DISSEMINATION OF WATER MANAGEMENT IN RICE PADDIES IN ASIA

Kazunori Minamikawa[1], Takayoshi Yamaguchi[2], and Takeshi Tokida[3]

[1]Japan International Research Center for Agricultural Sciences, Tsukuba, Japan
[2]Kyoto University, Kyoto, Japan
[3]Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization (NARO), Tsukuba, Japan

E-mail: minakazu@affrc.go.jp

ABSTRACT

Asia is the granary of rice production globally. Methane (CH_4) is a potent greenhouse gas that is produced in anaerobic flooded paddy soil and is emitted to the atmosphere. Water management is one of the most effective strategies to reduce CH_4 emission from rice paddies. However, rice farmers are not willing to adopt water management strategies unless incentives are provided. This article explains the conventional methods of water management that are currently being utilized in Asia, then outlines the history of and the current constraints to disseminate water management, and finally discusses the future perspective of further dissemination. There are two conventional methods of water management: midseason drainage, which is often followed by intermittent irrigation, and alternate wetting and drying (AWD). A Chinese agricultural book, published in the 7th century, which describes midseason drainage, represents the world's first record of this technique. In Japan, midseason drainage was first found to be reported in an agricultural book published in the 17th century. Surprisingly, a major proportion of the current knowledge regarding water management for good rice growth and high yield was already recognized by farmers in the ancient period. Recently, the effect of AWD on irrigation water saving has gained interest of researchers and farmers. The dissemination of water management is limited by natural and social factors at multiple spatial scales. Natural factors include climate, weather, soil, and topography. For example, climate determines water availability in the dry season, whereas weather determines the success of soil drying during a drained period. Social factors include *governmental policy, infrastructure, and farmers' perception. For example, the construction of water channels is essential for irrigation and drainage of a rice area, whereas the reduction of the fuel cost associated with pumping irrigation water is an incentive for farmers to adopt AWD. The question regarding what is necessary for further dissemination of water management in Asia is still to be answered. Future research should improve focus on the mechanisms underlying the positive effects on rice production, leading to the voluntary dissemination by farmers. However, there is a limit to voluntary dissemination. Under the Paris Agreement, several Asian rice-producing countries have declared to reduce* CH_4 *emissions from rice paddies to achieve the nationally determined contribution, using the institutional approach, such as carbon pricing (i.e., market mechanisms and carbon tax) and Nationally Appropriate Mitigation Action. It is therefore necessary to develop the methodology of monitoring, reporting, and verification to ensure the accuracy and reliability of asserted reduction in* CH_4 *emission by water management.*

Keywords: AWD, climate-change mitigation, midseason drainage, methane, MRV

INTRODUCTION

Methane (CH_4) is a well-mixed greenhouse gas (GHG) with a global warming potential (GWP) of 34 times that of carbon dioxide (CO_2) over a 100-year time scale considering the indirect effects, such as the production of tropospheric ozone, another potent GHG (Myhre *et al*. 2013). Because CH_4 has a relatively short lifetime in the atmosphere, immediate mitigation actions can reduce the risk of crossing the critical 2°C threshold for increase in the global air temperature more effectively than that caused by a reduction in CO_2 emissions alone (Shindell *et al*. 2012). Rice cultivation is a major source of the atmospheric CH_4 emissions, accounting for 10%–12% of the global anthropogenic CH_4 emissions (Ciais *et al*. 2013). CH_4 is produced in flooded paddy soils via anaerobic metabolism by methanogenic archaea using labile organic carbon (C) substrates (Fig. 1). Major rice-producing countries are located in Asia and rice production has increased steadily over the past decade (Table 1). Therefore, Asia is the hotspot of CH_4 emissions emanating from rice cultivation.

There are two promising, readily available alternatives for reducing CH_4 emissions from rice cultivation. The first alternative is organic matter management that is practiced before rice cultivation. It reduces labile organic C, leading to a delay in the development of reductive soil conditions and thus to a reduction in CH_4 production. For example, decreases in the incorporation rate of rice straw (e.g., Naser *et al*. 2007) and the composting of rice straw (e.g., Yagi and Minami 1990) are effective at reducing CH_4 emissions. However, there is concern regarding the loss of soil organic C by this strategy due to the limited C input into single-cropping soil over the long term (Shirato and Yokozawa 2005). In addition, in areas with multiple cropping (i.e., tropical and subtropical regions), there are limited choices for rice straw management (i.e., removal or field burning) because of the relatively short, and often wet, fallow season that is insufficient for the decomposition of incorporated straw before the subsequent rice season.

Another promising option is water management that is usually practiced during rice cultivation in irrigated fields. Field drainage results in oxidative soil conditions by supplying air containing oxygen (O_2) into the soil, and thus stops CH_4 production (Fig. 1). However, the emission of nitrous oxide (N_2O), a GHG with a GWP almost 300 times that of CO_2 over a 100-year period, can be enhanced during drained periods. There are two conventional methods of water management: midseason drainage, which is often followed by intermittent irrigation, and alternate wetting and drying (AWD). Kajiura *et al*. (2018) found that CH_4 emissions from midseason drainage were 39% lower (95% confidence interval: 32%–47%) than that from continuous flooding in Japan. Tirol-Padre *et al*. (2018) analyzed the data obtained at four sites in Southeast Asia (Indonesia, Philippines, Thailand, and Vietnam) and found that CH_4 emission from AWD was 31% lower (95% confidence interval: 23%–39%) than that from continuous flooding. Arsenic pollution is another environmental issue at the local scale that can be mitigated by water management (e.g., Linquist *et al*. 2015).

Although there have been advances in the development of mitigation options for CH_4 emissions from rice cultivation, there has been insufficient implementation of those options by farmers or incorporation of those options into administrative policies. This is true for water management. The question remaining is how to further disseminate water management to farmers as a way of achieving climate-change mitigation. A key to success for this dissemination would be the use of direct and/or indirect incentives for farmers that overcome possible negative concerns associated with water management, such as rice water stress and labor increase. Here we first explain the conventional methods of current water management, and then outline the history of and the current constraints on dissemination, and finally discuss the future perspectives for further dissemination.

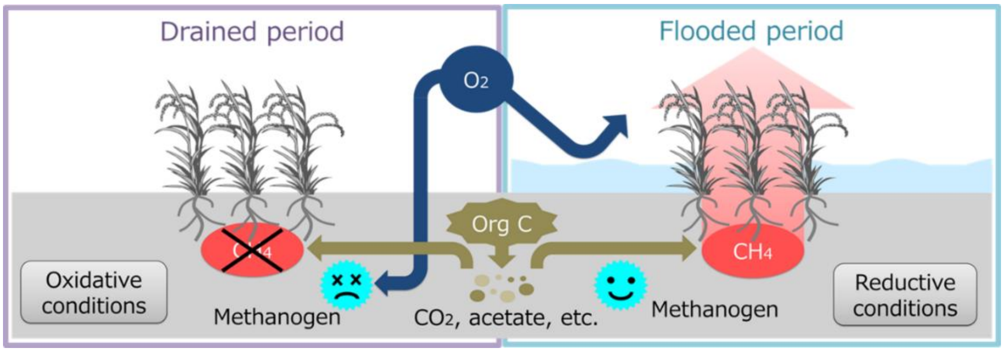


Fig. 1. Schematic representation of mechanisms underlying CH_4 emission from paddy soil.

Table 1. Top ten rice-producing countries worldwide (2016), the decadal production growth during 2007–2016, and CH_4 emissions from rice cultivation (2016)

Country	Rice production ($Mt\ y^{-1}$)	Decadal growth (%)	CH_4 emission ($Gg\ CO_2$-eq y^{-1})	
China, mainland	209.5	12.6	111383	(1)[a]
India	158.8	9.8	95243	(2)
Indonesia	77.3	35.2	63382	(3)
Bangladesh	52.6	21.8	23767	(7)
Viet Nam	43.4	20.9	28848	(6)
Myanmar	25.7	-17.1	22098	(8)
Thailand	25.3	-22.2	29145	(5)
Philippines	17.6	8.5	32010	(4)
Brazil	10.6	-4.0	2652	(21)
Pakistan	10.4	24.8	8131	(11)
World total	741.0	12.9	511495	—

Source: FAOSTAT (2018).
[a] In parentheses, the world ranking

CONVENTIONAL CURRENT METHODS OF WATER MANAGEMENT

Water management is usually feasible in irrigated rice paddies. Continuous flooding is the reference method of water management, in which the soil is kept flooded at about 5 cm above the soil surface from transplanting to the final drainage ca. 2 weeks before rice harvest (Fig. 2a). In case of direct seeding, the soil is first kept water-saturated or shallow flooded until crop establishment; this is also true for other methods of water management. There are two conventional methods of water management that can reduce CH_4 emissions as compared to continuous flooding: midseason drainage and AWD (Table 2). Both involve a similar shift in surface water level during rice cultivation (Fig. 2b, c) but have different purposes and historical backgrounds (Table 2). Below, this chapter explains different and shared points for the implementation of midseason drainage and AWD.

Midseason drainage is practiced for better rice production in East Asia, such as China and Japan (Table 2). The timing and duration of the drainage is based on the rice growth stage (Table 2 and Fig. 2b). Drainage for 1–2 weeks is intentionally practiced between later tillering and panicle differentiation stages considering the surface soil dryness that partly depends on the weather conditions. It is often associated with opening the water outlet for forced drainage of the surface water. Midseason drainage is often followed by intermittent irrigation, in which the soil is repeatedly drained for a few days until the final drainage (e.g., repeats of 3-day flooding and 3-day drainage). The current understanding of the positive effects of midseason drainage on rice production is as follows:

- to reduce non-productive tillers by inhibiting soil nitrogen (N) mineralization,
- to avoid lodging and enhance weather-resistance by inhibiting the production of substances harmful to rice, such as hydrogen sulfide and organic acids, and by enhancing root elongation (originally by increasing O_2 supply and soil oxidation), and
- to improve field workability at harvest by compacting soil.

Guo *et al*. (2017) conducted a meta-analysis of datasets in China and found that midseason drainage significantly increased rice yield as compared to continuous flooding.

The original purpose of AWD was water saving in rice cultivation during a dry season in the tropics and subtropics (Table 2). Under AWD, therefore, drainage of surface water depends on natural percolation and evapotranspiration. For example, Tirol-Padre *et al*. (2018) found that AWD reduced water use (i.e., irrigation + rainfall) in dry seasons by 6%–47% as compared to continuous flooding at the four sites in Southeast Asia tested, depending on environmental factors, such as topography and soil texture. Timing and duration of the natural drainage is usually based on surface water level that can be measured by a pre-installed pipe and a ruler. “15 cm below the soil surface” is often used as the threshold for re-flooding (Fig. 2c), which is called the “safe AWD” (safe for rice production; Lampayan *et al*. 2009).

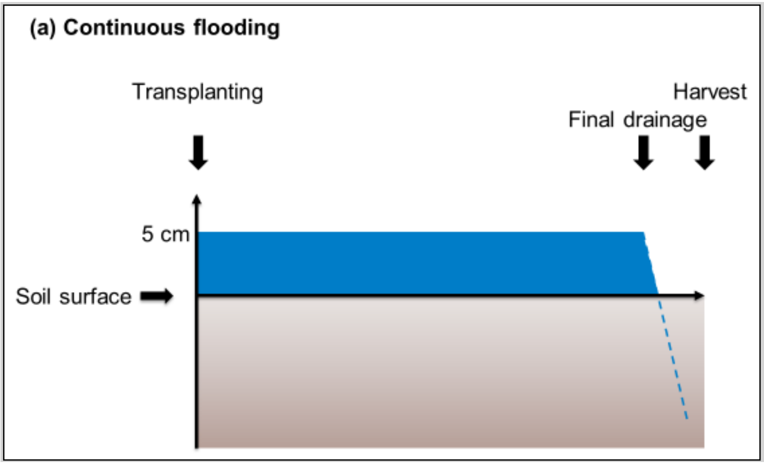
A recommendation shared between midseason drainage and AWD is to keep flooding (1) during the rooting and heading/flowering stages to meet rice’s physiological water demands, and (2) during and after N topdressing to improve the N-use efficiency of rice plants (Table 2). For example, urea-N topdressing during a drained or shallow-flooded period can result in substantial N loss of the applied N as a result of both ammonia volatilization

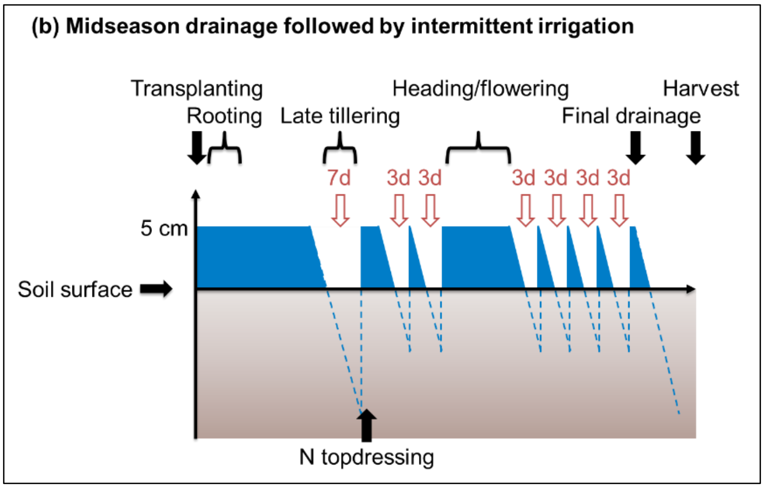
(Hayashi *et al*. 2008) and N_2O emission (Sibayan *et al*. 2018).

Table 2. Characteristics of midseason drainage and AWD

	Midseason drainage	AWD
Criteria for drainage	Duration	Surface water level
Original purpose	Good rice growth and higher yield	Water saving
IPCC's classification[a]	Single aeration	Multiple aeration
History[b]	7th century in China	1990s by IRRI
Adopted region in Asia	East	Southeast and South

[a] IPCC (2006)
[b] Based on our literature survey.





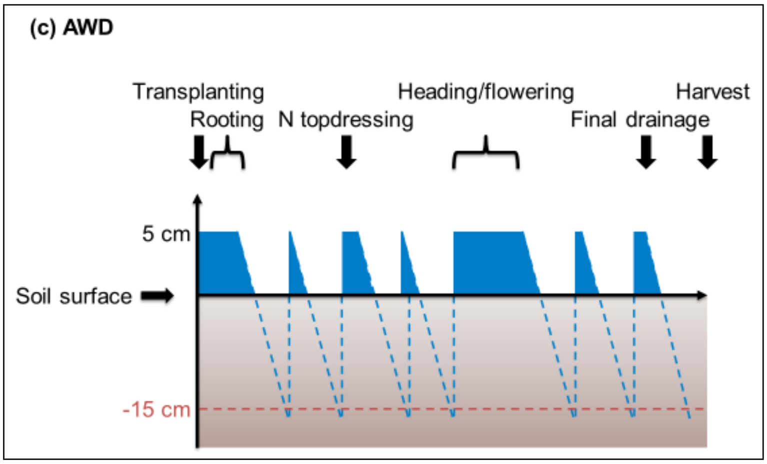


Fig. 2. Schematic representations of time patterns of water levels during (a) continuous flooding, (b) midseason drainage followed by intermittent irrigation, and (c) AWD.

HISTORY OF MIDSEASON DRAINAGE

There is an enormous difference in the history of dissemination between midseason drainage (7th century) and AWD (1990s) (Table 2). This chapter therefore focuses on the long history of midseason drainage in Asia and explores the reasons for its wide dissemination in Japan as an example.

A Chinese agricultural book, "*Qimin Yaoshu*," published in the middle of the 7th century (Fig. 3) mentioned that soil aeration (i.e., midseason drainage) had positive effects on rice production. As far as we know, this is the world's first record of midseason drainage. We also found that an Indian agricultural book, "*Krsiparasara*," published in about the 6th to 8th century, mentioned the beneficial effects of midseason drainage. In Japan, the first record of midseason drainage was found in "*Seiryoki*" published in the 17th century. In "*Noukagyouji*" published in the 18th century in Japan (Fig. 3), it was stated that, "from late July to early August (i.e., mid-rice season in Japan), farmers should drain rice paddies, especially for those which are easy to irrigate, and carry out soil aeration for a few days." We also found that Japanese agricultural books published during the Edo Period (1603–1868) mentioned midseason drainage (Fig. 4). Based on our literature survey, the old Japanese farmers during the Edo Period already knew the detailed beneficial effects of midseason drainage, such as yield increases in wet paddies, removal of aquatic weeds, soil drying ready for harvest and preparing for the subsequent crop, and inhibition of excessive tillering.

In modern times in Japan, midseason drainage was gradually disseminated to farmers (Table 3) for the following reasons. Firstly, the target of governmental policy for domestic rice production changed from maximizing yield quantity before the 1970s to maximizing grain quality after the 1970s. Before the 1970s, most of the studious, innovative farmers, who knew the positive effects of midseason drainage and intermittent irrigation, adopted them, and then normal farmers learned and followed, in order to obtain higher yields. Secondly, the modernization of agriculture, such as the introduction of agrochemicals, the development of irrigation infrastructure, and the reformation into well-drained paddy field, enabled farmers to solve the weed problem and to easily control surface water level. Lastly, a high-quality cultivar, 'Koshihikari' was widely disseminated after the 1970s although it is sensitive to the rice blast pathogen (*Magnaporthe grisea*) and prone to lodging. To produce high-quality 'Koshihikari' grain for a higher selling price, farmers followed a suite of locally standardized cultivation protocols, including midseason drainage to avoid rice lodging.

The current midseason drainage protocol still has some difficulties in terms of further dissemination. Farmers in the northern area of Japan, Hokkaido, do not dare to practice midseason drainage but keep their fields flooded to protect the rice crop from low temperatures, avoiding the risk of cold damage (Table 3; Leon *et al*. 2015). Flooding is also required elsewhere in Japan to protect rice from exposure to short periods of high temperatures, caused by the hot dry foehn winds in the southern area. Even where midseason drainage is practiced elsewhere, soil drying may occasionally fail due to rainfall during the draining periods, leading to no reduction in CH_4 emissions (Kajiura *et al*. 2018). In addition, the on-going dissemination of large-scale, extensive rice farming in Japan may hinder the implementation of midseason drainage, to save labor and time.

Fig. 3. Cover pages of old agricultural books in China (*Qimin Yaoshu*, left) and Japan (*Noukagyouji*, right).

Fig. 4. Old picture of N topdressing during midseason drainage published during the Edo Period in Japan (reprinted from Tsuchiya and Shimizu 1983)

Table 3. Historical transition of adoption rate of midseason drainage according to the area in Japan during the modern times (%)

Area[a]	1933[b]	1966[c]	2008–2011[d]
Hokkaido	0	2	25
Tohoku	18	52	92
Kanto	12	48	79
Hokuriku	71	64	96
Tokai-Kinki	43	66	87
Chugoku-Shikoku	39	69	87
Kyusyu	58	73	87
All	—	—	87

[a] From north to south
[b] Yamaguchi (2018)
[c] SSDBAFE-MAF (1967)
[d] Leon *et al*. (2015)

CURRENT CONSTRAINTS ON AWD

Most of the constraints on the long-term dissemination of midseason drainage, as mentioned above, hold true for the dissemination of AWD, albeit with a much shorter history, starting from the 1990s. However, as AWD is implemented primarily for water saving (Table 2), there is a large difference in water availability between the regions adopting midseason drainage and those adopting AWD. This chapter first outlines the constraints on the current dissemination of AWD, and then presents the results of a case study to explore the dissemination process in the An Giang province located in the Mekong Delta, Vietnam (Yamaguchi *et al*. 2016; 2017; 2019).

The dissemination of AWD is also underway in the tropics and subtropics. There must be rice-growing areas suitable in terms of environmental conditions such as climate, soil, weather, and topography at multiple spatial scales (Fig. 5). For example, Nelson *et al*. (2015) assessed the spatiotemporal pattern of climate suitability for AWD in Cagayan province, in the Philippines, using the water balance model that they developed and drew a suitability map for AWD implementation. On the other hand, social constraints are also heavily involved in the dissemination of AWD (Fig. 5). For example, the Vietnamese government is promoting the agricultural policy "1 Must Do, 5 Reductions (1M5R)," in which "1 Must Do" requests farmers to use certificated rice seeds and "5 Reductions" recommends reducing the amounts of seeds, agrochemicals, fertilizers, and irrigation water used, and reducing post-harvest losses (Fig. 6; Yamaguchi *et al*. 2016). In the 1M5R policy, AWD is considered to be the most important component by which to achieve the reduction in irrigation water usage.

Water availability determines the suitability of AWD. There are hierarchical constraints on the adoption of AWD by farmers in terms of water use (Fig. 7). The irrigated rice ecotype is more suitable to AWD than is the rainfed rice ecotype due to the high availability of water needed; however, AWD itself is conditionally possible even in the rainfed ecosystem (e.g., pump usage with extra cost). Even in the irrigated ecosystem, water may not be available on demand in case of gravity irrigation or tidal irrigation. If an irrigation pump is owned privately, there is an incentive to reduce the volume of irrigation water used to save pump fuel cost. Even if the pump is rented, the volumetric charging can give farmers an incentive to reduce water use.

The An Giang province, Vietnam, is proud of its high adoption rate of AWD, reaching 52% of the total paddy area in the 2014–2015 dry season (Fig. 8; Yamaguchi *et al*. 2019). One of the major reasons for the high dissemination rate is that, since the end of the 1990s, embankments (full-dike system) have been established and large-capacity pumps have been installed to drain rainwater from rice paddies surrounded by an embarkment to the outside, enabling rice triple-cropping and on-demand irrigation and drainage (Yamaguchi *et al*. 2019). Another major reason for the high uptake of AWD is the positive effect of AWD on rice growth and yield. Through interviews with local government staff, we found that AWD was effective at reducing rice lodging, thereby leading to higher yields (Yamaguchi *et al*. 2017). In addition, the farmers (1) used soil hardness as indicated by the footprints left and/or the cracks developed on the soil surface as the simplified criteria for AWD in a broad sense to decide the timing of re-flooding instead of assessing the surface water level; and (2) practiced AWD even in rainy seasons with the expectation of yield increases (Yamaguchi *et al*. 2016). Using statistics and GIS data, it was demonstrated that, in a dissemination campaign (to improve farmers' perception of AWD), paddy elevation (mid-lying is the best), and infrastructure status (channel density/network) were critical factors in disseminating AWD in the An Giang province (Fig. 5; Yamaguchi *et al*. 2019).

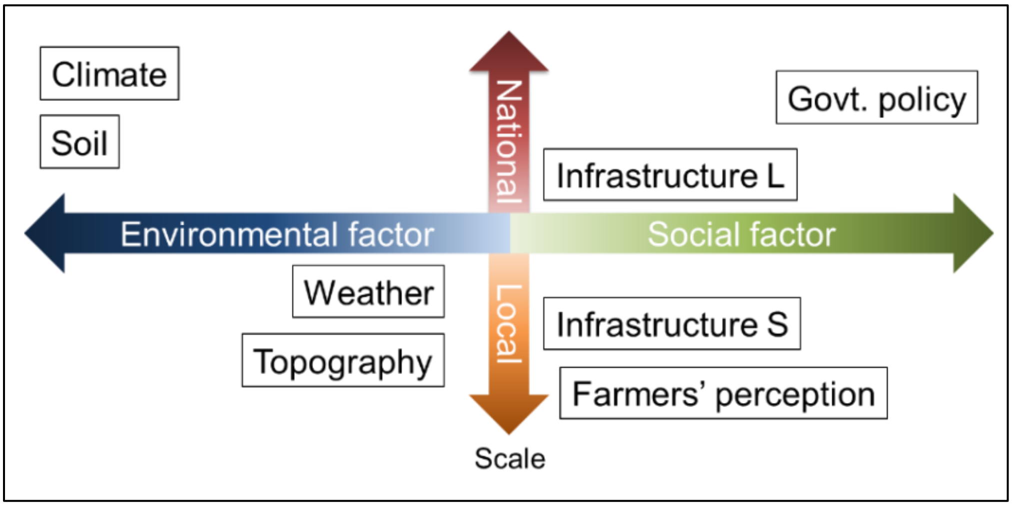


Fig. 5. Bottlenecks in adopting AWD. Adapted from Yamaguchi *et al*. (2016; 2017; 2019) and Nelson *et al*. (2015).

Fig. 6. Cover page of the guidebook on "1 Must Do, 5 Reductions" policy (Sub-department of Plant Protection in An Giang 2014).

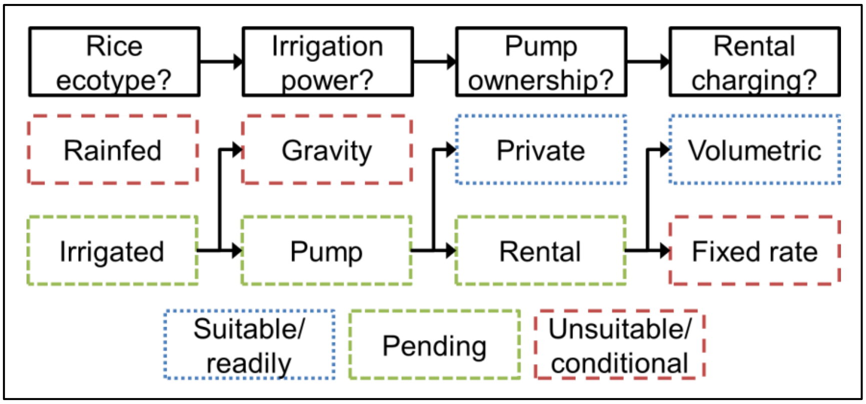


Fig. 7. A flowchart demonstrating the suitability of AWD in terms of water use. Adapted from Kurschner *et al.* (2010), Richard and Sander (2014), Sibayan *et al.* (2010), and Yamaguchi *et al.* (2016).

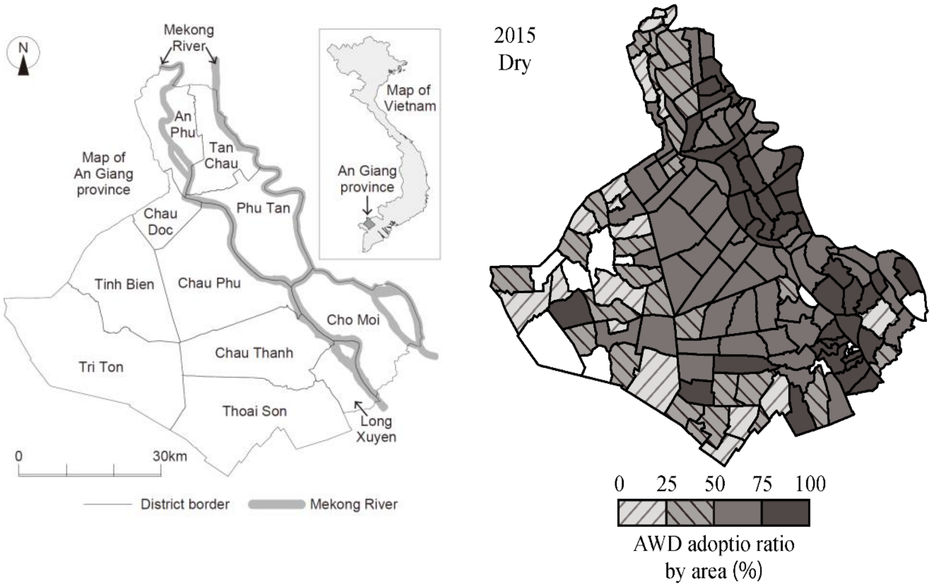


Fig. 8. Map of the An Giang province, Vietnam (left), and the AWD dissemination rate by commune in the 2015 dry season (right). A white parcel in right panel indicates a commune with missing data.

FUTURE PERSPECTIVES OF DISSEMINATION

What is necessary to achieve further dissemination of water management as a climate-change mitigation option? It is essential to formulate direct and/or indirect incentives for rice farmers. However, it is unclear how to develop what kind of incentive. This final chapter explains the detailed ways to develop further dissemination of water management protocols based on the study by Minamikawa *et al*. (2018).

There are three possible approaches for achieving a widespread dissemination of climate-change mitigation options by rice farmers (Table 4). The voluntary approach is the most acceptable one for farmers because it is directly linked to their own incentive. For example, soil C sequestration is effective in reducing soil CO_2 emissions and also in providing the long-term resilience of rice production in the face of climate change. In addition, the increase in rice yield, if achieved, can be a direct incentive for farmers to adopt water management in tropical and subtropical regions; thus it is necessary to accumulate a more scientific basis for the mechanisms of yield increase by water management similar to the aforementioned beneficial effects of midseason drainage. However, there must be an upper boundary to the mitigation, which can be achieved by voluntary efforts alone.

Through the semi-institutional approach, farmers can obtain some financial incentives in the form of governmental subsidies or added value through certification. For example, in Japan, farmers can obtain economic incentives by participating in the governmental subsidy program "Direct payment for environmentally friendly agriculture," in which the prolonging of midseason drainage is a regionally approved alternative in several prefectures. Although the semi-institutional approach helps in substantially reducing GHG emissions, the efforts of this approach in GHG reduction cannot readily be registered to the national GHG inventory that is submitted to the United Nations Framework Convention on Climate Change (UNFCCC).

The institutional approach is driven by carbon pricing (i.e., market mechanisms and carbon tax) or Nationally Appropriate Mitigation Action (NAMA). Farmers can gain economic incentives or avoid taxes by participating in a mitigation project that mandates them to practice additional agricultural management strategies, such as water management. For example, NAMAs that use AWD as a mitigation option of CH_4 emissions are in the preparation phase in Thailand (Thai Rice NAMA; NAMA Facility 2018) and in the preliminary phase with limited implementation areas in the Philippines (AMIA; UNDP 2015). However, till date, the methodology for implementing such mitigation projects for rice cultivation has not been well documented.

Monitoring, Reporting, and Verification (MRV) is a concept that integrates three independent processes of GHG emissions mitigation initiatives: monitoring or measurement (M), reporting (R), and verification (V) (Fig. 9). It assures the accuracy and reliability of the GHG emission baseline and, therefore, any reductions from it. Although each process should be independent of the others, MRV refers to a system that involves a systematic integration of the three processes (IGES, 2011). Recently, the use of market mechanisms has been articulated in the Article 6 of the Paris Agreement (UNFCCC, 2015), which prescribes the use of emission reductions achieved overseas for achieving national GHG emission reduction targets:

- Article 6.2: Internationally transferred mitigation outcomes between authorizing parties
- Article 6.4: A mechanism to contribute to mitigation and sustainable development

The use of market mechanisms under the Paris Agreement will accelerate the institutional spread of mitigation options through the development of MRV methodology for a certain project. Minamikawa *et al*. (2018) developed a handbook that provides people who are engaged or interested in the development and implementation of MRV methodologies for water management in irrigated rice paddies with (1) basic information regarding

MRV, particularly for quantifying GHG emissions and reductions and (2) updates on evolving issues facing these people.

Table 4. Characteristics of three approaches to disseminating mitigation options for GHG emissions from paddy rice cultivation (modified from Minamikawa *et al.* 2018)

	Voluntary	Semi-institutional	Institutional
Explanation	Get help from benefits and synergies for activities such as higher rice production and climate-change adaptation	Domestic subsidy, and governmental or private certification systems	International or domestic carbon pricing, and NAMA
Advantage	· No additional cost · Indirect financial incentive from improved products	· Financial incentive · Relatively easy documentation	· Financial incentive · Accountable to national GHG inventory
Drawback	· Limited number of options · Limited mitigation capacity	· Limited amount of subsidy · Limited purchasers	· Complicated documentation · Risks of low carbon price
Example	· Soil C sequestration · Early maturing variety	· Good Agricultural Practice (GAP) · Eco-labeling	· Clean Development Mechanism (CDM) · Thai Rice NAMA

Note: An activity of the voluntary approach can be an activity of the semi-institutional or the institutional approach, if approved.

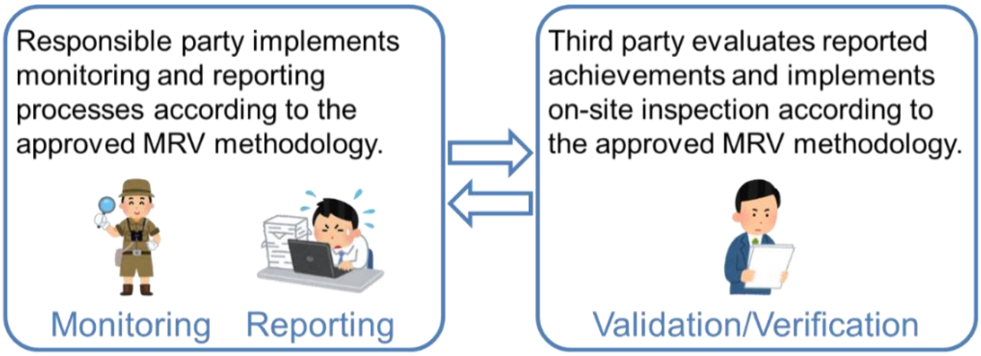


Fig. 9. Schematic representation of MRV implementation under a certain mitigation project.

REFERENCES

Ciais, P., C. Sabine, G. Bala *et al*. 2013. Carbon and Other Biogeochemical Cycles. pp. 465-570 *in*: T.F. Stocker, D. Qin, G.K. Plattner *et al*. (eds.) *Climate Change 2013: The Physical Science Basis*. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

FAOSTAT. 2018. Available from http://www.fao.org/faostat/en/#home.

Guo, J., Z. Song, Y. Zhu, W. Wei, and S. Li. 2017. The characteristics of yield-scaled methane emission from paddy field in recent 35-year in China: A meta-analysis. *Journal of Cleaner Production* 161: 1044-1050.

Hayashi, K., S. Nishimura, and K. Yagi. 2008. Ammonia volatilization from a paddy field following applications of urea: rice plants are both an absorber and an emitter for atmospheric ammonia. *Science of the Total Environment* 390: 485-494.

IGES (Institute for Global Environmental Strategies). 2011. Classification of MRV of Greenhouse Gas (GHG) Emissions/Reductions: For the discussions on NAMAs and MRV. Policy Brief Number 25, IGES. Available from https://mitigationpartnership.net/sites/default/files/iges_pb_mrv.pdf.

IPCC. 2006. Methane Emissions from Rice Cultivation: Cropland: Agriculture, Forestry and Other Land Use. pp. 5.44-5.53 *in*: H.S. Eggleston *et al*. (eds.) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IGES, Hayama, Japan.

Kajiura, M., K. Minamikawa, T. Tokida, Y. Shirato, and R. Wagai. 2018. Methane and nitrous oxide emissions from paddy fields in Japan: An assessment of controlling factor using an intensive regional data set. *Agriculture, Ecosystems and Environment* 252: 51-60.

Kurschner, E., C. Henschel, T. Hildebrandt, E. Julich, M. Leineweber and C. Paul. 2010. Water Saving in Rice Production-dissemination, Adoption, and Short-term Impacts of Alternate Wetting and Drying (AWD) in Bangladesh. *SLE Publication Series S241*. Humboldt Universität, Berlin, Germany.

Lampayan, R.M., F.G. Palis, R.B. Flor *et al*. 2009. Adoption and Dissemination of "Safe Alternate Wetting and Drying" in Pump Irrigated Rice Areas in the Philippines. pp. 1-11 *in*: *Proceedings of 60th International Executive Council Meeting and 6th Asian Regional Conference of the International Commission on Irrigation and Drainage*. Indian National Committee on Irrigation and Drainage, New Delhi, India.

Leon, A, K. Kohyama, K. Yagi, Y. Takata, and H. Obara. 2015. The effects of current water management practices on methane emissions in Japanese rice cultivation. *Mitigation and Adaptation Strategies for Global Change* 22: 85-98.

Linquist, B.A., M.M. Andreas, M.A.A. Adviento-Borbe, R.L. Chaney, L.L. Nalley, E.F.F. da Roda and C. van Kessel. 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology* 21: 407-417.

Myhre, G., D. Shindell, F.M. Bréon *et al*. 2013. pp. 659-740 *in*: T.F. Stocker, D. Qin, G.K. Plattner *et al*. (eds.) *Climate Change 2013: The Physical Science Basis*. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Minamikawa, K., T. Yamaguchi, T. Tokida, S. Sudo, and K. Yagi. 2018. *Handbook of Monitoring, Reporting, and Verification for a Greenhouse Gas Mitigation Project with Water Management in Irrigated Rice Paddies*. Institute for Agro-Environmental Sciences, NARO, Tsukuba, Japan. 42 pp.

NAMA Facility. 2018. *Thailand–Thai Rice NAMA*. Available from https://www.nama-facility.org/projects/thailand-thai-rice-nama.

Naser, H.B., O. Nagata, S. Tamura, and R. Hatano. 2007. Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. *Soil Science and Plant Nutrition* 53: 95-101.

Nelson, A., R. Wassmann, B.O. Sander, and L.K. Palao. 2015. Climate-determined suitability of the water saving technology" alternate wetting and drying" in rice systems: a scalable methodology demonstrated for a province in the Philippines. *PloS one* 10: e0145268.

Richards, M. and B.O. Sander. 2014. Alternate wetting and drying in irrigated rice. *CSA Practice Brief*. Copenhagen, Denmark.

Shindell, D., J.C.I. Kuylenstierna, and E. Vignati *et al*. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335: 183-189.

Shirato, Y. and M. Yokozawa. 2005. Applying the Rothamsted Carbon Model for long-term experiments on Japanese paddy soils and modifying it by simple tuning of the decomposition rate. *Soil Science and Plant Nutrition* 51: 405-415.

Sibayan, E.B., K. Samoy-Pascual, F. Grospe, M.E. Casil, T. Tokida, A. Padre and K. Minamikawa. 2018. Effects of alternate wetting and drying technique on greenhouse gas emissions from irrigated rice paddy in Central Luzon Philippines. *Soil Science and Plant Nutrition* 64: 39-46.

Sibayan, E.B., J.L. de Dios, M.L. Florague, L.C. Javier, A.S. Espiritu, R.M. Lampayan, and A.S. Nangel. 2010. Controlled irrigation adoption for efficient water management at the system level for increasing and sustaining water productivity. pp. 135-150 *in*: F.G. Palis, G.R. Singleton, M.C. Casimero and B. Hardy (Eds.) *Research to Impact: Case Studies for Natural Resource Management for Irrigated Rice in Asia*. IRRI, Los Baños, Philippines.

SSDBAFE-MAF (Statistical Survey Department, Bureau of Agricultural and Forestry Economics, Ministry of Agriculture and Forestry). 1967. *Crop Statistics in 1966 (No. 9)*. Association of Agriculture and Forestry Statistics, Tokyo, Japan. 488 pp. (in Japanese).

Sub-Department of Plant Protection in An Giang. 2014. *So Tay Huong Dan Trong Lua Can San Theo "1 Pahi 5 Giam."*

Tirol-Padre, A., K. Minamikawa, T. Tokida, R. Wassmann, and K. Yagi. 2018. Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis. *Soil Science and Plant Nutrition* 64: 2-13.

Tsuchiya, M. and Shimizu, T. 1983. Nihon-Nougaku-Zensyu: Vol. 26 Nougyou-Zue (Kaga). Rural Culture Association Japan, Tokyo, Japan. 312 pp. (in Japanese).

UNDP (United Nations Development Programme). 2015. *Adaptation and Mitigation Initiatives in Philippine Rice Cultivation*. Available from http://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/MDG%20Carbon%20Facility/AMIA%20Philippines%20Final.pdf.

UNFCCC. 2015. *Paris Agreement (FCCC/CP/2015/L.9/Rev.1)*. Available from http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

Yagi, K. and K. Minami. 1990. Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Science and Plant Nutrition* 36: 599-610.

Yamaguchi, T., L.M. Tuan, K. Minamikawa, and S. Yokoyama. 2019. Assessment of the relationship between adoption of a knowledge-intensive water-saving technique and irrigation conditions in the Mekong Delta of Vietnam. *Agricultural Water Management* 212: 162-171.

Yamaguchi, T. 2018. Diffusion of Nakaboshi–An implication for the diffusion of the water-saving irrigation in the Asian countries. *Research for Tropical Agriculture* 11: 51-52. (in Japanese).

Yamaguchi, T., L.M. Tuan, K. Minamikawa, and S. Yokoyama. 2017. Compatibility of alternate wetting and drying irrigation with local agriculture in An Giang Province, Mekong Delta, Vietnam. *Tropical Agriculture and Development* 61: 117-127.

Yamaguchi, T., L.M. Tuan, K. Minamikawa, and S. Yokoyama. 2016. Alternate wetting and drying (AWD) irrigation technology uptake in rice paddies of the Mekong Delta, Vietnam: relationship between local conditions and the practiced technology. *Asian and African Area Studies* 15: 234-256.