Journal of Wetlands Research
Vol. 21, No. 1, February 2019, pp. 043-056
ISSN 1229-6031 (Print) / ISSN 2384-0056 (Online)
DOI https://doi.org/10.17663/JWR.2019.21.1.043

Greenhouse Gas Reduction from Paddy by Environmentally-Friendly Intermittent Irrigation: A Review

Joongdae Choi[†]·Norman Uphoff[*]·Jonggun Kim·Suin Lee[**]

Department of Regional Infrastructure Eng., Kangwon National University
[*]Government and International Agriculture, Cornell Institute for Public Affairs, Cornell University
[**]Watershed and Total Load Management Research Division, National Institute of Environmental Research

환경 친화적인 간단관개를 통한 논에서의 온실가스 저감

최중대[†]·노만 우포프[*]·김종건·이수인[**]

강원대학교 지역건설공학과
[*]코넬대학교 행정·국제농업학과
[**]국립환경과학원 유역총량과

(Received : 04 December 2018, Revised: 12 February 2019, Accepted: 12 February 2019)

Abstract

Irrigated and flooded rice paddy contributes to the greenhouse gas emissions (GHG) that affect climate. This in turn affects the supply and reliability of the water needed for rice production. This dynamic makes current rice production methods foreseeably less sustainable over time while having other undesirable effects. Intermittent irrigation by a means of the system of rice intensification (SRI) and alternate wetting and drying (AWD) methods was reviewed to reduce global warming potential (GWP) from 29% to 90% depending on site-specific characteristics from flooded rice paddy and analyzed to be a promising option for enhancing the productivity of water as well, an increasingly constraining resource. Additional benefits associated with the SRI/AWD can be less arsenic in the grain and less degradation of water quality in the run-off from rice paddies. Adoption and expansion of intermittent irrigation of SRI/AWD may require costly public and private investments in irrigation infrastructure that can precisely make irrigation control, and the involvement and upgrading of water management agencies and farmer organizations to enhance management capabilities. Private and public collaboration as a means of earning carbon credit under the clean-development mechanism (CDM) with SRI/AWD for industries to meet as a part of their GHG emission quota as well as a social contribution and publicity program could contribute to adopt intermittent irrigation and rural investment and development. Also, inclusion of SRI and AWD in programs designed under CDM and/or in official development assistance (ODA) projects could contribute to climate-change mitigation and help to achieve UN sustainable development goals (SDGs).

Key words : alternate wetting and drying, climate change, greenhouse gas emission, intermittent irrigation, system of rice intensification

요 약

관개 및 담수 논은 온실가스 배출에 기여를 하고 있으며 이는 기후에도 영향을 미친다. 관개 및 담수는 벼 생산을 위해 필요로 하는 수분의 공급과 안전성에도 영향을 미친다. 현재 벼 생산 방법(담수재배)은 여러 측면에서 부정적인 영향을 미치면서 시간이 지날수록 지속 가능성이 낮아 질 것이다. 이에 담수 논의 지역적 특성에 따라 지구온난화를 29% ~ 90%까지 줄이기 위해 SRI(system of rice intensification)와 AWD(alternate wetting and drying) 방법을 적용한 간단관개 방식이 검토되고 있으며, 점차 제한된 자원인 물을 절약하기 위한 방법으로 알려지고 있다. SRI/AWD 적용에 따른 긍정적인 측면으로는 논에서의 유출로 인한 수질악화를 줄이고 곡물에 비소를 줄일 수 있다는 것이다. SRI/AWD와 같이 간단관개 방법의 적용 및 확장을 위해서는 정밀 관개 조절을 할 수 있는 관개 인프라 구축에 대한 공공 및 민간에서의 비용적인 투자가 필요하며, 관리 능력 향상을 위해 물 관리 기관 및 농민의 노력이 요구된다. 산업분야에서 SRI/AWD와 함께 청정개발체제(CDM, clean-development mechanism) 하에서 탄소 배출권을 얻는 수단으로서의 민간·공공 협력은 간단관개 방식의 적용과 농촌

[†] To whom correspondence should be addressed.
Department of Regional Infrastructure Eng., Kangwon National University
E-mail: jdchoi@kangwon.ac.kr

지역 투자 및 발전에 기여할 수 있을 것이다. 또한, 청정개발체제 하에서 설계된 프로그램 또는 ODA(official development assistance) 프로젝트에 SRI/AWD가 포함된다면 기후변화 완화에 기여할 수 있을 것이고, UN의 지속 가능한 발전 목표(SDGs)를 달성하는 데 도움이 될 수 있을 것이다.

핵심용어 : 기후변화, 온실가스배출, 간단관개, alternate wetting and drying, system of rice intensification

1. Introduction

Climate change is affecting most parts of the world with fluctuating precipitation and temperatures and with increasing episodes of drought, flooding and other stresses that affect crop production, particularly rice, one of the world's major staples, especially in Asia. Reversing climate change may not be possible in the foreseeable future, but mitigating this change must be a priority for governments, industries and citizens around the world, plus finding ways to adapt agricultural production and lifestyles to the new conditions to maintain food security and preserve quality of life.

One approach to abating climate change that warrants expansion is the trading of carbon credits such as through the clean development mechanism (CDM) established under the Kyoto Protocols to reduce greenhouse gas (GHG) emissions. This system was framed mostly with reference to the industrial, transportation, energy and related sectors, but it relates also to the agricultural sector, which contributes about 10% of the world's total of anthropogenic GHG emissions. These are an aggregation of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and some other gases, all expressed in terms of CO_2 equivalence to facilitate evaluations of their global warming potential (GWP). About 11% of the agriculture sector's GWP created by GHG emissions comes from irrigated and flooded rice cultivation, making this sector responsible for about 1% of the world's total emissions(Keith, 2005).

While rice production may not seem like a very large target for reducing GWP emissions, in countries that have large areas of rice paddy, diminishing such emissions can contribute substantially to the achievement of national goals for GHG reduction. In major countries (e.g., China and India) the share of their methane emissions that come from rice production and are about 20 times stronger potential than CO_2 is estimated at 6% and 10%, respectively (Leip and Bocchi, 2007). In Vietnam, the government has decided that making changes in that country's rice production, including promotion of System of Rice Intensification (SRI) and Alternate Wetting and Drying (AWD), is one component of its national plan to reduce its GHG emissions thereby at least 8% by 2030 over a business-as-usual scenario (GVN, 2015).

Paddy is the most important staple food source for more than one third of world population. There are many competing demands and uses for water. Its supply and distribution are increasingly subject to constraints from climate change, and water quality is also subject to degradation from agricultural practices. Modern paddy farming should thus be expected to use the minimum of irrigation water while also not degrading its quality, at the same time achieving substantially increased yields and reducing the GHG emissions that are associated with rice production. These are huge challenges for the rice sector and for policy-makers.

Growing rice with System of Rice Intensification (SRI) and Alternate Wetting and Drying (AWD) methods is thought to meet these modern paddy farming expectations although research on these methodologies has focused more agronomic and economic considerations than on their environmental benefits.

Numerous studies on production mechanisms for methane emissions from flooded paddy fields have reported on the factors influencing this, such as irrigation water management, redox potential, organic matter content of the soil, carbon and nitrogen sources, plant physiology (root exudation, methane transfer functions, etc.), the roles of micro-organisms, temperature effects, and so on. Methane is mainly produced as a by-product during the decomposition of organic matter under anaerobic soil conditions by micro-organisms (methanogens) that are very sensitive to the presence of oxygen. Unlike most other life forms, this element is toxic for them. Once a paddy soil surface is exposed to the air and aerated (i.e, oxidized), methanogens cannot survive in the large parts of the paddy soil, their production (fermentation) of methane drops sharply, and CH_4 emissions are reduced no matter what other factors are favorable. In contrast to methane, nitrous oxide (N_2O) emission is increased when the soil is oxidized as a result of microbial activity known as nitrification and denitrification. Unfortunately, studies on N_2O emissions from flooded, anaerobic rice paddies are limited because nitrous oxide emission from the soils is known to be low, and thus it has gotten less attention from researchers. Nitrous oxide is a much more potent GHG than methane, contributing about 12 times more to global warming potential, much as methane has 25 times more GWP effect than carbon dioxide.

When shifting crop, soil and water management from flooded to unflooded conditions, one has to consider carefully the interactions among the factors generating these GHGs, considering, for example, the effects on soil bacteria (methanotrophs) which consume and neutralize methane, or the abundant use of N fertilizers that provide (often excessive) substrate for organisms' synthesis of CH_4 or N_2O. Water management regimes such as SRI and AWD that inhibit methanogens in the soil and favor methanotroph populations can thus suppress methane emissions (Rajkishore et al., 2013), as discussed below. The interplay among levels of water (and conversely, of oxygen) in the soil, and soil temperature, and soil pH (acidity) can be complex (Setiawan et al., 2013, 2014). So assessing impacts of management practices on GHG emissions needs to be empirically grounded.

Technologies and policies to affect GHG emissions are getting more complex, and the probability of success is lowered as the number of influencing factors to be considered increases, making rice production of climate-friendly requires a multi-disciplinary effort. However, the main factor affecting GHG emissions is irrigation water management as this affects soil temperature, pH, microbial communities, and other factors and is a variable subject to decision-makers in the public and private sectors and by farmers. In rice-producing regions and countries, governments or government-run agencies seek to create and manage water supply for higher rice yield as well as for other purposes, such as flood control or domestic water supply. Experts in these agencies are mainly water engineers, however, but not plant scientists, microbiologists or ecologists. If asked to develop low-GHG-emission-farming methods by affecting the influencing factors, they may be limited in such an effort because they do not know all of the variables or the theories governing these very well. Accordingly, water experts and policy-makers should have a good understanding of innovations such as SRI and AWD as well as the underlying science so that recommendations and decisions can contribute to the development and spread of low-GHG-emission-farming methods as well as other development and policy objectives.

This paper reviews research on intermittent irrigation especially SRI, AWD, and GHG emissions, analyzing the relationships between irrigation management and GHG reduction, and providing rationale for climate-change mitigation through rural development efforts that pursue multiple objectives. It is hoped that policy makers, engineers and scientists in water sector will become more actively engaged in endeavors to deal with climate change and enhance security and well-being for both people and the environment.

2. SRI and AWD Method

The theory, practice and outcomes of SRI and AWD have been well-described in the literature (Lamayan et al., 2009; Richards and Sander, 2014; Siopongco et al., 2013; Stoop et al., 2002; Styger and Uphoff, 2016; Thakur et al., 2010; Thakur and Uphoff, 2017). SRI is a set of half a dozen modifications of long-standing irrigated rice production based on the work of a French priest working with rice farmers in Madagascar in the 1960s-1990s, while AWD has been disseminated and encouraged by International Rice Research Institute (IRRI) from the late 2000s and early 2010s.

The basic SRI practices can be summarized as: 1) early, careful establishment of healthy plants, 2) minimization of competition among plants through wider spacing, 3) build-up of fertile soil that is well endowed with organic matter and beneficial soil biota, and 4) careful management of irrigation water to avoid both flooding and water stress. By observing these principles, SRI reportedly increases the productivity and resilience of rice plants and provides other benefits including GHG reduction (Styger and Uphoff, 2016; Thakur and Uphoff, 2017). Uphoff (2017) has estimated that by the end of 2013, about 10 million farmers in China, India, Indonesia, Cambodia and Vietnam, where two-thirds of the world's rice is produced, were practicing many or all of SRI principles on about 7 million hectares, and these number have probably doubled by now. Average yield increase by the use of SRI in these countries was about 1.66 tons per hectare, with less irrigation water supply, lower cost, and more climate-resilience than by conventional practices. Considering cost reductions as well as the increased yield on this area, with the paddy rice valued at a conservative price of USD150 per tonne, the value from the additional rice production would have surpassed USD 1 billion, and twice that if valued at the more likely farmgate price of USD 300 per tonne.

AWD is a rice farming method where rice paddies are serviced by intermittent irrigation as farmers continue their other practices. With AWD, the paddy is flooded after transplanting for 1 to 2 weeks, and thereafter, intermittent irrigation supports a water level that ranges from 5 cm above to 15 cm below ground throughout the cropping season, except from 1 week before and 1 week after flowering. The shallow ponding of about 2.5 cm depth is maintained during the periods after transplanting and flowering (Siopongco et al., 2013; Lampayan et al., 2009). AWD is reported to significantly reduce GHG emissions (IPCC, 2006; UN FAO, 2010; Uprety et al., 2012). Bouman et al. (2007) reports that AWD saves water without decreasing yield, but there is no claim that it increases yield (Howell et al., 2015; Rejesus et al., 2011). It is estimated that in the Philippines, AWD is practiced on about 100,000 ha (Lampayan et al., 2009).

In terms of water management for rice production, both SRI and AWD involve intermittent irrigation so that the paddy soil has repeated cycles of shallow flooding and surface dryness, leading to alternating anaerobic and aerobic soil conditions. Under the latter, various populations of soil micro-organisms flourish, organic matter in the soil is decomposed quickly to release vital plant nutrients, and rice roots grow vigorously, both wide and deep into the soil to acquire nutrients rather than gradually suffocate and senesce over time as occurs under anaerobic soil condition (Kar et al., 1974). The changes in water management which both SRI and AWD introduce clearly will reduce irrigation water consumption and will change the conditions and processes whereby greenhouse gases are produced in the soil and emitted into the atmosphere. To the extent that there are also changes in nutrient management, reducing the application of inorganic nutrients, there can also be improvements in environmental quality through the reduction of non-point source (NPS) water pollution, as discussed later in this paper.

3. Methane and Nitrous Oxide Generation in Paddy Fields

It is generally understood that methane (CH_4) emissions from rice paddies originate from the fermentation processes driven by methanogens under anaerobic soil conditions which result from continuous flooding (Siopongco et al., 2013; Malyan et al., 2016). In addition to the increase in abundance and activity of methanogens in hypoxic soil, many other factors contribute to the production of CH_4: water management, redox potential in the soil, other micro-organisms (respective roles for and competition among different species), temperature, soil texture, applications of fertilizers (inorganic and organic) and pesticides, carbon sources (levels of organic matter) and C:N ratio, rates of nitrification and denitrification, root density and root exudates, plant physiology, soil pH, and others (Chu et al., 2015; Minamikawa and Sakai, 2006; Lee et al., 2010; Li et al., 2014; Malyan et al., 2016). These factors all play a role, but methanogens are the leading actors in the generation of methane.

A dynamic biotic element in this process of methane emission is the role and activity of methanotrophs, methane-oxidizing bacteria that live in the rhizosphere around rice roots and in the upper, aerobic surface soil of rice paddies. They reduce the methane produced in the unaerated part of soil before it gets released into the atmosphere, using CH_4 as a source of carbon and energy to assimilate for converting carbon dioxide into cellular biomass for their own purposes. It is reported that as much as 60-80% of the methane produced in the soil gets reduced by methanotrophs (Bodelier et al., 2000; Singh et al., 2010; Malyan et al., 2016). So there is an invisible drama going on in rice paddies between these two populations of countervailing microbes. Their respective population sizes and activities significantly determine what will be the net amount of methane that moves into the atmosphere.

It is also well understood that methane production is negatively affected by soil aeration that injects oxygen into the soil profile. Once part or all of the paddy soil is in contact with air, as results from intermittent water management, methanogens can no longer survive and do not easily revive even when the soil is re-flooded. Conversely, methanotrophs thrive under aerobic soil conditions, so methane emissions are sharply reduced by soil aeration (Siopongco et al., 2013; Choi et al., 2014; Chu et al., 2015). Along with intermittent water management, various other agronomic practices that affect the influencing factors listed above will also have an impact on methane production and inhibition to some extent, so they should also be considered.

Nitrous oxide (N_2O) is mostly produced under aerated soil conditions, so its emission from continuously flooded paddies under anaerobic conditions is thought to be negligible. Even what is produced will be, to a great extent, further reduced to N_2 gas under anaerobic conditions (Williams et al., 1992; Granli and Bockman, 1994; Henkel and Conrad, 1998). Moreover, Chu et al. (2015) have reported that nitrous oxide is produced when the soil's water potential is equal to or greater than −10 kPa. This means that, depending on soil texture, nitrous oxide is formed when water level is lower than approximately 10-15 cm below the soil surface. If the water table is not below that level but the soil is still near saturation or at field capacity, just aerated through small cracks and macro-pores, nitrous oxide production associated with AWD may still be neglible. Although production of nitrous oxide is also influenced by the similar factors affecting methane emission listed above (Chu et al., 2015; Yao et al., 2013; Miller et al., 2004), if the soil is repeatedly cycled through aerobic and anaerobic conditions, the increase of nitrous oxide emission with SRI and AWD may be small enough not to offset the gains from methane reduction. How this balance works out is an empirical question and the answer is determined by interactions among many factors.

Methane produced in paddy soil is transported into the atmosphere by the mechanisms of plant respiration, ebullition (bubbling action), and diffusion in general. Although methane exists in both gaseous and dissolved forms, most methane is emitted in the gaseous form because of its low solubility and lack of ionic form (Malyan et al., 2016; Tokida et al., 2005; Strack and Waddington, 2008; Green, 2013). Plant respiration or plant-mediated transport is the primary pathway of methane from the soil to the atmosphere through aerenchymatous tissue

(Das and Baruah, 2008; Watanabe et al., 1994; Sass et al., 1990; Nouchi et al., 1990; Seiler et al., 1984; Cicerone et al., 1983), although these measurements have mostly been made in flooded fields. The tissues that also transport oxygen from the leaves to the roots (Armstrong, 1978; Jensen et al., 1967) are reported to contribute about 80-90% of methane emission from rice paddies (Setyanto et al., 2004; IPCC, 1996; Holzapfel-Pschorn and Seiler, 1986; Holzapfel-Pschorn et al., 1986). Ebullition is reported as an important mechanism that transports methane in a form of bubbles. IPCC (1996) reported that this is prominent in clay-textured soils. Schütz et al. (1989) measured that between 4 and 100% of methane emissions in a paddy were transported through ebullition in Italian trials. Since ebullition processes are fast, the attenuation of methane during transport is thought to be negligible (Malyan et al., 2016). Diffusion which is a physical process driven by concentration gradient is not considered as a significant emission pathway due to its low solubility (Neue, 1993). However, it must be understood that under intermittent irrigation of SRI/AWD, the paddy soil surface is regularly dried and methane transportation might be different from that of flooded one.

3.1 Factors affecting methane emission

GHG emission reduction in terms of lowering the methane and/or nitrous oxide generated in and arising from paddy fields may be achieved by controlling the influencing factors. Farmers' willingness to adopt methods of emission control must also be part of any effective implementation plans. Many studies have tried to describe the effects of specified treatments (factors) on methane emission, and Malyan et al. (2016) have reviewed them well. Studies on nitrous oxide emission under flooded paddy conditions are very limited, as noted already. Their results are inconsistent (Sander et al 2013; Wang et al., 2006), and thus there is no consensus to summarize in this paper.

Organic matter and C:N (carbon : nitrogen) ratio are important factors in the production of methane in paddy soils. If the soil is flooded and made anaerobic, organic matter is subject to the processes of methane fermentation. If the soil is aerobic, nitrous oxide is produced instead of methane. The particular characteristics of organic matter are also important factors in methane production. If fresh wheat or rice straw is applied, methane production is often sharply increased as compared with other sources of organic matter such as composted animal waste or biochar (Yagi and Minami, 1990; Bronson et al., 1997; Agnihotri et al., 1999; Zhang et al., 2010; Pandey et al., 2014). Studies have shown that under anaerobic soil conditions, the application of organic materials as soil amendments increases methane flux by 2 to 4 times (Yagi and Minami, 1990) or even several fold (Bronson et al., 1997) as compared with what is measured from conventional plots. Sass et al. (1990) reported a linear relationship between plant biomass and methane emission under flooded condition, indicating that the greater the organic matter application, the higher will be methane emission in general. However, if a paddy is drained and the soil is regularly aerated through SRI or AWD water management, methane emission is reduced, regardless soil amendment (Chu et al., 2015). They reported that moderate AWD reduced GWP assessed in terms of CO_2-equivalent, including both methane and nitrous oxide, by 45% (with no wheat residue added) and by 56% (with wheat residue added) compared with conventional practices.

Methanogens thrive well in neutral (pH = 6.5-7.5) or slightly alkaline soil and very sensitive to fluctuations in soil pH (IPCC, 1996, Wang et al., 1993). And flooded paddy soil is naturally anaerobic and neutral in pH and thus, methane is well fermented and produced (Pathak et al., 2008; Dunfield et al., 2003; Wassmann et al. 1998).

The type and texture of soil that has different hydraulic conductivity (percolation), air and gas diffusivity, and organic matter content will affect methane production (Yagi and Minami, 1990; Yagi et al., 1998; Inubushi et al., 1992; Le Mer and Roger, 2001). Although methane emission tends to increase in sandy soil (Wang et al., 1993; Wagner et al., 1999), the emissions among different soil types and textures were not consistent, ranging from 153 to 285 kg ha^{-1} in clay loam, from 108 to 441 kg ha^{-1} in silt loam, from 113 to 246 kg ha^{-1} in sandy clay loam, and from 23 to 146 kg ha^{-1} in sandy loam soils (Malyan et al., 2016).

Soil redox potential, which is closely associated with aeration, is one of the key factors for methane production in paddy. It is known that the initiation of methane production begins when soil redox potential reaches between -100 to -200 mV (Dubey, 2005; Wang et al., 1993; Yagi and Minami, 1990). Once a paddy is flooded for rice culture, the redox potential drops fast (Takai et al., 1956). Babu et al. (2006) reported that it decreased sharply to -155 mV at 10 days and further to -287 mV at 30 days after transplanting of rice in an Indian paddy. Therefore, steady, continuous flooded conditions can create low redox potential that facilitates production of methane. Although there are other factors influencing redox potential (Neue and Roger, 1994), it is well understood that if paddy is periodically flooded and dried, redox potential cannot maintain low value and thus, methane production is also decreased.

Oxygen availability in the paddy soil is a critical factor for both methanogens and methanotrophs which are key players in the fermentation and oxidation of methane (Bender and Conrad, 1993). As more oxygen is supplied to the soil profile due to periodic exposure to the air by intermittent irrigation management, methanogens become inhibited and this causes methane emissions to decrease, at the same time that methanotrophs consuming methane increase.

Soil temperature is also a key factor for both methanogens and methanotrophs. In anaerobic soils, methane formation begins at 15-20 ° C (Nozhevnikova et al., 2007) and may take place optimally between 25 ° C and 40 ° C, depending on climate and soil condition (Chen et al., 2015; Yang et al., 2015; Hattori et al., 2001; Yagi et al., 1997; Neue and Scharpenseel, 1984). The oxidation of methane also depends on temperature (Borken and Beese 2006; LeMer and Roger, 2001), with optimum temperature ranging between 25 and 35 ° C in paddy soil (Mohanty et al., 2007; Min et al. 2002).

Methane emission is affected by the application rate, timing and methods as well as type of chemical fertilizers. Methane increases in response to urea application due to changes in redox potential and in soil pH to create a more favorable environment for methanogenesis processes as well as because this provides more substrate (Wang et al., 1993). Conversely, the application of ammonium sulfate or thiosulfate decreases methane emission due to the changes this makes in C:N ratio (Serrano-Silva et al., 2014; Rath et al., 2002; Wu et al., 2009; Singh et al., 2003). Balanced fertilization among nitrogen, phosphorus and potassium components reduces methane emission (Zheng et al., 2008; Datta et al., 2013a).

The stimulatory and inhibitory effect of fertilizers on the balance between methanogens and methanotrophs is believed to be a main cause for differentials in methane emission (Malyan et al., 2016). However, there are also conflicting studies on methane emission (Kiese et al., 2003; Hutsch et al., 1994; Jacinthe and Lal, 2006). Under repeated flooding and dried soil conditions with intermittent irrigation, studies about the effects of chemical fertilizers on methane and nitrous oxide emission are difficult to conduct and thus not yet very conclusive (Siopongco et al., 2013). Further studies are required.

Methane emission can also be substantially affected by rice variety (Kumar and Viyol, 2009; Aulakh et al., 2000; Mitra et al., 1999; Adhya et al., 1994) and by the stage of growth. Late-maturing, high-yielding, and high vegetative growth varieties have been reported to emit more methane compared to others (Khosa et al., 2010). Methane emission, relatively low at the beginning of vegetative growth (Conrad, 2007), increases with growth and generally peaks during tillering up to panicle initiation (Meijide et al., 2011). These measurements were made, however, under flooded soil conditions, so these conclusions would not necessarily apply with different water management schemes.

Depending on the rice cultivar and stage of growth, root exudates, decomposition of senesced roots and other organic matter, oxygen transport to roots, and populations of methanogens might be different, and these differences would affect the emissions (Li et al., 2011). The physiological differences of plant under flooded paddy soil might be different from those under repeated wet and dry soil by SRI and AWD. Thus, studies of rice varieties to select for both higher rice yield and lower GHG emission are further needed.

Application of pesticides and herbicides can have a significant inhibitory effect on methane production due to either negative effects on both methanogens and methanotrophs or changes in redox potential (Jiang et al., 2015; Bharati et al., 1999). Kumar and Viyol (2009) reported that under flooded condition, methane emissions vary diurnally and peak around noon. Elevated carbon dioxide concentration may contribute to increased methane emission (Lou et al. 2008) although Tokida et al. (2010) did not find any relationship between CO_2 concentration and the emission.

Once a flooded paddy is drained, numerous changes in the soil's physical, chemical and micro-biological properties take place. Physical modifications include changes in percolation, aeration, shrinkage and expansion of the soil as the soil-water content is repeatedly lowered below the saturation level. Chemical changes including redox potential and pH also result. Microbiological changes include the soil's bacteria shift from anaerobic families to both aerobic and facultative ones. As aerobic and facultative bacteria thrive under drained soil conditions provided that they have sufficient substrate as well as oxygen. Organic materials are decomposed faster, and more vital nutrients become plant-available than under flooded conditions. As significant as the shift in the composition of bacterial populations is the abundance of fungal populations, particularly arbuscular mycorrhizae, whose numbers and benefits are largely precluded under anaerobic soil conditions, and beneficial microorganisms such as Trichoderma (Doni et al., 2016). Actinomycetes which also have beneficial effects on rice crop growth, since they are aerobes, will also be more abundant in soils under AWD or SRI management (Lin et al., 2011).

The cumulative soil changes driven by intermittent irrigation management can override the effects of particular individual factors and given environmental as well as economic objectives need to be given weight in decisions for modern sustainable rice farming, which should achieve healthier plant growth, higher rice yield, and less net GHG emissions. This conclusion is supported by Malyan et al. (2016) who analyzed the effect of various influencing factors in detail, concluding that intermittent irrigation including midseason drying is the best methane-mitigating option for lowland flooded and irrigated rice fields management.

4. GHG Emissions under SRI and AWD

It is well understood that SRI and AWD can demonstrably change soil properties for better crop productivity and environmental quality. Although the effects of factors influencing GHG emission under SRI or AWD have not been thoroughly investigated, many studies have reported significant reductions in methane emissions while nitrous oxide was not increased enough to offset the methane reduction, leading to substantial net reduction in GHG emissions. Given reductions in nitrogen substrate with less application of chemical fertilizers, there could even be a decline in N_2O emission, but this is not likely to be common.

Choi and Kim (2016) reported from a 2-year study that SRI water management reduced GWP (combined methane and nitrous oxide emissions) by 77% in terms of CO_2-equivalence when compared with conventional flooded management during the growing season. The reduction with SRI was greater, by 46%, than that achieved by two mid-season dryings as done in one version of AWD. They also found that the addition of vermicompost failed to have a significant effect on methane and nitrous oxide emissions, meaning that the effect of vermicompost might be synergistic but included within the effects of water management.

Ahn et al. (2014) have reported that water-saving, shallow irrigation reduced methane by 78% while increasing nitrous oxide by 533% compared with conventional practice. Although the nitrous oxide increase was very high in percentage terms, the amount of emission was only 0.109 kg ha−1. Although N_2O is a more potent GHG than CH_4, its amount was very small, so that overall GWP reduction was 78% compared with conventional practice. Chu et al. (2015) reported that even with fresh wheat straw application, GWP in CO2-equivalence was substantially reduced under moderate AWD compared with under conventional flooded management. The reduction was greater in the straw-added-plots than that in no-straw-added-plots.

Jain et al. (2013) reported that SRI reduced methane emissions by 61~64% while it increased nitrous oxide by 22.5% compared with conventional practice. The net effect was that GWP was reduced by SRI between 30~36%. Yang et al. (2012) reported from their 2-year study that controlled irrigation during the growing period reduced methane emissions by 79% and increased nitrous oxide by 10.6%. Since the latter was relatively small, GWP as CO_2-equivalence was reduced during the period by 61% with controlled irrigation compared with conventional flooded irrigation. Setiawan et al. (2013) reported that methane and nitrous oxide emissions not only varied considerably, but also were not always inversely related because of intervening influences like soil temperature or pH. Emissions are also a factor not limited to the cropping season. As part of a 57-74% reduction in annual GWP when AWD was evaluated in trials in California, USA, fallow-season emissions accounted for 22-53%, or approximately one-third of the annual average (LaHue et al., 2016).

A Life Cycle Assessment (LCA) in India, which included also estimates of effects on CO_2 emissions, calculated that SRI significantly reduced GHG emissions while rice yield was raised by >60%, with 60% less extraction of groundwater and 74% lower fossil fuel consumption. The 40% reduction in GWP was mainly due to reduced methane emissions and embodied emissions in the generation of electricity for pumping groundwater (Gathorne-Hardy et al., 2013, 2016).

That N_2O emissions do not necessarily increase with intermittent irrigation, especially if more organic means of fertilization are used in rice production, has been seen in large-scale trials comparing SRI with farmers' rice-growing practices under a program set up in the Mekong Delta of Vietnam by German development cooperation (GIZ). There were >240 plots for each set of comparisons. Methane emissions on SRI fields were found to decline by 25% ($p=<0.01$), while nitrous oxide emissions decreased at the same time, by 1.4% (Dill et al., 2013). Although this latter decline was not significant in statistical terms, it was significant substantively that in this evaluation, with SRI management N_2O emissions did not increase, which would have been expected.

As seen from the various studies, GHG, methane and nitrous oxide emissions by controlled irrigation are highly variable, affected by experimental conditions, location, climate, and other factors. GWP reduction with SRI, AWD or other similar controlled irrigation has ranged from 29% (Xu et al., 2015) to 90% (Linquist et al., 2014). Data on GWP, methane and/or nitrous oxide emissions can be found also in Hou et al. (2016), FAO (2010), Uprety et al. (2012), Suryavanshi et al. (2012), Wang et al. (2007) and Liang et al. (2016). The wide range of variation indicates that while intermittent irrigation, rather than flooding, is the best option for reducing GHG emission, other factors such as use of ammonium-based nitrogen fertilizer, balanced fertilization, and proper cultivar selection need to be optimized along with irrigation methods for better emissions reduction (Malyan et al. 2016; Rajkishore et al. 2015).

Additional benefits from SRI and AWD other than GHG emission reduction, yield increase, and water saving can be the improvement of food and water quality. Elevated levels of arsenic (As) in rice grain has recently gained attention because of health risks, especially in Asian countries where rice is consumed as the main staple food (Banerjee et al., 2013). Linquist et al. (2014) and LaHue et al. (2016) have, respectively, reported that AWD, compared with conventional flooded-paddy cultivation, reduced arsenic concentration in rice grain by 64% and by 59-65%. Flooding of rice paddies is also an important source of water pollution, especially in conjunction with heavy application of inorganic fertilizer. Such water pollution called non-point source (NPS) or diffuse pollution, is said to contribute between 30 and 55% of total pollution of freshwater supplies in Korea. Choi et al. (2014) reported from a 3-year field experiment that SRI water management reduced NPS pollution in various respects: biochemical oxygen demand (BOD) by 44%, suspended solids (SS) by 43%, total nitrogen (TN) by 23%, and total phosphorus (TP) by 36%. They concluded that SRI water management could contribute to substantial improvement of the rural water quality in Korea's rivers and lakes.

The range of GHG reduction with SRI and AWD may still be too wide to have a satisfactory quantitative index for proposing and assessing overall GHG policy and practices. However, these studies give results that are consistent and great enough to endorse intermittent irrigation through SRI or AWD as a means for reducing GHG emissions from rice paddies while also securing other benefits.

5. Policy strategies for More Sustainable Rice Farming through SRI and AWD

Sustainable rice farming is now required to balance improving yield with minimizing adverse environmental impacts, such as GHG emission and water quality degradation. Some studies have recommended AWD water management as a practical option for sustainable rice production because it involves only a simple change in the mode of irrigation (Malyan et al. 2016; Minamikawa and Sakai, 2006; Fazli et al. 2013; Yang et al. 2012). Others such as Jain et al. (2013) have proposed that SRI be promoted because its methods beyond water control produce a greater number of benefits and its impact on GHG emissions could be a basis for farmers to earn carbon credits, thereby warranting government support policies. Wang et al. (2017) insist that the Indian government should take initiative for farmers to get credit for their reduced GHG emissions through controlled irrigation, offering them financial incentives, undertaking capacity building for spreading better practices, and instituting enabling policies at different levels. Without government support, accessing carbon credits and carbon markets for better rice farming is not possible, and the Indian government faces difficulties in meeting the GHG reduction target that it promised to the world. Siopongco et al. (2013) reported that if GHG reduction through AWD is recognized and corresponding carbon credits are established in carbon trading, there will be additional stimulus for wider adoption of AWD for both water saving and GHG reduction to cope with climate change. The same would apply for SRI with a number of other benefits (Thakur and Uphoff, 2017). Having additional benefits such as resilience to biotic and abiotic stresses or shorter cropping cycle or higher milling outturn will give farmers more intrinsic incentive to change to new crop management of intermittent irrigation methods of SRI, AWD or other controlled water schemes.

While SRI and AWD both use less water to irrigate paddy fields, they also require farmers to invest more time and effort in more frequent and precise irrigation than with conventional flooding. SRI or AWD are only possible where both the necessary water and labor are readily available, and where there are sufficient financial incentives to change familiar conventional practices. The amount of farmer effort required can be reduced by making investments in more structured and automated irrigation systems. As the value of water increases because of scarcity, such investments will become more and more economically justified. In general, the hardware and software for irrigation system management need to be improved for the adoption and maintenance of SRI or AWD, especially where labor is limited for any reason. If systems are equipped with automated flow-control devices, this can encourage for farmers to adopt these water-saving methods in both developed and developing countries.

Irrigation system construction is very costly because it involves structures for water storing and for conveying and distributing water with reliable water control devices (the hardware) as well as establishing or upgrading agencies for operation and maintenance, and often appropriate water-user organization (the software). Irrigation system construction is commonly planned as the part of more comprehensive rural development efforts. These need large government investments while their economic return are often not competitive with urban or industrial development, leading to government hesitancy to make such investments under the current paradigm of agriculture. The returns to such investment are very much a function of prevailing food prices and the value placed upon food security. Climate change which puts more pressure on food production and food supply will change economic calculations because of the primacy of meeting food supply requirements.

The agricultural sector is not only for food and fiber production; it needs to be assessed and appreciated also for its contribution to environmental services (Garbach et al., 2017), or conversely, for how more environmentally-friendly food production can reduce adverse impacts on our natural resources of soil, water and air. Such thinking about the agricultural sector to encompass its multi-functionality requires a paradigm shift among the public and policy-makers who are tasked with protecting the public's interests, based on a recognition of the interdependence between rural and urban areas, both served by the UN Sustainable Development Goals which aim to end poverty, protect the planet, and ensure prosperity.

Intermittent irrigation scheme such as SRI and AWD may not be sufficient to achieve these goals, but it can contribute to such achievement, consistent with a concept of agricultural activity and rural areas which appreciates their linkage to the welfare and sustainability of the nation and indeed the world, warranting investments from governments, industries, and donor agencies. Scientific data on SRI and AWD that show reductions in water consumption – in competition with industrial and domestic uses – and in GHG emissions – driving the climate change that affects whole nations and continents – should provide governments and international agencies with justification for making climate-smart investments to agricultural and rural development.

Industries which have to justify their own carbon emissions could gain carbon credits by supporting changes in the agricultural sector, also demonstrating their environment-friendliness to the public. And ODA institutions can show their effectiveness in contributing to climate-change mitigation as well as poverty reduction by making food production more environmentally-benign. A meta-analysis of published SRI evaluations across eight countries found that the methods reduced total per-hectare water consumption in rice production (rainfall plus irrigation) reduced by 22%, and irrigation water by 35%, while rice production was increased. Total water use efficiency (kg of rice produced per liter of water) was improved with SRI methods by 52%, and irrigation water use efficiency by 78% (Jagannath et al., 2013).

The 'clean development mechanism' (CDM) developed under the Kyoto Protocols, as discussed in IRRI Technical Bulletin No. 17 (Siopongco et al., 2013), could be a vehicle for encouraging and facilitating technical improvements in irrigated rice production, a sector which is currently one of the largest employers of land and labor worldwide. CDM is a project-based mechanism for carbon trading that can be applied in the agricultural sector, as reported in the IRRI bulletin on the results of a CDM demonstration project in the Philippines. This obtained very promising results and recommended the use of CDM as a channel for mobilizing private-sector investment in the expansion of AWD in exchange for certified emission reduction (CER) which benefits the industrial sector, although there are still some obstacles and challenges that need to be overcome. The demonstration project revealed that understanding of the CDM concept and collaboration among water managers, policy makers, farmers, and related stakeholders is very important for success.

Planning and implementation of CDM resource mobilization to support expansion of SRI and AWD whereby an industry can earn CER credit may not yet be simple under current legal and administrative systems. However, this mechanism could facilitate contributions from the agricultural sector to help industries and national governments to meet their respective objectives, micro and macro, of reducing GHG emissions while also reducing competition for scarce water supplies and enhancing income of farmers which creates purchasing power for industry and greater GNP and poverty reduction for countries. For this mechanism to be effective, however, there must be demonstration projects planned and implemented which can establish norms for CER estimation, with also improvements in legal and administrative support systems, education of and technology transfer to various stakeholders, and publicity and public relations to support the spread of SRI and AWD application. Since CDM implementation requires strict monitoring, evaluation and reporting for CER credits, it is essential that institutional arrangements be established for producing benchmarks and validating results. Institutions such as the International Rice Research Institute, the UN Food and Agriculture Organization, the International Commission on Irrigation and Drainage, the SRI-Rice Center at Cornell University, the International Program on Land and Water Management at Wageningen University, and interested donor agencies and foundations could collaborate to establish the necessary demonstration projects for giving impetus to utilize the environmentally-friendly methods of SRI and AWD more broadly, to contribute to climate change mitigation in addition to achieving higher food production and less water consumption.

6. Conclusions

Climate change partly due to GHG emission is increasingly affecting every aspect of livelihood in the world, and comprehensive endeavors of all sectors with available technologies to cope with it are required. Methane and nitrous oxide are important components of the gas emission, especially methane emission from paddy fields. Intermittent irrigation such as SRI and AWD is practically effective and a scientifically proven alternative that substantially reduce GHG emission. The two methods are practically the same with respect to water management in that they are based on intermittent irrigation. Intermittent irrigation make a paddy soil repeatedly flooded and dried, resulting in physical, chemical and micro-biological changes of the soil toward healthier and higher yield as well as methane reduction.

Among many factors reviewed, water management is mostly referred to be the most effective option for methane reduction, leading to lower GHG emission. However, nitrous oxide emission increase due to the change from anaerobic to aerobic soil was small enough not to offset the methane reduction. Although the intermittent irrigation substantially reduced methane emission, the range of reduction varied widely. It means that other factors such as use of ammonium fertilizer, balanced fertilization, proper cultivar and other relevant factors considering the site-specific weather and soil conditions need to be further investigated for better description and control of GHG emission reduction and higher earning of carbon credit. Additional benefits of arsenic content decrease in rice and water quality improvement strengthen the validity of SRI and AWD.

Adoption and expansion of SRI or AWD may require costly hydraulic infrastructures, active involvement of water management agencies and large government investment. But the lack of understanding on SRI and AWD in the realm of decision makers, field water engineers and managers as well as UN and international donor agencies hinders the spread of them. Public relations and education for the personnel as well as collaboration with them are asked for engineers and scientists in SRI and AWD world to actively collaborate with them. By collaborating with them, plans for CDM and/or ODA implementation together with the host government can be formulated and SRI and AWD can have better opportunities to contribute to both yield increase and climate change mitigation. SRI and AWD as a part of UN SDG actions, are strongly suggested to work together to aim to end poverty, protect the planet and ensure prosperity for all.

Acknowledgement

This study was supported by 2017 Research Grant from Kangwon National University (No. 52017 0214) and authors appreciate the generous support.

References

Ahn JH, Choi MY, Kim BY, Lee JS, Song JK, Kim GY, Weon HY., (2014), Effects of water-saving irrigation on emissions of greenhouse gases and prokaryotic communities in rice paddy soil. *Microb. Ecol.* 68; 271–283.

Agnihotri S, Kulshreshtha K, Singh SN., (1999), Mitigation strategy to contain methane emission from rice fields. Environ. *Monit. Assess.* 58; 95–105. http://dx.doi.org/10.1023/A:1006081317688.

Armstrong W., (1978), *Root aeration in the wetland condition. In: Hook DD. Crawford RMM, eds.* Plant Life in Anaerobic Conditions, 269-297.

Babu YJ, Nayak D, Adhya TK., (2006), Potassium application reduces methane emission from a flooded field planted to rice. *Biol. Fertil. Soils,* 42; 532–541. http://dx.doi.org/10.1007/s00374-005-0048-3.

Bender M, Conrad R., (1993), Kinetics of methane oxidation in oxic soils. *Chemosphere,* 26; 687–696. http://dx.doi.org/10.1016/0045–6535(93)90453-C.

Borken W, Beese F., (2006), Methane and nitrous oxide fluxes of soils in pure and mixed stands of European beech and Norway spruce. *Eur. J. Soil Sci.,* 57; 617–625. http://dx.doi.org/10.1111/j.1365-2389.2005.00752.x.

Bronson KF, Neue HU, Singh U., (1997), Automated chamber measurement of CH_4 and N_2O flux in a flooded rice soil. I. Effect of organic amendments, nitrogen source, and water management. *Soil Sci. Soc. Am.,* 61; 981-987.

Bouman BAM, Lampayan RM, Tuong TP., (2007), *Water Management in Irrigated Rice: Coping with Water Scarcity.* International Rice Research Institute, Los Baños, Philippines.

Chen H, Wu N, Wang Y, Peng C., (2015), *Methane is an important greenhouse gas: Methane emissions from unique wetlands in China: Case studies,* Meta Analyses and Modelling. Higher Education Press, and Walter de Gruyter GmbH, Berlin/Boston.

Choi J, Kim G, Park W, Shin M, Choi Y, Lee S, Kim S, Yan D. 2014. Effect of SRI water management on water quality and greenhouse gas emission in Korea. *Irrig. Drainage,* 63;263-270.

Choi J, Kim GY., (2016), *SRI Water Management on NPS Pollution and GHG Emission. Presented at Side Event 17 (Appropriate Practices for Rice Cultivation),* 2nd World Irrigation Forum, ICID, Nov. 2016, Chiang Mai, Thailand.

Chu G, Wang Z., Zhang H., Liu L., Yang J., Zhang J., (2015), Alternate wetting and moderate drying increases rice yield and reduces methane emission in paddy field with wheat straw residue incorporation, *Food Energy Secur.,* 4; 238-254. https://doi.org/10.1002/fes3.66

Cicerone RJ, Setter JD, Delwiche CC., (1983), Seasonal variation of methane flux from a California rice paddy. *J. Geophys. Res.,* 88; 11022–11024. http://dx.doi.org/10.1029/JC088iC15p11022.

Das K, Baruah KK., (2008), Methane emission associated with anatomical and morphophysiological characteristics of rice (Oryza sativa) plant. *Physiol. Plant,* 134; 303–312. http://dx.doi.org/10.1111/j.1399-3054.2008.01137.x.

Dill J, Deichert G, Le TNT, eds., (2013), *Promoting the System of Rice Intensification: Lessons Learned from Trà Vinh Province, Vietnam.* German Agency for International Cooperation (GIZ) and International Fund for Agricultural Development, Hanoi.

Doni F, Radziah C, Zain CM, Isahak A, Fathurrahman F, Sulaiman N, Uphoff N, Yusoff WMW., (2016), Relationships observed between Trichoderma inoculation and characteristics of rice grown under System of Rice Intensification (SRI) vs. conventional methods of cultivation. *Symbiosis,* 72; 45-59.

Dubey SK., (2005), Microbial ecology of methane emission in rice agroecosystem: A review. *Appl. Ecol. Environ. Res.,* 3(2); 1-27.

FAO, (2010), *Climate-smart Agriculture Policies: Practices and Financing for Food Security, Adaptation and Mitigation.* Food and Agriculture Organization, Rome, Italy.

Fazli P, Hasfalina CM, Azwan M, Azni I, Shah UKM, Aimrun W., (2013), Effect of cultivation system on the methane emission from rice soil. *Intl. J. Engineer. Technol.,* 10(2); 73-81.

Garbach K, Milder JC, DeClerck FAJ, de Wit MM, Driscoll L, Gemmill-Herren B., (2017), Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification, *Intl. J. Agric. Sust.,* 15; 11-28.

Gathorne-Hardy A, Reddy D, Venkatanarayana M, Harriss-White B., (2013), A life-cycle assessment (LCA) of greenhouse gas emission from SRI and flooded rice production in SE India. *Taiwan Water Conserv.,* 61; 110-125.

Gathorne-Hardy A, Reddy D, Venkatanarayana M, Harriss-White B. (2016), System of Rice Intensification provides environmental and economic gains but at the expense of social sustainability — A multidisciplinary analysis in India. *Agric. Syst.,* 143; 159-168.

Granli T, Bockman OC., (1994), Nitrous oxide from agriculture. *Nor. J. Agri. Sci.,* 12; 7-127.

Green SM., (2013), Ebullition of methane from rice paddies: the importance of furthering understanding. *Plant Soil,* 370; 31-34. http://dx.doi.org/10.1007/s11104-013-1790-1.

GVN., (2015), *Intended Nationally-Determined Contributions of Vietnam,* Government of Vietnam.

Hattori C, Ueki A, Seto T, Ueki K., (2001), Seasonal variations in temperature dependence of methane production in paddy soil. *Microbes Environ.,* 16; 227-233. http://dx.doi.org/10.1264/jsme2.2001.227.

Henkel T, Conrad R., (1998), Characterization of microbial NO production, N_2O production and CH_4 oxidation initiated by aeration of anoxic rice field soil. *Biogeochem.,* 40; 17-36.

Holzapfel-Pschorn A, Conrad R, Seiler W., (1986), Effects of vegetation on the emission of methane from submerged paddy soil. *Plant Soil,* 92; 223-233. http://dx.doi.org/10.1007/BF02372636.

Holzapfel-Pschorn A, Seiler W., (1986), Methane emission during a cultivation period from an Italian rice paddy. *J. Geophys. Res.,* 91; 11803-11814. http://dx.doi.org/10.1029/JD091iD11p11803.

Hou H, Yang S, Wang F, Li D, Xu J., (2016), Controlled irrigation mitigates the annual integrative global warming potential of methane and nitrous oxide from the rice-winter wheat rotation systems in Southeast China. *Ecol. Engineer,* 86; 239-246.

Howell, KR, Shrestha P, Dodd IC., (2015), Alternate wetting and drying irrigation maintained rice yields despite half the irrigation volume, but is currently unlikely to be adopted by smallholding lowland rice farmers in Nepal. *Food Energy Security,* 4; 144-157. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4998133/

Inubushi K, Muramatsu Y, Umebayashi M., (1992), Influence of percolation on methane emission from flooded paddy soil. *Jpn. J. Soil Sci. Plant Nutr.,* 63; 184-189.

IPCC, (1996), *Guidelines for National Greenhouse Gas Inventories.* Cambridge University Press, Cambridge.

IPCC, (2006), *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, edited by Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, published for the Intergovernmental Program on Climate Change by the Institute for Global Environmental Strategies, Tokyo, Japan.

Jagannath P, Pullabhotla H, Uphoff N., (2013), Meta-analysis evaluating water use, water saving, and water productivity in irrigated production of rice with SRI vs. standard management methods. *Taiwan Water Conserv.* 61; 14-49.

Jain N, Dubey R, Dubey DS, Singh J, Khanna M, Pathak H, Bhatia A., (2013), Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic plains. *Paddy Water Environ.,* 12; 355-363.

Jensen CR, Stolzy LH, Letey J., (1967), Tracer studies of oxygen diffusion through roots of barley, corn, and rice. *Soil Sci.,* 103; 23-29. http://dx.doi.org/10.1097/00010694-196701000-00005.

Kar S, Varade SB, Subramanyam TK, Ghildyal BP., (1974), Nature and growth pattern of rice root system under submerged and unsaturated conditions. *Il Riso (Italy),* 23; 173-179.

Keith A. Smith (2005) The impact of agriculture and other land uses on emissions of methane and nitrous and nitric oxides, Environmental Sciences, 2:2-3, 101-108, DOI:10.1080/15693430500370423

LaHue GT, Chaney RL, Adviento-Borbe MA, Bruce A, Linquist BA., (2016), Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. *Agric. Ecosyst.*

Environ.., 229; 30–39.

Lampayan RM, Palis FG, Flor RB, Bouman BAM, Quicho ED, de Dios JL, Espiritu A, Sibayan EB, Vicmudo VR, Lactaoen AT, Soriano JB., (2009), *Adoption and dissemination of 'safe alternate wetting and drying' in pump irrigated rice areas in the Philippines.* In: Proceedings of the 60th International Executive Council Meeting and 5th Asian Regional Conference.

Le Mer J, Roger P., (2001), *Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil Biol.,* 37; 25–50. http://dx.doi.org/10.1016/S1164-5563(01)01067-6.

Lee CH, Park KD, Jung KY, Ali MA, Lee D, Gutierrez J, Kim PJ., (2010), Effect of Chinese milk vetch (Astragalus sinicus L.) as a green manure on rice productivity and methane emission in paddy soil. *Agric. Ecosyst. Environ.* 138; 343–347. https://doi.org/10.1016/j.agee.2010.05.011.

Leip A, Bocci S., (2007), *Contributions of rice production to greenhouse gas emissions in Europe.* Proceedings of the 4th Intl. Temperate Rice Conference 2007.

Li X, Ma J, Yao Y, Liang S, Zhang G, Xu H, Yagi K., (2014), Methane and nitrous oxide emissions from irrigated lowland rice paddies after wheat straw application and midseason aeration. *Nutr. Cycl. Agroecosyst.,* 100; 65–76.

Liang K, Zhong X, Huang N, Lampayan RM, Pan J, Tian K, Liu Y., (2016), Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. *Agric. Water Manage,* 163; 319–331.

Lin, XQ, Zhu DF, Lin XJ., (2011), Effects of water management and organic fertilization with SRI crop practices on hybrid rice performance and rhizosphere dynamics. *Paddy Water Envir.,* 9; 33-39.

Linquist BA, Anders M, Adviento-Borbe MA, Chaney RL, Nalley LL, da Rosa EFF, van Kessel C., (2014), Reducing greenhouse gas emissions, water use and grain arsenic levels in rice systems. *Global Change Biol.,* doi:10.1111/gcb.12701.

Malyan SK, Bhatia A, Kumar A, Gupta DK, Singh R, Kumar SS, Tomer R, Kumar O, Jain N., (2016), Methane production, oxidation and mitigation: A mechanistic understanding and comprehensive evaluation of influencing factors. *Science Total Environ.,* 572; 874–896.

Minamikawa K, Sakai N., (2006), The practical use of water management based on soil redox potential for decreasing methane emissions from a paddy field in Japan. *Agric. Ecosyst. Environ.,* 116; 181–188. https://doi.org/10.1016/j.agee.2006.02.006.

Min H, Chen ZY, Wu WX, Chen MC., (2002), Microbial aerobic oxidation of methane in paddy soil. *Nutr. Cycl. Agroecosyst.* 64; 79–85. http://dx.doi.org/10.1023/A:1021127621257.

Mohanty SR, Bodelier PLE.,Conrad R., (2007), Effect of temperature on composition of the methanotrophic community in rice field and forest soil. *FEMS Microbiol. Ecol.,* 62; 24–31.

Neue H., (1993), Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming. *Bio. Sci.,* 43(7); 466–473.

Neue HU, Scharpenseel HW., (1984), *Gaseous products of the decomposition of organic matter in submerged soils. In: Organic Matter and Rice,* International Rice Research Institute, 311–328.

Neue HA, Roger PA., (1994), *Potential of methane emission in major rice ecologies.* Climate Biosphere Interactions: Biogenic Emissions and Environmental Effect of Climate Change. Wiley, New York.

Nouchi I. Mariko S. Aoki K., (1990), Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. *Plant Physiol.,* 94; 59–66.

Nozhevnikova AN, Nekrasova V, Ammann A, Zehnder AJ, Wehrli B. Holliger C., (2007), Influence of temperature and high acetate concentrations on methanogenesis in lake sediment slurries. *FEMS Microbiol. Ecol.,* 62; 336–354. http://dx.doi.org/10.1111/j.1574-6941.2007.00389.x.

Pandey A, Mai VT, Vu DQ, Bui TPL, Mai TLA, Jensen LS, Neergaard A., (2014), Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agric. Ecosyst. Environ.,* 196; 137–146. http://dx.doi.org/10.1016/j.agee.2014.06.010.

Rajkishore SK, Doraisamy P, Subramanian KS, Maheshwari M., (2013), Methane emission patterns and their associated soil microflora with SRI and converntional systems of rice cultivation in Tamil Nadu, India. *Taiwan Water Conserv.,* 61; 126-134.

Rajkishore SK, Vignesh NS, Doraisamy P, Maheshwari M., (2015), *Methane emission from rice ecosystems: 100 years of research. Ecoscan,* 9 (1&2); 183-195.

Rejesus, RM, Palis F, Rodriguez DG, Lampayan RM, Bouman BAM., (2011), Impact of the alternate wetting and drying (AWD) water-saving irrigation technology: Evidence from the Philippines. *Food Policy,* 36; 280-288.

Richard M, Sander BO., (2014), *Alternate Wetting and Drying in Irrigated Rice.* Practice Brief on CSA. Global Alliance for Climate-Smart Agriculture, FAO, Rome.

Sass RL, Fisher FM, Harcombe PA, Turner FT., (1990), Methane production and emission in a Texas rice field. *Global Biogeochem. Cycles,* 4; 47–68. http://dx.doi.org/10.1029/GB004i001p00047.

Schütz H, Seiler W. Conrad R., (1989), Processes involved in formation and emission of methane in rice paddies.

Biogeochem., 7; 33－53. http://dx.doi.org/10.1007/BF00000896.

Seiler W, Holzapfel-Pschorn A, Conrad R, Scharffe D. (1984), Methane emission from rice paddies. *J. Atmos. Chem.,* 1; 241－268. http://dx.doi.org/10.1007/BF00058731.

Setyanto P, Rosenani AB, Boer R, Fauziah CI, Khanif MJ., (2004), The effect of rice cultivars on methane emission from irrigated rice field. *Indones. J. Agric.,* 5(1); 20－31.

Setiawan BI, Irmansyah A, Arif C, Watanabe T, Mizoguchi M, Kato H., (2013), Effects of groundwater level on CH_4 and N_2O emissions under SRI paddy management in Indonesia. *Taiwan Water Conserv.,* 61(4); 135-146.

Setiawan BI, Irmansyah A, Arif C, Watanabe T, Mizoguchi M, Kato H., (2014), SRI paddy growth and GHG emissions at various groundwater levels. *Irrig. Drainage,* 63; 612-640.

Siopongco JDLC, Wassmann R, Sander BO., (2013), *Alternate wetting and drying in Philippine rice production: Feasibility study for a clean development mechanism.* IRRI Technical Bulletin No.17.

Strack M, Waddington JM., (2008), Spatio-temporal variability in peatland subsurface methane dynamics. *J. Geophys. Res.,* 113; 1－12. http://dx.doi.org/10.1029/2007JG000472.

Styger E, Uphoff N., (2016), *System of Rice Intensification－Revisiting Agronomy for a Changing Climate.* Practice Brief on CSA. Global Alliance for Climate-Smart Agriculture.

Suryavanshi P, Singh YV, Prasanna R, Bhatia A, Shivay Y.S., (2012), Pattern of methane emission and water productivity under different methods of rice crop establishment. *Paddy Water Environ.,* 11; 321-329.

Takai Y, Koyama T, Kamura T., (1956), Microbial metabolism in reduction process of paddy soils (Part 1). *Soil Sci. Plant Nutr.,* 2; 63－66. http://dx.doi.org/10.1080/00380768.1956.10431859.

Thakur AK, Uphoff N, Antony E., (2010), *An assessment of physiological effects of System of Rice Intensification (SRI) practices compared with recommended rice cultivation practices in India. Exper Agric.,* 46; 77-98.

Thakur AK, Uphoff N., (2017), How the System of Rice Intensification can contribute to climate-smart agriculture. *Agron. J.,* 109; 1163-1182.

Tokida T, Miyazaki T, Mizoguchi M., (2005), Ebullition of methane from peat with falling atmospheric pressure. *Geophys. Res. Lett.,* 32; L13823. http://dx.doi.org/10.1029/2005/GL022949.

Tokida, T., Fumoto, T., Cheng, W., Matsunami, T., Adachi, M., Katayanagi, N., Matsushima, M., Okawara, Y., Nakamura, H., Okada, M., Sameshima, R., and Hasegawa, T.. (2010), Effects of free-air CO2 enrichment (FACE) and soil warming on CH_4 emission from a rice paddy field: impact assessment and stoichiometric evaluation. *Biogeosciences,* 7; 2639-2653. https://doi.org/10.5194/bg-7-2639-2010.

Uphoff N., (2017), *Developments in the System of Rice Intensification (SRI). In: T. Sasaki, ed., Achieving Sustainable Cultivation of Rice,* 2.

Uprety DC, Dhar S, Hongmin D, Kimball BA, Garg A, Upadhyay J., (2012), *Technologies for Climate Change Mitigation: Agriculture Sector,* Department of Management Engineering, Technical University of Denmark.

Wagner D, Pfeiffer EM, Bock E., (1999), Methane production in aerated marshland and model soils: effects of microflora and soil texture. *Soil Biol. Biochem.,* 31; 999－1006. http://dx.doi.org/10.1016/S0038-0717(99)00011-5.

Wang SW, Lee WK, Son Y., (2017), Low carbon development pathways in Indian agriculture, Change Adapt. *Socioecol. Syst.,* 3; 18－26.

Wang ZP, Lindau CW, Delaune RD, Patrick Jr. WH., (1993) Methane emission and entrapment in flooded rice soils as affected by soil properties. *Biol. Fertil. Soils,* 16; 163－168. http://dx.doi.org/10.1007/BF00361401.

Wang Y, Zhu B, Hu C, Wang Y, Ma X., (2007), Methane emission from the system of rice intensification (SRI) in paddy field. *Ecol. Environ.,* 16(4); 1271-1276. [Chinese Literature]

Wang Y. Zhu B. Wang Y. Gao M. Ma X., (2006), N_2O emission from paddy field under different rice planting modes. *Wuhan Univ. J. Natural Sci.,* 11(4); 989-996.

Watanabe A, Kimura M, Kasuya M, Kotake M, Katoh T., (1994), Methane in groundwater used for Japanese agriculture: its relationship to other physico-chemical properties and possible tropospheric source strength, *Geophys. Res. Lett.,* 21; 41－44. http://dx.doi.org/10.1029/93GL03325.

Williams EJ, Hutchinson GL, Fehsenfeld FC., (1992), NO_x and N_2O emission from soil. *Global Biogeochem,* 6(4); 351-388.

Xu Y, Ge J, Tian S, Li S, Nguy-Robertson AL, Zhan M, Cao C., (2015), Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Science Total Environ,* 505; 1043－1052.

Yagi K, Minami K, Ogawa Y., (1998), Effects of water percolation on methane emission from paddy fields. *Plant Soil,* 198; 193－200. http://dx.doi.org/10.1023/A:1004379914540.

Yagi K, Minami K., (1990), Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Sci. Plant Nutr.,* 36; 599－610. http://dx.doi.org/10.1080/00380768.1990.10416797.

Yagi K, Tsuruta H, Minami K., (1997), Possible options for mitigating methane emission from rice cultivation. *Nutr. Cycl. Agroecosyst.,* 49, 213－220. http://dx.doi.org/10.

1023/A:1009743909716.

Yang B, Chen Z, Zhang M, Zhang H, Zhang X, Pan G, Zou J, Xiong Z., (2015), Effect of elevated atmospheric CO_2 concentration and temperature on the soil profile methane distribution and diffusion in rice–wheat rotation system. *J. Environ. Sci.,* 32; 62–71. http://dx.doi.org/10.1016/j.jes.2014.11.010.

Yang SH, Peng SH, Xu JZ, Luo YF, Li DX., (2012) Methane and nitrous oxide emissions from paddy field as affected by water–saving irrigation. *Physics Chemistry Earth,* 53–54; 30–37. doi:10.1016/j.pce.2011.08.020.

Yao Z. Zheng X. Wang R. Xie B. Butterbach–Bahl K. Zhu J., (2013), Nitrous oxide and methane fluxes from a rice–wheat crop rotation under wheat residue incorporation and no–tillage practices. *Atmos. Environ,* 79; 641–649. https://doi.org/10.1016/j.atmosenv.2013.07.006.

Zhang A. Cui L. Pan G. Li L. Hussain Q. Zhang X. Zheng J. Crowely D., (2010), Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain. *China Agric. Ecosyst. Environ,* 139; 469–475.