparisons were sorted according to the location of the experiments into five groups: China (Table 12.1), India (Table 12.2), Japan and South Korea (Table 12.3) and Indonesia and the Philippines (Table 12.4).

As an initial observation, the published studies from South-east Asia are older than 10 years, whereas many studies were conducted in India, China and Japan in more recent years. Emission rates from rice fields in India are much lower than from other parts of Asia, i.e. only 10% of the emission rates observed in field studies in China, Japan and South Korea. One exception is the study by Yue *et al.* (2005) that reports emissions from a CF field in China as low as 24.8 kg CH_4 ha^{-1} $season^{-1}$, but the authors explain the low emission by very low soil temperature in the region of the experiment.

Methane emissions

In total, 19 articles report comparative CH_4 emissions from a continuously flooded field or pot with a field/pot under MA management.

Relative CH_4 emissions in the MA plots as given in these 19 articles (compiling 60 experimental observations) were found in

Table 12.1. Compilation of field studies on GHG emissions as affected by water-saving techniques conducted in China.

		Methane			Nitrous oxide			
		EF under CF	rel. CH_4 emission		EF under CF	rel. N_2O emission		
Citation	Location	kg ha^{-1} season^{-1} (kg ha^{-1} day^{-1})	MA (%)	SA (%)	g N ha^{-1} season^{-1} (g N ha^{-1} day^{-1})	MA (%)	SA (%)	Remarks
Zhang *et al*. (2012)	China, Jiangsu	185 (1.48)		30.8				
Wang *et al*. (2012)	China, Jiangsu	221 (1.77)		33.8	160 (1.28)		137.5	
		278 (2.22)		22.8	550 (4.40)		123.6	
		548 (4.38)		38.9	130 (1.04)		153.8	
		515 (4.12)		52.7	280 (2.24)		121.4	
Qin *et al*. (2010)	China, Jiangsu	127 (1.04)		43.8	180 (1.48)		194.5	
		105 (0.88)		41.0	50 (0.42)		1390	
Jiao *et al*. (2006)	China, Liaoning	230 (1.56)	75.77		296 (2.00)	123.72		4 aerations
Yue *et al*. (2005)	China, Liaoning	24.8 (0.20)	67.74		382 (3.05)	133.33		2 aerations, low soil temperature
Zou *et al*. (2005)	China, Jiangsu	85 (0.72)		35.29	60 (0.51)		2583.3	
		220 (1.86)		64.09	30 (0.25)		4766.7	
Wang *et al*. (2000)	China, Beijing	503 (3.73)	41.2	76.5				Automated system
Lu *et al*. (2000)	China, Zheijang	565 (4.25)	38.9	56.1				Automated system
Wang *et al*. (1999)	China, Beijing	748 (7.48)	41.6					
		145 (1.18)	74.6					Automated system

EF, emission factors given per season and per day, respectively; CF, continuous flooding; MA, multiple aeration; SA, single aeration.

Table 12.2. Emission factors of methane and nitrous oxide under continuous flooding and relative emissions under multiple aeration (MA) from different studies in India.

		Methane		Nitrous oxide		
Citation	Location	EF under CF kg ha^{-1} season^{-1} (kg ha^{-1} day^{-1})	rel. CH_4 emission MA (%)	EF under CF g N ha^{-1} season^{-1} (g N ha^{-1} day^{-1})	rel. N_2O emission MA (%)	Remarks
Khosa *et al*. (2011)	India, Punjab	62.3 (0.53)	46.4			
		36.8 (0.31)	36.2			
Pathak *et al*. (2002, 2003)	India, New Delhi	24.3 (0.27)	34.2	323 (3.63)	95.0	N_2O reported 2002, CH_4 reported 2003, rice/wheat system
		28.1 (0.32)	52.0	735 (8.26)	126.4	
		45.4 (0.51)	61.0	593 (6.66)	120.4	
		20.2 (0.23)	47.5	483 (5.43)	111.8	
Adhya *et al*. (2000)	India, Cuttack	15.7 (0.16)	84.6			Automated system
		30.5 (0.32)	75.0			
Jain *et al*. (2000)	India, New Delhi	39.8 (0.41)	81.4			
		34.8 (0.37)	86.2			
		22.7 (0.23)	42.8			
		23 (0.23)	77.8			
		16.6 (0.17)	78.0			

Table 12.3. Compilation of field studies on CH_4 emissions as affected by water saving techniques conducted in Japan and South Korea (no studies comparing N_2O emissions from this region could be identified; abbreviations, see Table 12.1).

		Methane			
		EF under CF	rel. CH_4 emission		
Citation	Location	kg ha^{-1} $season^{-1}$ (kg ha^{-1} day^{-1})	MA (%)	SA (%)	Remarks
Itoh *et al*. (2011)	Japan, Nagaoka	307 (2.38)	48.1		
		318 (2.50)	25.5		
		662 (5.25)		77.0	
		1044 (8.92)		68.7	
	Japan, Koshi	65 (0.58)		38.0	
		52 (0.44)		102.6	
	Japan, Minamisatsuma	270 (2.48)		129.6	Average of 3 observations
Minamikawa and Sakai (2006)	Japan, Tsukuba	139 (1.03)		47.3	
		142 (1.06)	51.44		
		227 (1.79)	30.77		
		252 (1.98)	25.60		Aeration after EH control
Yagi *et al*. (1996)	Japan, Ryugasaki	148 (1.19)	58.31		
		94.9 (0.65)	54.58		Automated system
Kwun *et al*. (2003)	S. Korea, Milyang	503 (4.70)	85.1		Assumed growth period: 107 days
Park and Yun (2002)	S. Korea, Suwon, Iksan, Milyang	257 (2.40)	62.5		Average of 7 observations, assumed growth period: 107 days
		599 (5.60)	64.3		Average of 5 observations, assumed growth period: 107 days
		396 (3.70)	62.2		Average of 3 observations, assumed growth period: 107 days
		289 (2.70)	63.0		Average of 4 observations, assumed growth period: 107 days
		175 (1.40)	81.8		Average of 4 observations, assumed growth period:125 days

the range between 19.9% and 86.2% of the emissions of the corresponding CF plot. The arithmetic mean is 56.9% (CV: 36%). For single aeration, a total of 40 experiments in 13 articles were identified. One out of four field comparisons in Wassmann *et al*. (2000) was disregarded for this analysis because of non-achievement of the drainage. The relative CH_4 emissions of the remaining 40 experiments varied between 17.9% and 152.6% with an arithmetic mean of 63.5% (CV: 47%) compared to a continuously flooded paddy field/pot.

The absolute CH_4 reduction (in kilograms per hectare per day) has also been assessed for SA and MA. For this assessment, however, only field experiments were considered as explained above. Figures 12.2 and 12.3 show the absolute CH_4 emissions (in CO_2-equivalents) of CF and WST fields for SA and MA, respectively. For further analysis of the absolute mitigation potential, only field experiments with seasonal emissions of 80 kg CH_4 ha^{-1} or more were considered because low-emission fields might not give potential for further emission reduction. For all 42 field experiments on MA, the arithmetic mean of CH_4 reduction was 1.26 kg ha^{-1} day^{-1} with a CV of 69%. For SA the arithmetic mean of reduction of the 26 field experiments was 1.15 kg CH_4 ha^{-1} day^{-1} (CV: 94%).

Table 12.4. Compilation of field studies on GHG emissions as affected by water saving techniques conducted in Indonesia and the Philippines (abbreviations, see Table 12.1).

		Methane			Nitrous oxide			
		EF under CF	rel. CH_4 emission		EF under CF	rel. N_2O emission		
Citation	Location	kg ha^{-1} season^{-1} (kg ha^{-1} day^{-1})	MA (%)	SA (%)	g N ha^{-1} season^{-1} (g N ha^{-1} day^{-1})	MA (%)	SA (%)	Remarks
Suratno *et al*. (1998)	Indonesia, West Java				249 (1.98)	134.94		Water level down to '0 cm' only; assumed growth periods of 91 days and 112 days, respectively
					254 (2.02)	158.10		
					514 (4.08)	95.28		
					622 (4.93)	143.41		
					716 (5.69)	78.69		
					713 (5.66)	117.84		
Husin *et al*. (1995)	Indonesia, West Java	437 (3.06)	43.1					
		381 (2.95)	61.7					
Corton *et al*. (2000)	Philippines, Nueva Ecija	89 (0.91)		57.1				Automated system
		75 (0.73)		63.0				
		348 (3.75)		92.5				
		272 (3.23)		55.1				
Wassmann *et al*. (2000)	Philippines, Laguna	251 (2.51)		17.93				Automated system
		35 (0.35)		31.43				
		10 (0.10)		80.00				
		28 (0.28)		121.43				Rain in SA, no drainage
Bronson *et al*. (1997)	Philippines, Laguna	17.3 (0.20)		38.5	259 (3.05)		246.33	Automated system
		371 (4.36)		57.2	28 (0.33)		589.29	

Table 12.5. Compilation of pot studies on GHG emissions as affected by water saving techniques (abbreviations, see Table 12.1).

		Methane			Nitrous oxide			
		EF under CF	rel. CH_4 emission		EF under CF	rel. N_2O emission		
Citation	Location	kg ha^{-1} season^{-1}	MA (%)	SA (%)	g N ha^{-1} season^{-1}	MA (%)	SA (%)	Remarks
Katayanagi *et al*. (2012)	Philippines, Laguna	580.7	27.2		10.19	32,476.2		
Minamikawa and Sakai (2005)	Japan, Tsukuba	1353	19.9	55.6				Int. irrigation only after 81 DAT
		1926	29.7	69.5				
Mishra *et al*. (1997)	India, Cuttack		43.80	59.65				BL: 6.393 mg pot^{-1} day^{-1}

Nitrous oxide emissions

Only nine different studies comprising 23 experiments could be identified that measured N_2O emissions from rice fields under different water management practices. N_2O emissions were generally higher under water-saving strategies as compared to continuously flooded fields. However, the

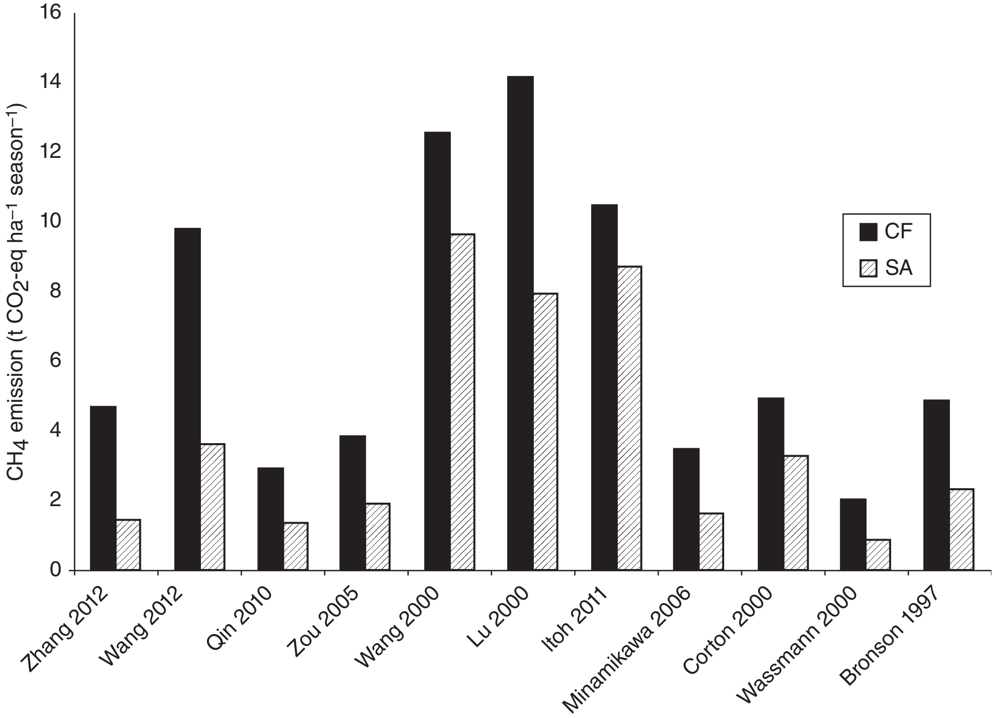

Fig. 12.2. Methane emissions from studies comparing continuous flooding (black) and single aeration (grey). Values are arithmetic means of all experiments in the respective article. GWP (CH_4) = 25.

variation of the results was also higher than for CH_4 results.

For multiple aeration, 12 experiments were analysed and the arithmetic mean of the relative N_2O emissions was found to be 120% (CV: 19%) compared to CF. For SA, 11 relevant experiments were found and the relative N_2O emissions were between 121% and 4767% with an arithmetic mean of 907% (CV: 171%) as compared to a CF reference field. The high coefficient of variation is mainly caused by results of one study (Zou *et al.*, 2005) that reports very high N_2O emission increases for SA. Due to this fact, it might be more meaningful to use another statistical measure, namely the median, which is 176% for relative N_2O emissions under SA. The median for relative N_2O emissions under MA is 122%.

Global warming potential

Only seven field studies were identified measuring both CH_4 and N_2O emissions, as affected by different water management strategies (Fig. 12.4). In all of the studies, CH_4 emissions decrease under WST while N_2O emissions increase. The total GWP, however, decreases in all of them (between 18% and 59%). The contribution of N_2O to the total GWP of continuously flooded fields is between 0.6% and 2.4% for the five studies with a GWP higher than 1 t CO_2-eq ha^{-1} season^{-1}. For the other two studies with a very low GWP, Yue *et al.* (2005) and Pathak *et al.* (2002, 2003), contribution of N_2O is 22% and 25%, respectively. In the WST plots, the contribution of N_2O increased from 3.8% to 6.4% for Bronson *et al.* (1997), Jiao *et al.* (2006), Qin *et al.* (2010) and Wang *et al.* (2012), to 25% for Zou *et al.* (2005) and to 36% and 44% for Yue *et al.* (2005) and Pathak *et al.* (2002, 2003), respectively. The increase of N_2O emissions by switching from CF to WST, however, in all the studies (except Zou *et al.*, 2005) is between 17% and 180%, while Zou *et al.* report an N_2O increase of 3300%.

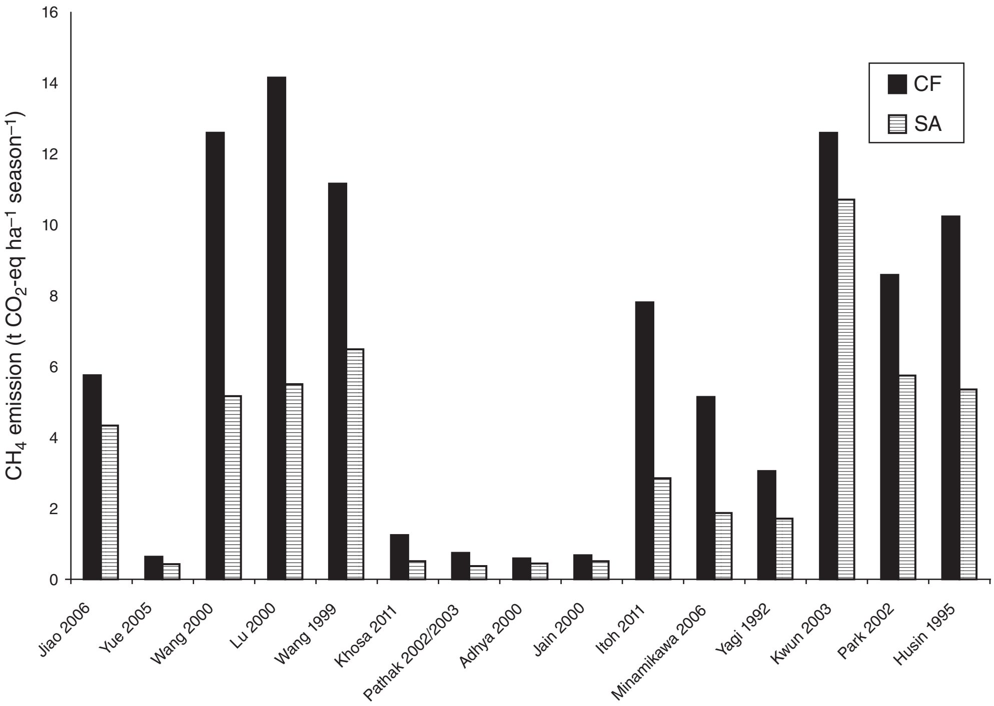

Fig. 12.3. Methane emissions from studies comparing continuous flooding (black) and multiple aeration (grey). Values are arithmetic means of all experiments in the respective article. GWP (CH_4) = 25.

Taking the average of all these seven studies, the GWP decreases from 4.2 t CO_2-eq ha^{-1} season^{-1} under CF to 2.4 t CO_2-eq ha^{-1} season^{-1} under a WST with the contribution of N_2O increasing from 3% to 11%.

12.3.2 Discussions

Derived from this meta-analysis, field drainage in irrigated rice production can be deemed a promising mitigation option with the potential to substantially reduce GHG emissions. Although N_2O emissions increase under WSTs, this increase does not offset the reduction in CH_4 emissions.

The CH_4 reduction potentials of SA and MA are at similar levels – which is a somehow unexpected result. SA was found to reduce CH_4 emissions by 36.5% on average, MA by 43.1%. The explanation for this could be how the drainage is carried out in detail. In studies with only one dry period in the growing season, this drainage might be executed more accurately and maybe even longer (i.e. a lower water level) than the drainages in studies on MA. Hence, this one dry period would have a higher mitigation effect than one dry period in a field managed under MA. Also, the stronger increase of N_2O emissions in SA (median: 176%) than in MA (median: 122%) supports this hypothesis.

Furthermore, CH_4 emissions tend to increase slowly in the beginning of the growth period. The highest flux rates are found towards the middle of the season (Yagi *et al*., 1996; Hou *et al*., 2000). Thus, practising a WST in the beginning of the season has a lower mitigation effect than practising it around the middle of the season. After a dry period, CH_4 flux only slowly increases again (Cai *et al*., 1997).

The relative CH_4 emission levels of plots treated with SA and MA, respectively, as assessed in this literature study are in good agreement with what the IPCC suggests

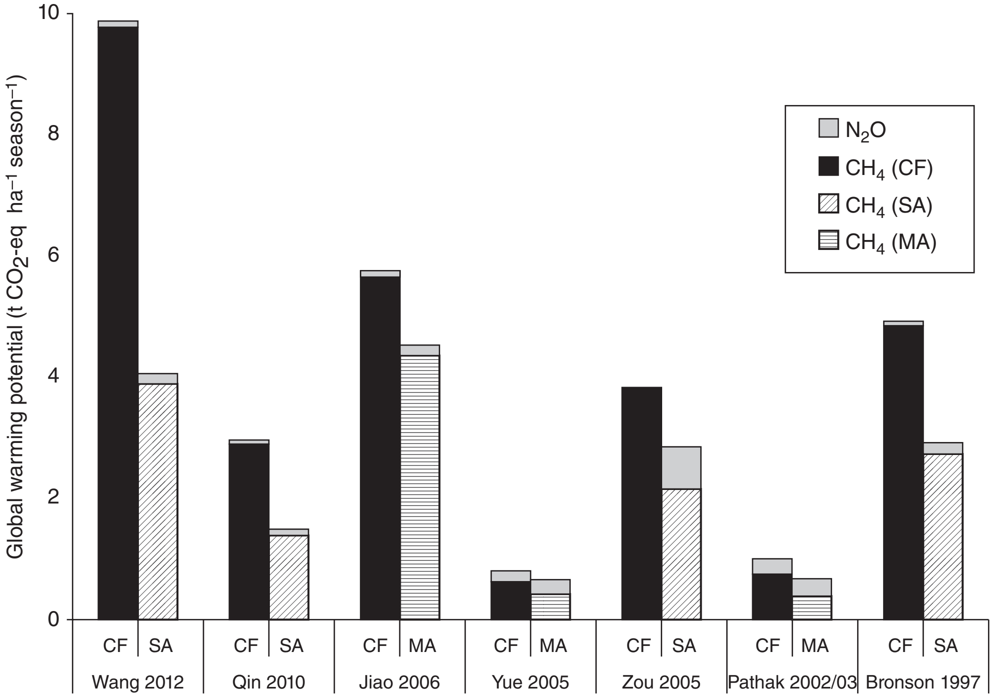

Fig. 12.4. Global warming potential of different water management practices as derived from articles comparing both methane and nitrous oxide emissions. Values are arithmetic means of all experiments in the respective article. GWP (CH_4) = 25, GWP (N_2O) = 298 (CF, continuous flooding; SA, single aeration; MA, multiple aeration).

using the default values given in its 2006 guidelines (IPCC, 2006). For SA the IPCC guidelines recommend a ‘scaling factor’ of 0.6, i.e. a relative CH_4 emission level of 60% compared to continuous flooding. The average emission level for SA as found in this study is 63.5%. For MA, the IPCC suggests a default scaling factor of 0.52 (i.e. relative CH_4 emissions in a MA field are 52% of those in a CF field) while the average emissions as assessed in this study are 56.9%. It should be noted that the IPCC scaling factors were also founded on a literature survey that probably in large parts is included in this study. But this analysis shows that the IPCC factors still represent good default means even if articles from after 2006 are included in the assessment.

Comparing the absolute values of CH_4 reduction as found in the available literature with what the CDM methodology for rice production gives as standard values, it can be said that for both practices, SA and MA, the CDM standard values are higher than was found in the available literature. The CDM methodology suggest a reduction of 1.8 kg CH_4 ha^{-1} day^{-1} for shifting to intermittent flooding with MA and the arithmetic mean of CH_4 reduction as found in the literature is 1.26 kg ha^{-1} day^{-1}. For midseason drainage, the CDM methodology suggests a reduction of 1.5 kg CH_4 ha^{-1} day^{-1} while the arithmetic mean of all literature findings for SA is 1.15 kg CH_4 ha^{-1} day^{-1}.

The share of N_2O emissions to the total GWP is higher under an applied WST than under continuous flooding. Nitrous oxide contributions under both management strategies, CF and WST, are generally below 10% except when CH_4 emissions are very low as e.g. found in India. Only in one study (Zou *et al.*, 2005) did N_2O emissions exceeded 0.3 t CO_2-eq ha^{-1} season^{-1}.

12.4 Conclusions

AWD and MSD as representative forms of MA and SA, respectively, are potent mitigation options for irrigated rice production systems. The average relative CH_4 emission under SA and MA are at similar levels according to the findings in this literature study. This could have implications on the dissemination of water-saving strategies as mitigation options. Farmers adopt the AWD technology primarily because of the water saved, yet maintained yields. While in areas with pump irrigation AWD is easily adopted because of the direct monetary pay-out, in areas with improved canal irrigation facilities with more than adequate water supply farmers are more reluctant to adopt AWD. Instead of introducing AWD, which might require more effort for a farmer to accurately practise and could be considered as too harsh with its alternating dry phases (thus, has a high adoption barrier), the entry point in those areas could be a single MSD. The mitigation potential of MSD is similar to AWD but it only requires water control during approximately 1 week of the growth period. Thus, farmers might be more willing to adopt this water management strategy and might even practise it more accurately. After adoption of MSD, introduction of AWD could follow. The clean development mechanism may serve as additional incentive if properly coordinated. Aside from this, it is important that other indirect benefits from AWD (e.g. less crop lodging, reduced pest damage, better soil conditions) are further explored and scientifically validated.

This study further shows that the IPCC scaling factors represent good average values according to the articles analysed. However, CH_4 emissions are very low in India compared to other parts of Asia (e.g. China or Japan), which shows that disaggregation for any mitigation strategies is important. Moreover, this finding shows limits for the transfer of any mitigation option from one region to another. Assessment of region-specific characteristics is necessary.

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