cirad
LA RECHERCHE AGRONOMIQUE
POUR LE DÉVELOPPEMENT

AFD

Climate smart rice cropping systems in Vietnam

State of knowledge and prospects

Acknowledgements

The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of CIRAD or AFD. Responsibility for the information and views expressed in the report therefore lies entirely with the authors.

Authors

Florent Tivet, Stéphane Boulakia CIRAD Research Unit AIDA

Agroecology and Sustainable Intensification of Annual Crop

Citation

Tivet, F., Boulakia, S. 2017. *Climate Smart Rice Cropping systems in Vietnam. State of knowledge and prospects.* Montpellier, France: CIRAD, 41 p.

Contenu

Climate smart rice cropping systems in Vietnam

Rice is the primary food crop covering 165 million ha that is more than one tenth of the worldwide-cultivated area. Rice small-scale farming, representing 200 million households, in South-East Asia represents 144 million ha on less than 1ha farms.

In Vietnam, increases in rice production are the overlapping effect of the Green Revolution as well as political and economic reforms (Doi Moi) put in place from 1986 onward. It is undeniable that intensive rice farming, which relied heavily on irrigation, has provided huge productivity gains under conditions of intensive resource use and a controlled, predictable environment. Hydraulic controls, regulating floods and preventing saline intrusion, have indeed boosted production in the Mekong Delta and others basins of production. This has partly been through land reclamation but mostly by enabling double or triple cropping in a single year. However, rice production is increasingly constrained by water scarcity and climatic events (i.e., floods, drought, and sea level rise in the deltas). High dependency on energy, technologies, engineered landscapes, and infrastructures have also increased the fragility of the rice farming system, which can be seriously threatened if any elements of its production cycle are disrupted.

In addition, climate change has become an important issue. Agriculture is one of the principal sources of greenhouse gas (GHG) emissions globally (IPCC, 2013). Flooding of irrigated rice fields produces anaerobic soil conditions which are conducive to the production of methane (CH_4). The annual CH_4 emission from rice paddies has been estimated to be 36 Tg year^{-1}, contributing approximately 18% of the total anthropogenic CH_4 emission to the atmosphere. In Vietnam, rice cultivation accounts for one third of the total GHG emissions.

Rice farming is facing a dual challenge of delivering sufficient and nutritious food to meet the projected demands of population growth and markets, and overcoming issues such as climate change, soil fertility depletion and water scarcity through sustainable agricultural intensification. Soil fertility depletion, loss of biodiversity, water scarcity and sea level rise in vulnerable deltas are major constraints.

Vietnam is the 4th rice producer with 40 million tons of paddy and ranks as the 2nd largest global exporter, selling ~ 8 million tons of milled rice (2014). Even if new exporters like Cambodia and Myanmar arise, if several importing countries in Africa have initiated support policy to reduce their food dependency, maintaining the Vietnamese exports capacity to address growing demands from China and developing countries in Middle East and Africa is of utmost importance to prevent global market crisis and its strike on Poor like in 2008.

In Vietnam, population increase and intensification of economic development are leading to the changes in rice cropping patterns and management intensity (i.e., multicropping, water management, fertilizer nature and use, and cultivars). Throughout the year, changes in the rice cropping patterns are driven by the availability of water supply and crop management practices, leading to a variety of land cover patterns across the regions. The diversity of rice cultivation, soil, water management, inorganic fertilizers uses have a different contribution to GHG emissions. Different forms of water saving techniques as alternate wetting and drying (AWD) and midseason drainage (MSD) have been developed, assessed and disseminated to reduce CH_4 emissions in several countries including Vietnam. Irrigated rice is not only the largest source of CH_4, it represents also one of the most promising targets for mitigating CH_4 emissions and reducing the net GHG emissions from the use of agricultural inputs and by sequestering atmospheric CO_2 into soil organic C.

Alternative management techniques are therefore needed to reduce the environmental burden associated with rice cultivation without jeopardizing rice production, commoditization and global food security. There is a need to bring together a large range of stakeholders with:

- policy-makers to deal with changes linked to multiple drivers such as socio-economic evolutions (i.e., urbanization, population growth, new trade-offs around water resource) and environmental changes (i.e., climate change, its immediate impact on weather variability, medium and long term impacts on average temperature and sea level rise),
- civil engineers to design new forms of infrastructures facilitating sediment deposition recognized as a potential adaptation strategy and incorporated recently into the management plans of the Mekong delta (MDP, 2013),
- farmer's organizations and agronomists to design alternative and innovative diversified rice farming systems **to first adapt** these systems to environmental attributes that are becoming unstable and changing at an accelerating rate.

Agricultural policies need to account for the needs of both mitigation and adaptation. Investing substantially in adapting rice farming to climate change can result in substantial mitigation co-benefits (i.e., CH_4 reduction, soil organic C accumulation, improving nutrients cycling, water and nutrient-use efficiency, and improved straw management).

Rice cropping systems should be driven by organic carbon and water management strategies embedding a high functional diversity (crops, relay/cover crops, and soil biota), to build soil resilience, to advance in rice farming sustainability, and capacity to deal with risks at farms and irrigation schemes/water management units levels.

The aim of this paper is to introduce adaptation measures that have the potential, in the multiple Vietnamese rice agro-ecosystems, with specific emphasis on Mekong River Delta, to assist in designing a new generation of rice farming systems with strengthened resilience and adaptation capacity in front of climate change, enhancing natural capital and ecosystem services.

Context

Doi Moi and the green revolution

Vietnam is the 4th rice producer and ranks as the 2nd largest global exporter, selling ~ 8 million tons of milled rice (2014), that is one fifth of the globally trade volume ($4 billion in rice exports). Rice production has jumped from 16 million tons in 1986 to ~ 40 million tons nowadays. The Mekong Delta has generated the largest share of that increase, delivering 57% of the national production gain between 1995 and 2008.

The reason behind this growth is the overlapping effect of the Green Revolution (i.e., high yielding rice varieties, irrigation, pesticides, and fertilizers) since the 1970s as well as political and economic reforms (Doi Moi) put in place from 1986 onward to facilitate the transition from a centralized economy to a socialist-oriented market economy (Fortier and Tran Thi Thu Trang, 2013). Doi Moi abolished agricultural cooperatives, allocated communal land to individual farm households, promoted free-market incentives and foreign investments, removed price controls on agricultural goods and enabled farmers to sell their goods in the open market.

Hydraulic controls, regulating floods and preventing saline intrusion, have drastically increased production in the Mekong Delta and others basins of production. This has partly been through land reclamation but mostly by enabling double or triple cropping (Mekong delta) in a single year. Productivity gains were also obtained through the the adoption of high-yielding cultivars across the country, rising to about 90% by 2000 (Tran Thi Ut and Kajisa, 2006) and through the increasing use of inorganic fertilizers and pesticides (Pingali et al., 1997; Van Toan et al., 2013).

With time, the focus of Doi Moi changed to industrialization. As a consequence of this new policy orientation, many productive rice areas were converted to industrial and urban land uses leading to a decrease in rice cultivated areas and to a higher level of intensification of rice production.

Trading and rice policies

Present rice policies in Vietnam are a balance between maintaining domestic food security and promoting rice exports. Government intervention is limited in the domestic market and a majority of rice exports in the country are made through state-owned trading enterprises (50% share), particularly by the Vietnam Food Association (VFA). VFA buys rice from farmers to keep the price stable and also to prevent rice importers from haggling prices down too low during the harvest seasons. Vietnamese rice strains tend to be more diversified than in the past notably with the development of more lucrative type like fragrant and glutinous rice but remain of low or middling quality, in comparison with the premium varieties (Hom Mali) grown in Thailand. In addition, Myanmar is emerging again as an export rival. The bulk of Vietnam's crop is sold directly to other governments, but some of its biggest clients, including Indonesia and the Philippines, are boosting domestic production.

Rice and poverty reduction

Hoang et al. (2016) emphasized that rice production and rice productivity did not contribute significantly to poverty alleviation. They also observed that increases in rice prices did not contribute to poverty reduction, even for the two regions with the largest rice production, the Mekong River Delta and the Red River Delta. More generally, their analysis suggests that:

- Households who were unable to benefit from Vietnam's economic reforms in the 1990s and remained poor in that period were likely to belong to the group of the most destitute households. Consequently, it seems that rice price rises did not help these households with moving out of the poverty trap they had fallen into even in the following decade.
- The majority of these extreme poor households owned only small fields, so they were unable to experience the positive income effect of rice price increases as they were mainly rice consumers.

- Finally, geographic barriers (between delta and northern mountainous areas) played an adverse role for the higher rice prices to reach the extreme poor.

As a current trend in the region, diversification out of agricultural production is likely to assist with poverty alleviation.

Main rice-growing regions

The Red River delta and the Mekong Delta are the two main rice producers in Vietnam with 2 to 3 rice cycles (Mekong Delta) and diversification in the fall/winter after summer season rice (Red River Delta). High and short yielding varieties are widely used with mineral fertilizers and pesticides. The other major rice-growing regions are the northeast, and the north-central coast.

In the Mekong Delta, the study conducted by Nguyen et al. (2012) emphasizes the diversity of rice cropping patterns throughout the year (Figure 1), driven by the availability of water supply, crop management practices, flood occurrence in Summer-Autumn and saline intrusion influence in Winter-Spring leading to a variety of land cover patterns across the region. The diversity and changes in rice cropping patterns and impacts of urbanization on rice intensification have a strong influence on GHG emissions.

The Mekong River Delta (MRD) has played a central role in sustaining Vietnam's high level of rice production. The delta (~ 4.0 Mha of rice production) produces more than 60% of the national rice production and represents approximately 90% of annual rice exports. Although the Mekong Delta is naturally affected by saline intrusion due to tidal influences, sea level rise (SLR) is likely to increase the salinity problem in the future particularly when combined with other factors such as high groundwater extraction rates, changes in river discharge rates and timing due to climate change or upstream and transboundary dam operations on river's catchments.

The Mekong Delta faces both challenges: high population density and the need to sustain it by intensifying agriculture. Additionally, national food security considerations and export aspirations contribute to the pressure on the Mekong Delta's agricultural production. Several studies also warn that the Mekong delta is showing signs of environmental stress. The earth dykes that were built to keep seasonal floods from inundating the rice paddies prevent the Mekong River's alluvial floodwaters from bringing nutrients to the delta's soil.

Yet, regardless of such achievements, the country's capacity to keep food production growing at par with demand appears uncertain due to (i) the steady decline in cropping areas, particularly paddy fields, observed over the past decade, and (ii) the soaring impacts of climate change due to the low resilience habit of irrigated rice farming. The adverse weather conditions in the last years have also contributed to emphasize the sensitivity of rice farming to climate variability and climate changes.

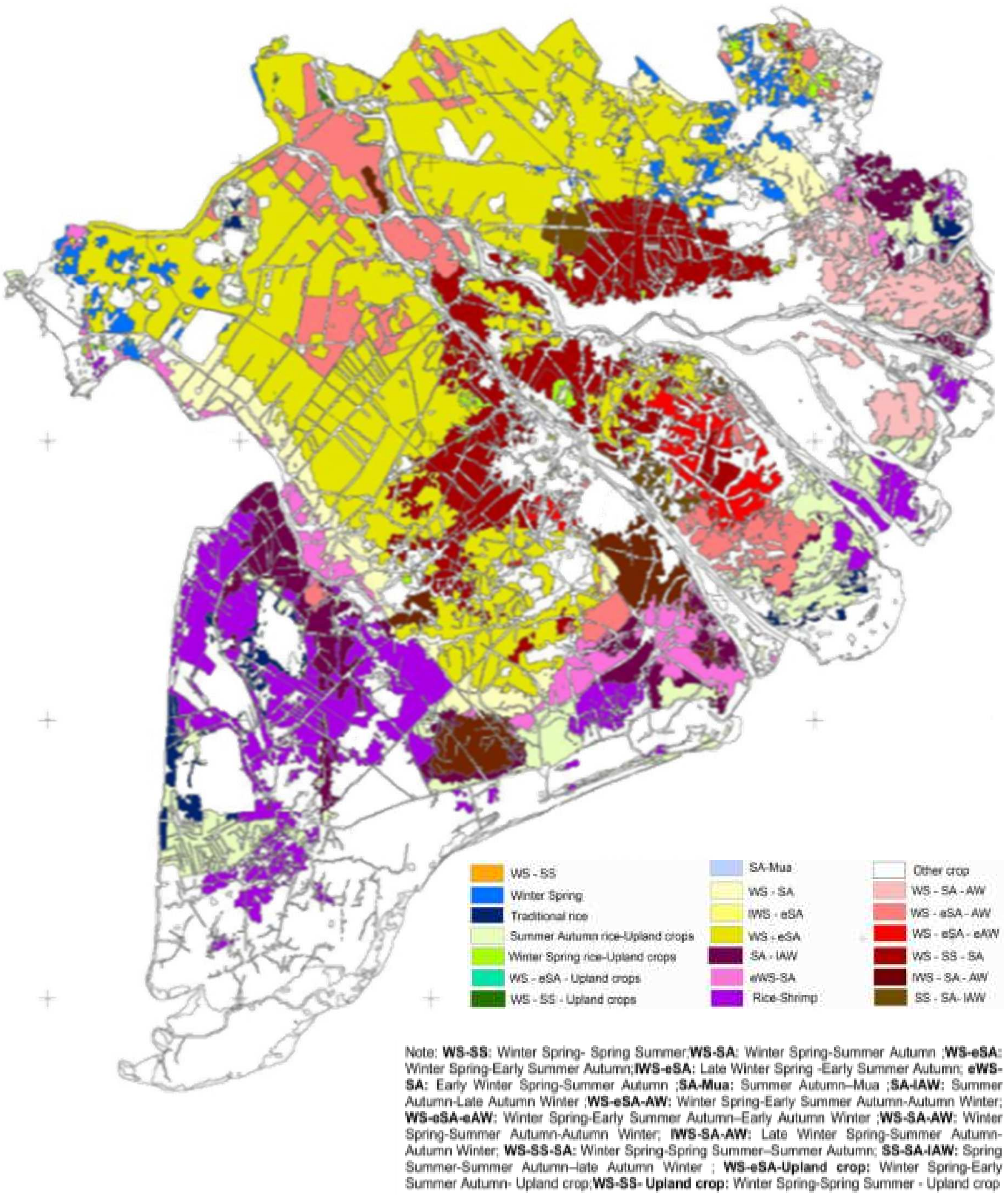

Figure 1: Map of Rice cropping pattern in the Mekong Delta in 2008 (From Land resource department in Ngo and Wassmann, 2016).

Contribution of agriculture and rice farming to the emission of greenhouse gazes

Agriculture and the global GHG emissions

Global warming potential (GWP)
$CO_2 = 1$
$CH_4 = 25$
$N_2O = 298$

Annual GHG emissions from agricultural production in 2000 – 2010 were estimated at 5.0 – 5.8 Gt CO_2eq/yr, representing 10-12% of total global anthropogenic emissions of greenhouse gases. GHG emissions from agriculture are predominately due to nitrous oxide (N_2O) emissions from N fertilization and methane (CH_4) emissions from livestock and rice cultivation. Of the total anthropogenic emissions, CH_4 and N_2O have a large global warming potential (GWP) that is 25 and 298 times, respectively, greater than CO_2 over a 100-year period.

Agriculture: 10 to 12% of total global anthropogenic emissions of greenhouse gases 5.0 – 5.8 Gt CO_2eq/yr

Agriculture accounts for:
50% of CH_4
60% of N_2O

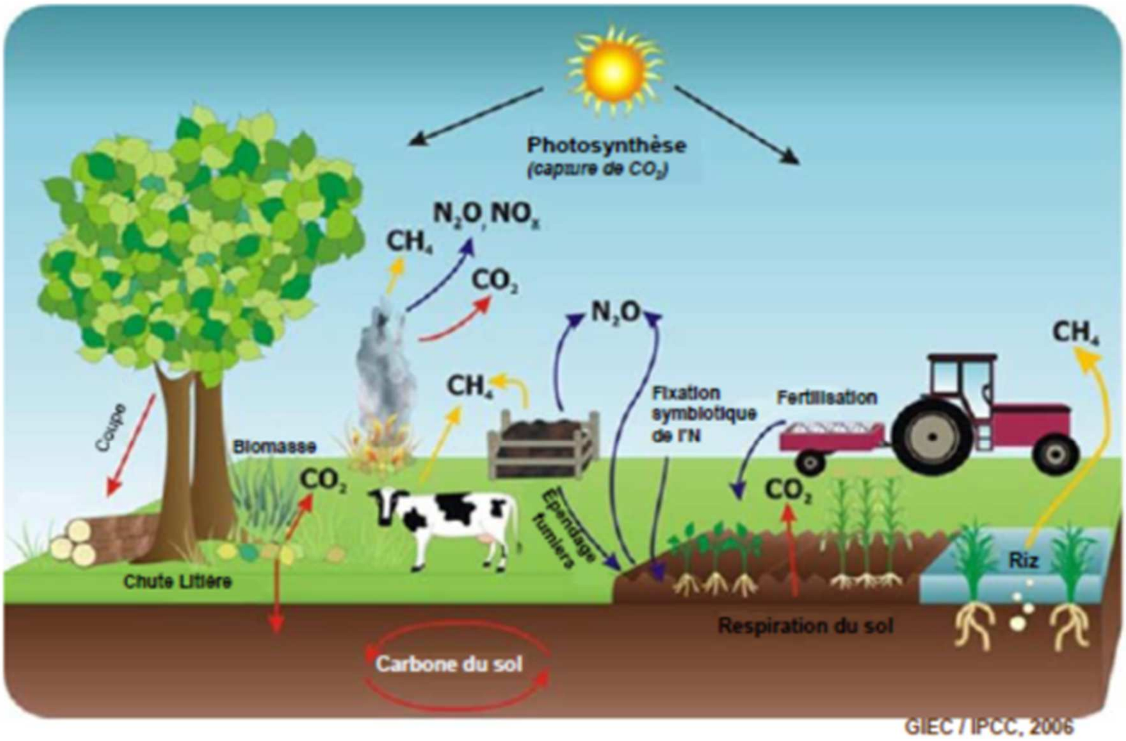

Figure 2: Agriculture and emission of greenhouse house gases (from Chapuis-Lardy, 2016 and IPCC 2006).

Of global anthropogenic emissions, agriculture accounts for about 60% of N_2O and about 50% of CH_4 (IPCC, 2013).

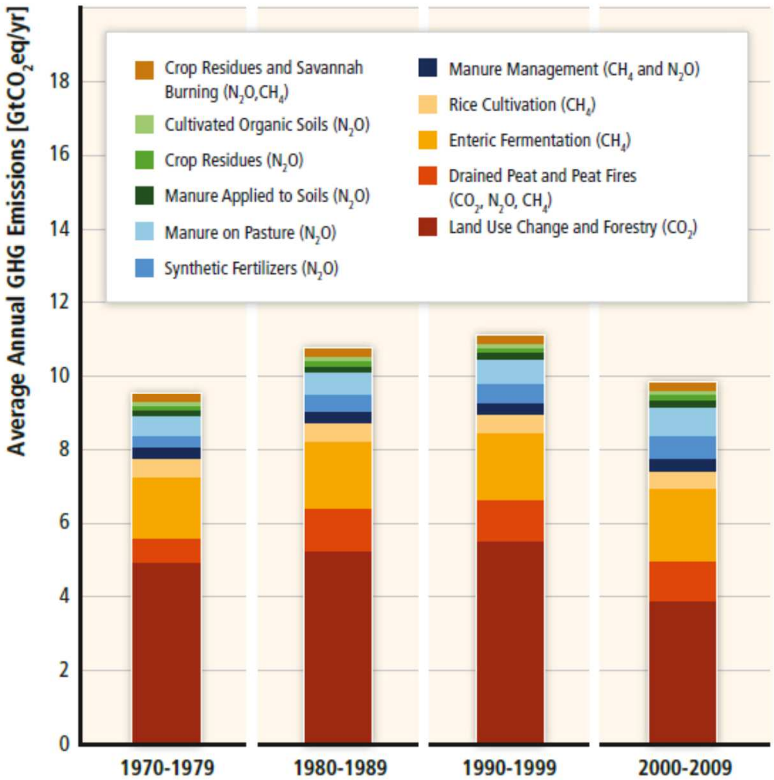

Figure 3: Top: Agriculture, Forestry, and Other Land Use (AFOLU) emissions for the last four decades. For the agricultural sub-sectors emissions are shown for separate categories, based on FAOSTAT, (2013). Emissions from crop residues, manure applied to soils, manure left on pasture, cultivated organic soils, and synthetic fertilizers are typically aggregated to the category 'agricultural soils' for IPCC reporting. For the Forestry and Other Land Use (FOLU) sub-sector data are from the Houghton bookkeeping model results (Houghton et al., 2012).

Between 1970 and 2010, emissions of CH_4 increased by 20 %, whereas emissions of N_2O increased by 45 to 75 %. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands (photosynthesis vs. plant respiration, decay of residues and soil organic C oxidation), the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 Gt CO_2/yr only (IPCC, 2014).

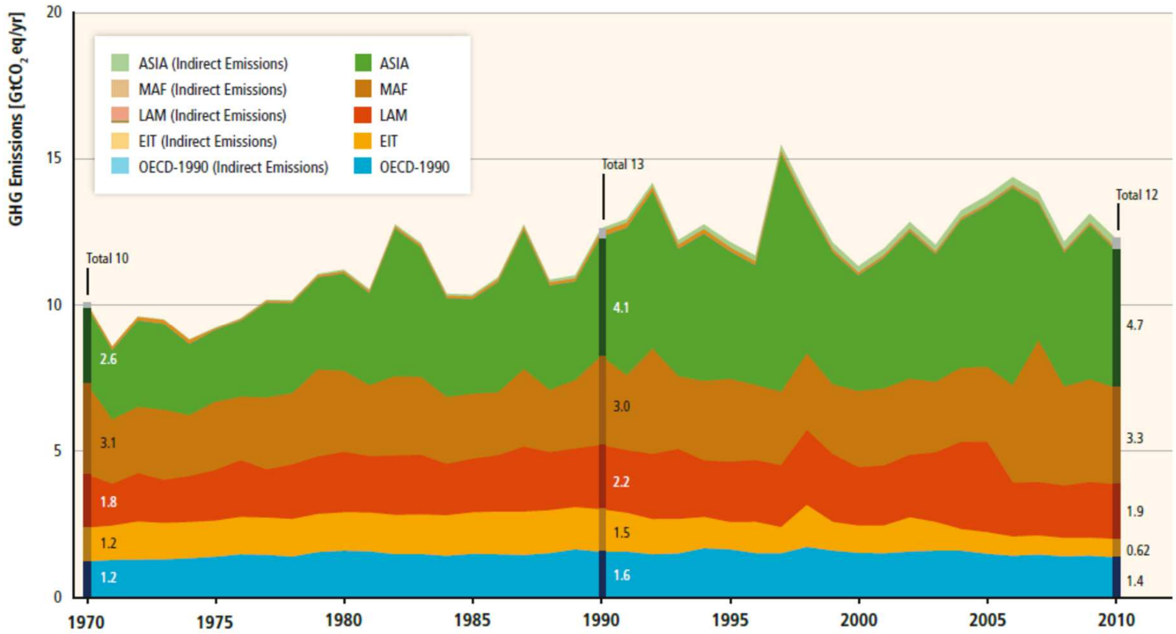

Figure 4: Agriculture, Forestry, and Other Land Use (AFOLU) emissions for the last four decades and per region LAM: Latin America, MAF: Middle East and Africa, ASIA: Asia, EIT: Economies in Transition, OECD-1990.

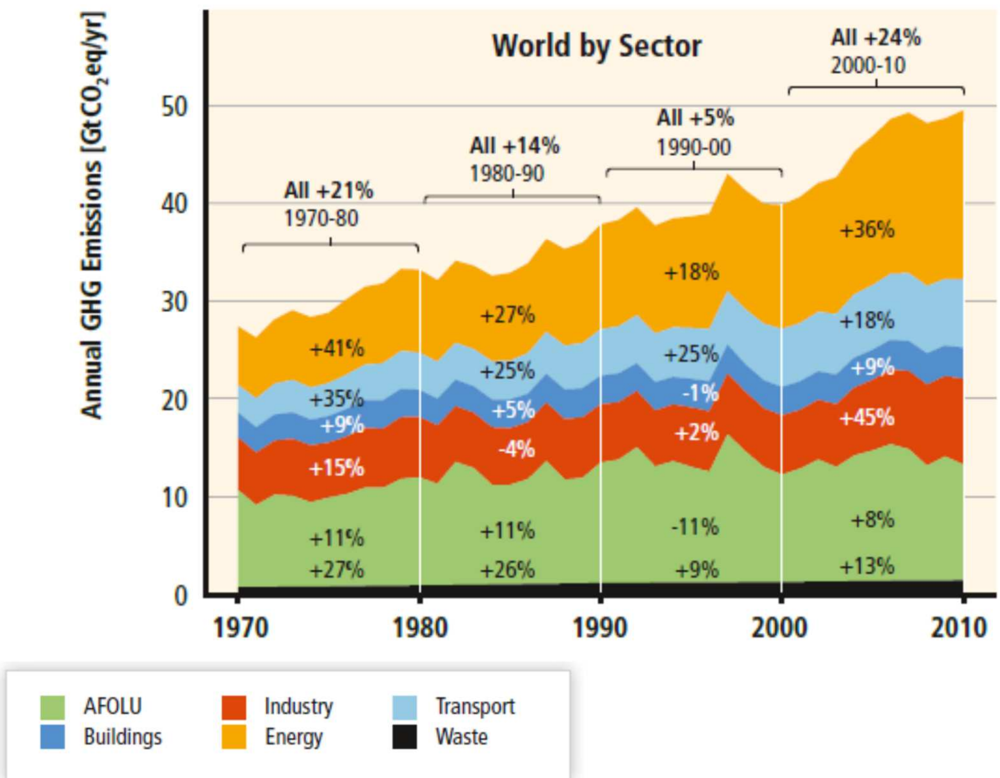

Figure 5: Annual GHG emissions for the six key sectors. AFOLU: Agriculture, Forestry, and Other Land Use (from IPCC 2014. p 381)

Rice specificities in GHG emissions

Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (IPCC, 2013). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (Janzen, 2004). ***CH_4 is produced when organic materials decompose in oxygen-deprived conditions***, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (Mosier et al. 1998). CH_4 is a potent GHG with a global warming potential (GWP) of 25 (IPCC, 2006), which means that it is 25 times more effective in trapping heat inside the Earth's atmosphere than CO_2. Soil CH_4 emission encloses a series of complex processes involving methanogens and methanotrophs microbial communities (Le Mer and Roger, 2001), and is dependent on soil dissolved organic carbon (DOC) availability (Bossio et al., 1999). Under anaerobic condition of submerged soils of flooded rice fields, methane is produced and much of it escapes from the soil into the atmosphere via gas spaces in the rice roots and stems, and the remainder CH_4 bubbles up from the soil and/or diffuses slowly through the soil and overlying flood water.

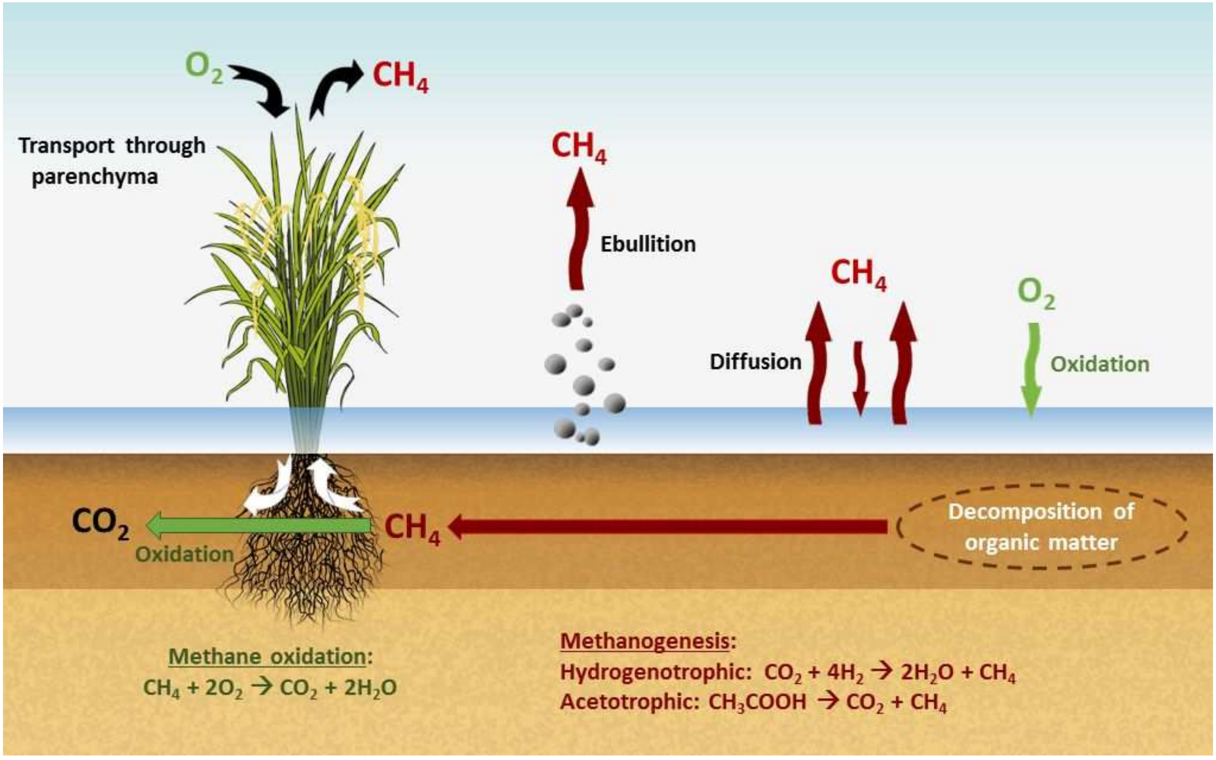

Figure 6: Principal pathways of methane production and emission in an inundated rice field (adapted from Le Mer et al., 2001)

Soil N_2O is formed predominantly through nitrification and denitrification processes, and is often enhanced when available nitrogen (N) exceeds plant requirements, especially under wet conditions (Smith and Conen, 2004).

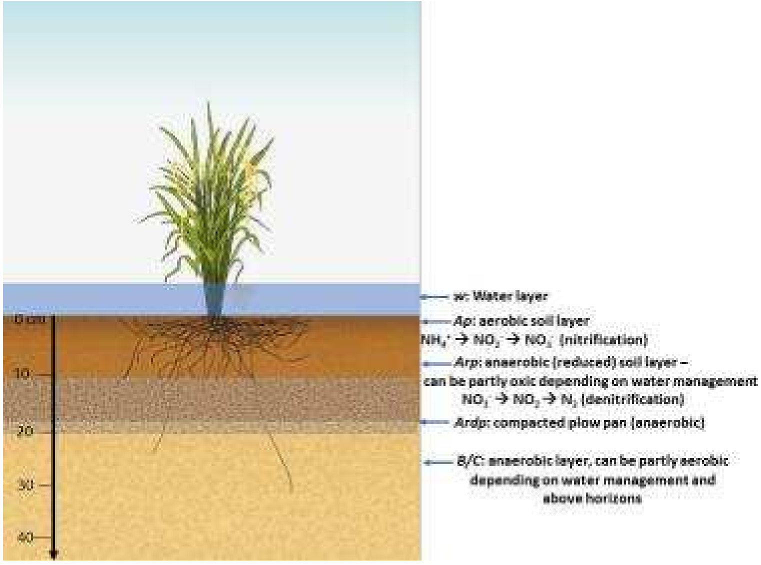

Figure 7: water and soil layers in an inundated rice field and dynamics of N_2 (adapted from Chapuis-Lardy, 2016)

Rice cultivation is a significant source of CH_4 emissions (Linquist et al., 2012), contributing about 10–14% of total global anthropogenic CH_4 emissions (Nazaries et al., 2013). Flooding of irrigated rice fields produces anaerobic soil conditions which are conducive to the production of CH_4. Methane is produced anaerobically by methanogenic bacteria, which thrive well in paddy rice fields. Neue et al. (1997) observed two distinct peaks of CH_4 fluxes in tropical rain-fed lowland rice. The first peak occurs within one month after transplanting and is mainly controlled by CH_4 production from soil organic matter and organic amendments. The second peak occurs at the heading or flowering stage and is mainly governed by the stable low soil redox potential and neutral soil pH, the increased release of plant-borne carbon sources, and the increasing capacity of plant mediated CH_4 emission.

N_2O emissions from agricultural soils, representing approximately 5% of total global anthropogenic GHG emissions (WRI, 2014), are predominantly linked to inorganic and organic nitrogen fertilizer applications to arable upland systems (Davidson, 2000). Numerous studies report high CH_4 but relatively low N_2O emissions from flooded rice production (Linquist et al., 2012) because anaerobic conditions limit nitrate availability and strict anaerobiosis favours complete denitrification to nitrogen gas (N_2) (Zou et al., 2007).

Several parameters strongly influence CH_4 emission including:

- Soil, crop management (soil preparation and transplanting or direct seeded practice).
- Residues use (incorporation and timing, burning, exporting for other purposes …) (Lu et al. 2000; Le Mer et al., 2001; Wang et al. 2012 ; Coulon et al., 2016).
- Water management with permanent flooding or alternate drying and wetting approach reducing the period of flooding (Cai et al., 1997; Wassmann et al., 2000; Tyagi et al., 2010; Coulon et al., 2016).
- Texture and clay type protecting soil organic C from enzymatic attack (Le Mer et al., 2001).
- Rice varietal differences in CH_4 emission of almost 500 % have been reported. Root exudation, which produces organic substrates directly or indirectly utilized for CH_4 production, varies qualitatively and quantitatively with rice varieties (Ladha et al., 1987; Mayer and Conrad, 1990).

In addition, ***open-burning of straw is a common practice in Vietnam*** and, thus, responsible of marked GHG emissions. It is reported that the Mekong Delta yields ~ 20 Mt of paddy and an estimated 24 Mt of dry straw (Hong Van et al. 2014) annually. Streets (2003) reported that ~ 6.1 Mt of crop residues is burned annually on-field in Vietnam which ranges as the sixth largest amount in Asia. In the Mekong delta, in one triple rice cropping system, most of the rice straw harvested during the dry season is burned on-field. By contrast, the straw harvested during the rainy season is removed from paddies and utilized for straw mushroom cultivation. Then, this biomass is sun-dried and burned to remove the mushroom beds and to sell the ash. Consequently, 23% of the total aboveground straw biomass was burned annually in the triple rice cropping system (Hong Van et al. 2014). On-field burning of rice straw is commonly practiced in intensive rice production systems when there is a short time to prepare the field for the next crop. This situation mainly occurs between the spring and the summer rice cycles in most of the coastal provinces of Vietnam generating negative environmental and societal (air quality, and higher occurrence of breathing diseases) impacts. Rice cropping patterns (2 or 3 rice cycles) and the nature of rice harvesting (combine harvester or by hands and threshing on the side of the fields) have a strong incidence on open-burning and GHG emissions. With the increasing use of combine harvesters the threshed straw is (poorly) scattered on the soil surface and remains in rows. When harvested by hands the rice straws (after threshing) is piled in a stack for burning or used for mushroom cultivation and then burnt later on. Arai et al. (2015), conducting and assessment of GHG emissions from rice straw burning in a triple rice cropping system in the Mekong Delta, reported that the total GHG emissions amounted to 1688 g CO_2-eq. kg dry straw^{-1}. This result is in accordance with the study conducted by Gadde et al. (2009) in Thailand, Philippines and India, but is significantly higher than results reported from Japan (Miura and Kanno 1997). In addition, higher moisture content during open-burning (mainly the case during the transition spring – summer rice cycle) inhibits N_2O emissions but enhances CO, CH_4 and non-methane volatile organic carbon (NMVOC) when compared with lower moisture content of the rice straw.

The figure 8 presents the carbon footprint of rice with field emissions representing 62% to 73% of the total.

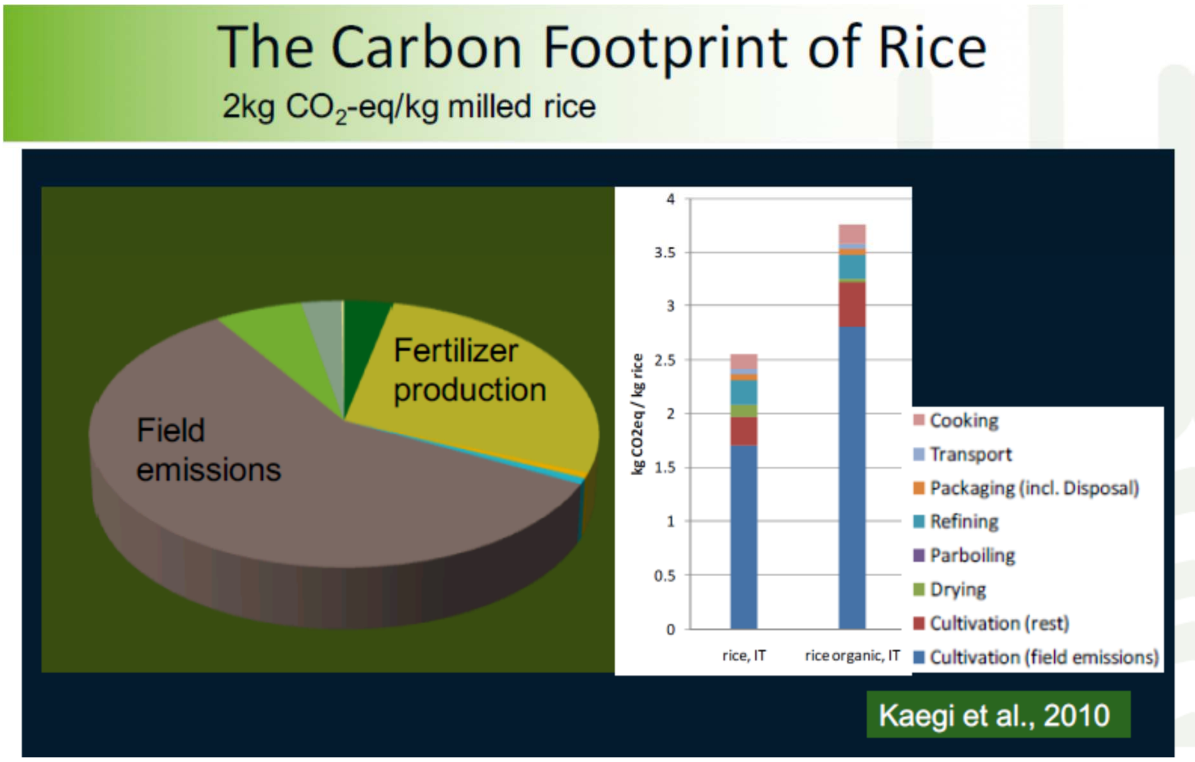

Figure 8: The carbon footprint of rice, from Vidal et al., 2016 (COSTEA)

Climate smart rice cropping systems

The dissemination of climate-smart rice cropping systems requires a close match between the water needs of rice during his cycle, the efficiency of the irrigation network to provide water when needed and of the drainage system to remove any excess of water. That means that different scenarios should be designed and assessed taking into account the designs of the irrigation/drainage scheme, its efficiency, the climatic variability (rainfall and sum of temperature) of the different seasons (spring, summer, autumn and winter), and its impacts on the growth stages of rice (delay in the winter impacting the land preparation and sowing of the summer/autumn cycle). To be consistent with water regulations between water users and operation of the water networks (pumping, gravitation), the analysis should be done at the hydraulic frame scale. This will allow to arrange cropping systems capable to fit with varying capacities of irrigation and drainage at schemes functionnal unit level.

In the following paragraphs the distinction is made between thematic adjustments (alternate wetting and drying/AWD; mid-season drainage/MSD; rice genetic adaptation to submersion, salinization, drought …) and systemic approaches; systemic approaches with Sustainable Rice Intensification (SRI), Conservation Agriculture (CA) and direct seeding mulch-based cropping (DMC) systems are principles-based and thus more flexible than thematic/recipes-based.

A water saving tactic and CH_4 emission reduction: the alternate wetting and drying

Irrigated rice is not only the largest source of CH_4, but also the most promising target for mitigating CH_4 emissions from rice (Wassmann et al., 2000). Aeration of the paddy field can reduce methane emissions and at the same time save water.

More efficient water management practices are needed so that rice production levels can still be maintained or increased even with the use of less irrigation water. Different forms of water saving techniques as alternate wetting and drying (AWD) and midseason drainage (MSD) have been developed, assessed and disseminated to reduce CH_4 emissions. AWD has principally been promoted in Asia, with the most widespread adoption to date occurring in Bangladesh, Philippines, and Vietnam (Lampayan et al., 2015) in An Giang Province (study from 2009 to 2011).

AWD is an irrigation technique where intermittent periods of submergence occurred during the growing stages of rice. This is in contrast to the traditional irrigation practice of continuous flooding. This means that the rice fields are not kept continuously submerged but are allowed to dry intermittently during the rice growing stage. This approach, reducing the water amount with drying periods, reduces CH_4 emission and thus contributes positively to the mitigation of climate change. With the exception of SRI (System of Rice Intensification/SRI) which is based on transplanting, most of the AWD approaches are based on rice sowing on 'dry soil' reducing of about 2 to 3 weeks the field submergence. Depending of the country the practice is based on different AWD periods. For example, in China, South Korea and Japan only one drying period is considered from 5 to 10 days. By contrast, in the Philippines several AWD periods are conducted from 20 days after sowing to 15 days before flowering. Farmers monitor the depth of the water table using a perforated water tube that is inserted into the soil (Figure 9).

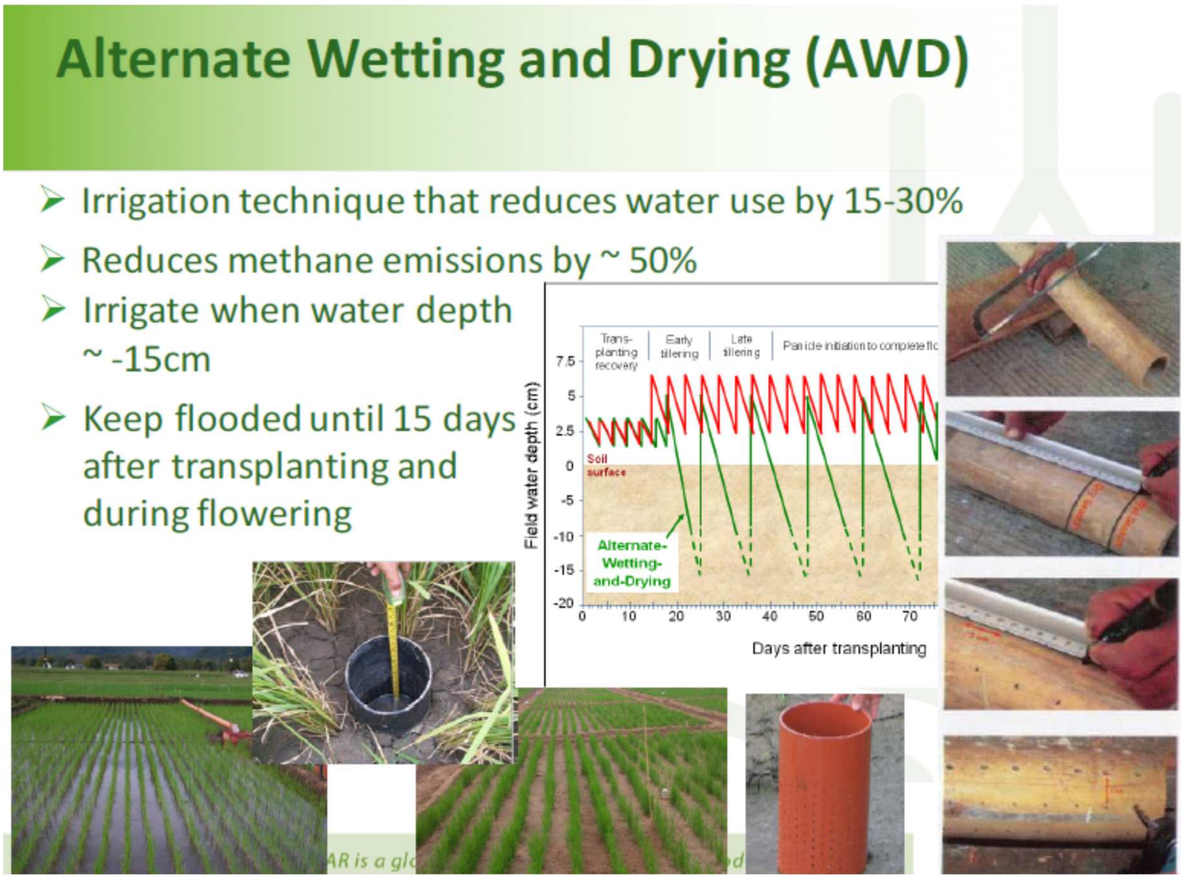

Figure 9: from Vidal et al., 2016. Atelier de travail COSTEA sur la riziculture et le changement climatique Montpellier, 9/6/2016

The practice involves draining the field until the water level reaches 15 cm below the soil surface after which the field is re-flooded to a depth of around 5 cm. The threshold of water at a 15 cm level below soil surface will not cause any yield decline because the roots will still be able to capture water from the saturated soils (Lampayan et al., 2009). In Vietnam, farmers (An Giang Province) adopting AWD reported lower labor cost than non-AWD adopters; irrigation frequency was also lower for the AWD adopters. The increase in net income (by 26%) was attributed to increased rice yield that was partly due to reduced lodging.

AWD of rice paddy, has been promoted as a strategy to decrease irrigation water use and reduce GHG emissions from rice cultivation while maintaining or improving yields (Richards and Sander, 2014). Because periodic aeration of the soil inhibits CH_4-producing bacteria, AWD can reduce CH_4 emissions and, thus, has a proven potential to mitigate methane emission.

Various studies on GHG emissions under AWD and other water-saving strategies have been conducted to quantify the mitigation potential of those water management strategies. The capability of AWD to reduce CH_4 emissions is also reflected in the IPCC methodology (IPCC, 2006) and it is presumed that AWD reduces CH_4 emissions by 48% compared to continuous flooding of rice fields. Moreover, a single aeration of the field (midseason drainage), reduces CH_4 by 40% (IPCC, 2006). In addition, several studies (Pandey et al., 2014; Xu et al., 2015) reported a mitigation potential of AWD that ranges from 48 to 93%.

However, AWD may also have tradeoffs (Ahn et al., 2014; Wang et al., 2012) in terms of higher emissions of nitrous oxide (N_2O), a GHG even more potent than CH4 with a GWP of 298 (IPCC, 2006). Under water saving strategies, N_2O emissions tend to increase due to increased nitrification and denitrification activities with the soil conditions constantly changing between anaerobic and aerobic and related changes in the redox potential. However, in most cases this trade-off does not eliminate the overall reduction in global warming potential (GWP) associated with AWD (Linquist et al., 2015; Pandey et al., 2014; Xu et al., 2015). In addition, LaHue et al. (2016) observed that AWD reduced growing season CH_4 emissions by 60–87% while maintaining low annual N_2O emissions (average = 0.38 kg N_2O–N ha^{-1}); N_2O emissions accounted for <15% of the annual global warming potential[1] (GWP) in all treatments tested. The AWD treatments reduced annual GWP by 57–74% and growing season yield-scaled GWP by 59–88%. Other studies suggested that the incremental N_2O emission through AWD is insignificant as long as the N fertilization remains within a reasonable range.

Addition of fertilizer N influences CH_4 emission through enhanced CH_4 oxidation, increased transport for CH_4 and more carbon substrate for CH_4 production (Schimel, 2000). Linquist et al. (2012) emphasized that the impact of N fertilizer on growing season CH_4 emissions are N rate-dependent. They also found that deep placement or banding of fertilizer N in continuously flooded rice systems reduced CH_4 emissions by 40%. Deep placement of N can also lead to increased N use-efficiency, minimizing N losses as the ammonium is protected from nitrification/denitrification in anaerobic soil layers (Savant and Stangel, 1990).

The following figure represents the decrease in CH_4 emission under AWD management when compared with conventional irrigation pattern, and the yields for a range of rice cultivars.

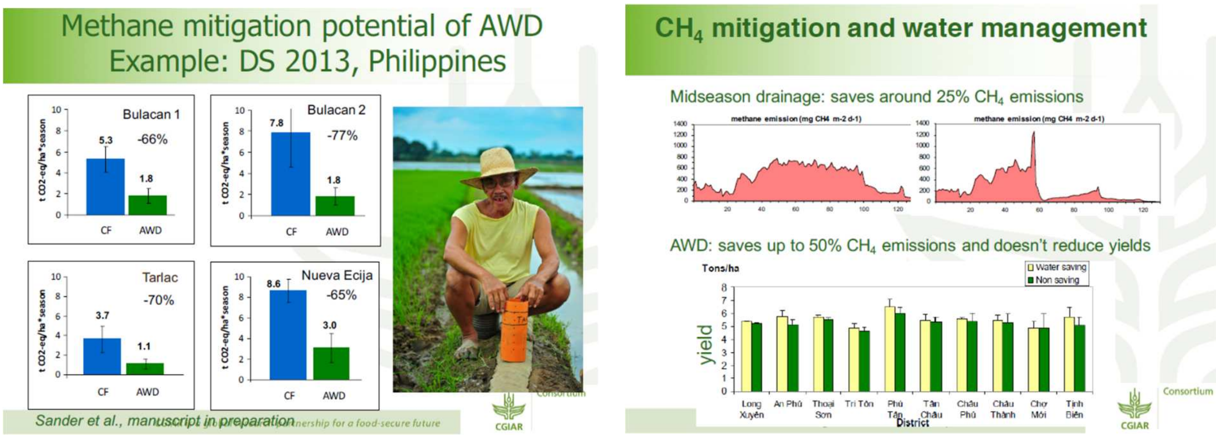

Figure 10: Methane mitigation potential of AWD (Philipines) and water management; from Vidal et al., 2016 (COSTEA)

In these water-saving technologies, the main constraints are related to the water management. AWD approach can be implemented only if the irrigation can be fully managed and water available when needed. It will also depend of the efficiency of the drainage system during the wet season as water should be drained out in time. Promoting water-saving technologies implies that the characteristics of the irrigation system allow changes in water distribution rules and that the drainage capacity is efficient. Thus, and before targeting the AWD approach, it is essential to identify within the irrigation scheme where these conditions are available during the dry and rainy seasons based on the results of the analysis of the operation of the hydraulic frame. On this basis, on-farm demonstrations would ensure that the constraints of monitoring related to these practices are compatible with agricultural practices (level of mechanization) and the availability of labor. Such approach would ensure the conditions of upscaling of proposed technologies. In addition, the adoption of AWD depends on the incentive for the farmer that is directly linked to the irrigation system. In a pump system where farmers can achieve direct financial savings due to reduced diesel use for pumping under AWD, it is easily adopted and properly implemented. In irrigation systems where farmers pay seasonal fees independent of the actual water usage, farmers could be reluctant to use water-saving techniques and it will imply additional labor inputs (Lampayan et al., 2015).

[1] Global warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. GWP is expressed as a factor of carbon dioxide.

Rice straw management

The use of combine harvester increases drastically to offset the scarcity of labor force. This technology has a direct impact on straw management and thus GHG emissions. Combine harvesters that are widely used in the region (Kubota DC60 and DC70) are not equipped with crushers and straw spreaders leaving after harvest windrows that are valued in part (livestock, mushroom production, energy) but mostly burned prior land preparation (ploughing, harrowing or rotary tiller) for the summer cycle. The first option would be to use straw spreader to allow a homogeneous distribution of rice straw on the soil surface to avoid the massive open-burning. Another option is to use straw baling machines (available in southern Vietnam, figure 11) to export the straw for other purposes (mushroom cultivation, livestock and energy).

Figure 11: Straw baling machine available in the Mekong Delta (Galan, Japanese brand, Binh Chanh, province de Hô Chi Minh)

Managing rice straw will allow diversifying the use of agricultural implements for the field preparation. Given the recent changes in the use of agricultural machinery it is useful to test a wider range of implements that should bring flexibility especially while initiating a transition toward direct seeding mulch-based cropping (DMC) systems. For instance, the uses of cultivator (Fig. 12) or roller (Fig. 13) exhibit a higher workable capacity when compared with conventional plough-based tillage and/or the use of rotary tiller. With the use of roller or cultivator rice straws will be incorporated in the top soil layer. Based on water management rice sowing can then be done by broadcasting dry or pre-germinated rice seeds. Seed broadcaster (Fig. 22) can be used with cultivator and roller allowing in one pass the field preparation and the rice sowing.

Figure 12: Cultivator for land preparation

Figure 13: Use of roller for a fast land preparation between 2 rice cycles. Rice straws are buried on the top soil

AWD, new management of rice straw, introduction of new tools to prepare soil can be considered as example of thematic modifications of the practiced cropping system. Thematic change plays on the modification of a sole element; for instance, variety, fertilizer type or dose, seeding density and pattern, pesticides active ingredient … constitute classical thematic pathways to improve performance of existing systems. Regarding the adaptation to climate change, several genetic programs head for rice adaptation to environment alteration, working on the development of tolerance to salt injury, to submergence by flood events or to drought and temporal dry spells.

However, if we intend to adapt rice farming systems to climate changes and to mitigate GHG the whole management of the soil, water and biodiversity should be considered. Thematic adjustment based only on water control, new rice varieties adapted to submergence and/or salt will not solve the problems on the long run. It is also largely reported that land use intensification is characterized by a high environmental footprint (soil and biodiversity erosion) and increasing debts as a result of the high capital requirement of intensive cropping practices. The current negative impacts on natural resources (soil, water and plant diversity) and decreasing trend of productivity call for pronounced holistic changes of the practices. It is widely reported that marginal modifications (*thematic*, e.g. fertilizer, variety, pesticides) are not sufficient because they do not address the intrinsic non-sustainable patterns of the current practices and often introduce an economic risk that cannot be taken on by farmers.

Systemic changes do not consist in modifying several elements of a pre-existing system in the meantime. They are more principles-based than attached to specific *prescriptions* like thematic adjustments; it means that new practices converge to mobilize processes that sustain the cropping systems.

- In SRI, practices design is focusing first on rice ecophysiology and the maximization of the number of productive tillers.
- In Conservation Agriculture (CA), cropping systems are built around the organization, across crops – cover crops successions and associations, of the largest and most diversified flow of organic matter inputs on soil surface with the aim to generate a soil organic carbon-integrated fertility management. Thus, systemic changes are flexible and keep evolving in time within their essential framework of principles.

SRI, a cropping system change driven by the rice crop management

In its first development in Madagascar, SRI was introduced to farmers under a single message: practice, as early as possible, of transplanting from nursery to field (ideally between 8 and 15 days after emergence) at large spacing between plants (up to 0,4 x 0,4 m) in order to limit the biotic constraints and enhance the tillering capacity. Obviously, this apparently simple technical message pairs with directly induced necessities: transplant a seedling of less than 10 cm high requires a perfect land levelling combined with a smart water management to avoid submergence; transplant very small plants at large spacing means a cautious weeds management (with tools contributing to soil aeration) during the first 50 days of the crops. At first, SRI was based on rice crop management (early transplanting, large spacing, water management) with a progressive aggregation of an integrated soil fertility management through the use of manure and compost, AWD exclusively at the beginning of the rice cycle, and an integrated pest management.

SRI should be considered as a systemic change primarily based on rice crop management.

However, SRI does not offer option for the management of the cropping systems (i.e., crop diversification, integration with animal husbandry) beyond the optimization of biomass flows at farm level (use of manure and compost). Rotation, crop diversification, intensification of biomass production at the field level (ecological intensification based on an increase of biomass-C inputs: quantity and quality of the biomass produced and restituted to the system), and adaptations to restrictions on water access are not considered.

The fact remains that SRI allows changing the perceptions of producers, organized around simple messages. It is part of a systemic change when compared with the patterns and rationale of the green revolution. In addition, SRI, including alternate drying and wetting period, decreases CH_4 emissions when compared with conventional management based on transplanting under irrigation management (Ly et al., 2013).

Conservation Agriculture (CA), innovative cropping systems based on soil and plant diversity management

Before presenting CA, it appears important to clarify the terminology when it comes about "direct seeding" in rice production.

Direct seeded and no-till rice

Direct Seeding (DS) of rice is a worldwide-spread expression that covers various technical management of rice crop implementation:

- In region where transplanting is the dominant practice, DS means that rice has been directly sown in the field, skipping the nursery stage. Soil is generally tilled, and rice is sown in line or by seeds broadcasting.
- In region, generally with more advanced mechanization, where rice is sown with seeders, DS means that no soil tillage has been operated prior to rice sowing. However, a soil preparation is regularly done along the crops sequence, usually built upon an annual succession including one rice cycle a year.

For the latest group, we can cite numerous examples of cropping patterns that include DS or no-till rice implementation:

- In temperate/sub-tropical regions of India, China, Pakistan, more than 25 million ha, are managed under a rice-winter cereal annual succession where wheat is direct seeded on rice straws, but soil preparation usually precedes rice implementation.
- In the inter-Andean valleys of Colombia (Tolima, Huila) with a bimodal equatorial rains regime, producers often skip a costly soil preparation and directly sow rice in the rice stubbles (dominant rice mono-cropping).
- In southern subtropical regions of Brazil (Santa Catarina and Rio Grande do Sul), rice is direct seeded on a cover of ryegrass that has been sown in fall season after soil and field (temporary canal and drainage system) preparation. In spring, the ryegrass cover is desiccated by herbicide application and rice is directly sown in the mulch.

In this type of cropping system, DS is more motivated by production cost reduction and time saving for crops implementation than backed on an agronomic rationale of soil fertility management. While CA covers about 150 million ha in rain-fed upland agro-ecosystems across the world, there are very few irrigated rice production systems combining permanent NT with the inclusion of permanent soil cover by crops residues and cover-crop management. Among known example we can cite:

- The historical and pioneer experience of Matsubara Fukuoka (1978) in Japan based on rice – barley succession managed on a living cover crop of clover.
- In India, the contemporary development of the Saguna approach based on conservation agriculture developed on permanent bed management.
- Research and development works developed by CIRAD and its partners in Madagascar, Cambodia, Colombia and more lately in Ivory Coast.

In the following paragraphs, we consider the terms of Conservation Agriculture (CA) and Direct seeding Mulch based Cropping system (DMC) as equivalent, the second having the advantage to be more explicit from a technical point of view.

CA principles and agro-ecological rationale

Since more than 3 decades, CIRAD, and the research unit AIDA/CSIA, are involved in the design and assessment of diversified Conservation Agriculture and Direct Seeding Mulch-based Cropping (DMC) systems (Séguy et al. 1998; Séguy et al., 2006; Husson et al., 2013). They are based on 3 technical principles with: (i) minimum soil disturbance, (ii) permanent soil protection with plant cover and (iii) species diversification based on crops and cover crops succession and/or association. These principles trigger ecological processes particularly with a litter system, a continuous flow of fresh organic matter, driving soil biota diversity and functionality (Lienhard et al., 2013), soil structure and soil organic C and N accumulation (Tivet et al., 2013) contributing to the resilience of the system. Biological processes and systems properties are enhanced and extended by multifunctional cover crops and a higher degree of crops diversification (Husson et al., 2013).

Figure 14: Technical principles of direct seeding mulch-based cropping systems

The primary goal is to build a permanent flow of carbon from above and belowground biomass to improve all compartments (physical, chemical and biological) of the soil's fertility. Thus, DMC systems constitute a biological integrated way to manage soil's fertility when classical approach tends to manage more independently each of these compartments: soil tillage to improve physical conditions (and partially weeds), fertilizers (inorganic and organic) to first improve nutrients' availability, herbicides and fungicides to control weeds and diseases. Thus, the strategy is to restore and build a living soil using a large diversity of plants over time and space at the field and landscape levels, optimizing nutrient availability, minimizing losses of water and nutrients, enhancing soil functional biodiversity, and enhancing beneficial biological interactions and synergies.

> Under DMC, plant diversity is the engine that drives soil-crop interactions and enhances ecosystem services (regulation and provision). The introduction of cover crops leads to better utilization of available natural resources, maximization of biomass production and higher organic restitutions to the soil

Soil-plant relationship between 'conventional' and DMC management

The following diagram (Boulakia et al., 2013) highlights the changes in the soil-plants relationship progressively induced by the introduction of DMC based management in lowland rice agro-ecosystems.

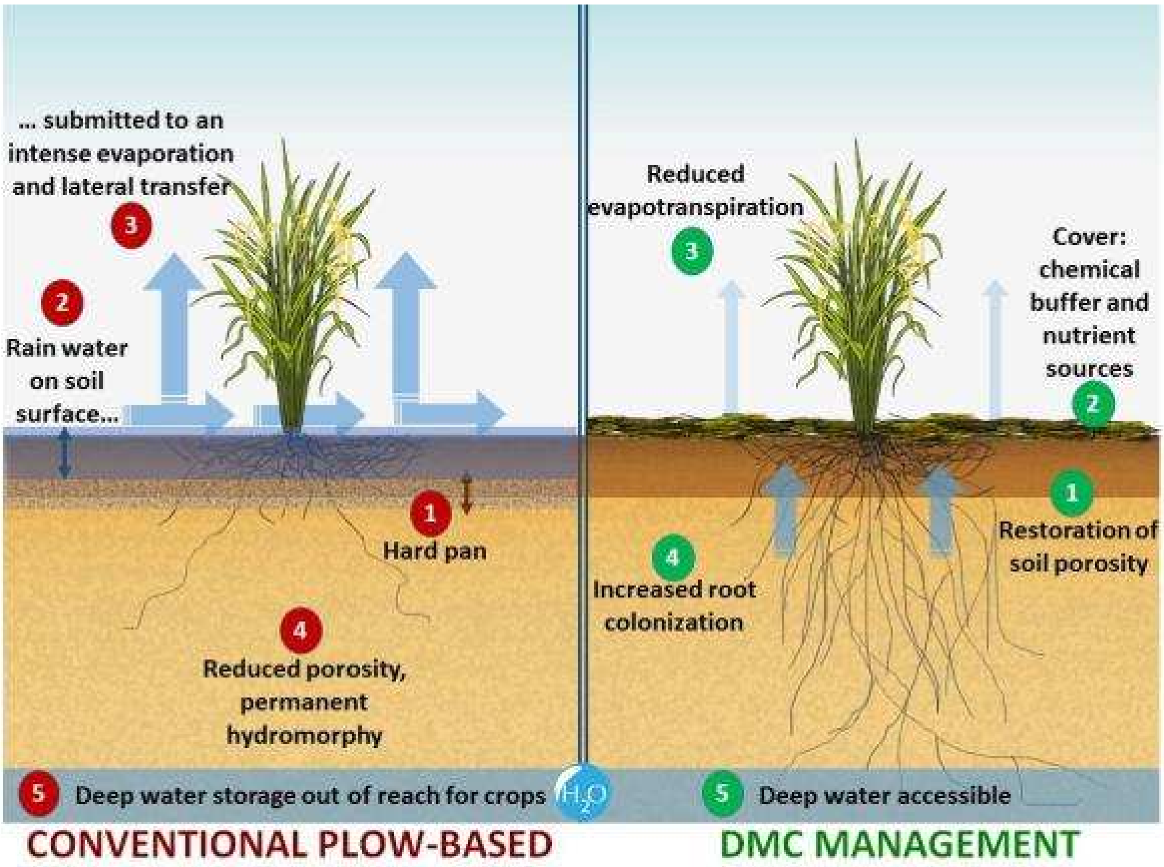

Figure 15: Changes in the soil-plants relationship induced by DMC management in lowland rice agro-ecosystems (From Boulakia et al., 2013)

Rice cropping systems should shift from a non-sustainable agricultural system where the biodiversity has collapsed and which is exclusively "perfused" by fossil fuel leading to massive use of chemical inputs to a rice farming system built on biological processes. DMC systems generate drastic changes of soil/plants/microorganisms interactions with diverse nutrients conserving strategies (cycling of nutrients through biomass growth-decomposition successions, increased storage capacities of nutrients into soil organic C …), requiring less amount of water from the irrigation system thanks to higher soil water infiltration and retention, integrated pests and diseases management. These changes lead to the progressive elaboration of a complex agro-ecosystem "equipped" with its self-regulation capacities that favors better plant growth.

At the field level, DMC systems restore progressively the biological processes that allow the gradual substitution of inorganic fertilizer by activating organo-biological fertility. Improved soil profiles combined with the presence of a permanent litter on the top soil leads to better efficiency of rainwater and irrigation, offering less anoxic conditions, reducing CH_4 emissions and accumulation of soil organic C. In addition, these systems open ways of diversification with the use of relay and/or cover crops (secondary crops, fodder sources).

DMC and soil fertility management

The following figures are based on an experiment conducted in Cambodia (Kampong Thom province, Stung Chinit irrigation scheme) on a sandy podzolic soil (80% sand, < 1% or soil organic matter on 0-10 cm depth) (Leng et al., forthcoming). DMC rice cropping systems are based on one or two rice cycle with the use of legume cover crops after summer rice. Rice cropping systems in Vietnam and Cambodia are extremely different and cannot be compared but this example illustrates the diversification process with fodder legumes after rice. This fodder source can be partially used for livestock while contributing to an organo-biological improvement of soil fertility through a DMC management.

Figure 16: Cover/relay crops of *Stylosanthes guianensis* and *Centrosema pascuorum* (April 2015, dry season, no irrigation) on sandy podzolic soils. Both species (legume, fodder) were broadcasted prior harvesting (early Nov).

Figure 17: Permanent cover of the top soil with the mulch of *Stylosanthes guianensis* and *Centrosema pascuorum*, continuous flow of fresh organic matter (8 t dry matter/ha; May 2015).

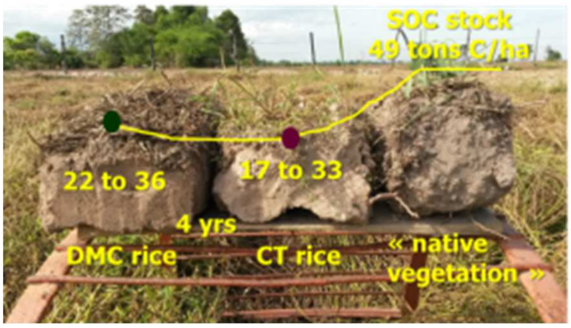

Figure 18: Changes in soil organic C stocks under 'native vegetation' (right), conventional plough-based tillage (CT, middle) and DMC (left).

Figure 19: Jasmin rice (Phka Rumdoul) direct seeded on mulch of *Stylosanthes guianensis* and *Centrosema pascuorum* + rice straw (June 2015).

Figure 20: Changes in the color of the soil layer under plough-based management (CT, left) and DMC (right) after 4 years (double rice cycle – spring and summer - and use of cover crops under DMC)

[0 – 10 cm]	CT	DMC
SOC (Mg. ha^{-1})	8,2	10,1
Labile-C (kg.ha^{-1})	231	317
Total N (Mg.ha^{-1})	0,85	1,10
N miner. (kg.ha^{-1})	170	215

Table 1: changes in total soil organic C (SOC), N, labile-C pool and mineralizable N between CT and DMC (Leng et al. , forthcoming)

After 4 years on a sandy podzolic soil (80% sand), soil organic C, labile-C pool, N and mineralizable N stocks, and soil microbial respiration increased under DMC management when compared with CT. SOC and N stocks increased by 23% and 30% under DMC in 0-10 cm depth, respectively, contributing significantly to an increase in nutrients stocks under an organic form (no leaching). With reduced reliance on external N inputs under DMC, due to a continuous flow of fresh organic C and the use of legumes cover crops, emissions per ha can also be reduced.

Generally, nitrogen applied per rice cycle is not always used efficiently and/or available N exceeds plant requirements. The surplus N is particularly susceptible to emission of N_2O and runoff. Consequently, improving N use efficiency contributes to reduce N_2O emissions and indirectly reduce GHG emissions from N fertilizer manufacture. In a secondary process, once efficient and attractive systems are designed, thematic adjustments should also be considered, particularly avoiding N supplies exceeding the immediate plant requirements, e.g. by fractioning the fertilizers applications, using slow- or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation), among others practices (balanced supply of nitrate and ammoniacal nitrogen).

Diversification and systems flexibility

The adoption of DMC opens ways to an integrated management system where the main investments will be allocated to the design of a diversity of cropping systems (integrating crops diversification, integration with animal husbandry and producing additional fodder sources) for different topographic positions and water regimes (rainfed lowland exposed or not to floods, irrigation schemes with gradient of water control -irrigation/drainage- conditions) and offers (climatic variations), less costly in terms of investment and maintenance (controlling runoff, reducing lateral flows).

Once transition toward DMC-based management achieved, systems are based on “elementary brick” composed of “cover-crop/crop” successions. These “bricks” are designed (crop and cover crop species, calendar, modalities of association/ relay, intensification level, tools …) according to the bio-physical and socio-economic contexts. But their succession in time will depend on farmers’ decisions ruled by production objectives and decisions making integrating price prediction, climate trends forecast (Niño/Niña) or anticipated schemes’ irrigation capacities.

For instance, once a cover-crop is properly established, various decisions could be taken at the onset of the rainy season, according to production goals and environment conditions:

- Keep the cover to maximize soils improvement (i.e., investment in soil fertility recovery while departing from severely degraded situation) or exploit it has a fodder source for livestock with multiple trades-offs options between these uses.
- Opt for sowing:
    - Rain-fed crops with or without possibility to supply punctual irrigations,
    - Irrigated crops (crops duration conditioning the water consumption).

In addition, when practiced in irrigation scheme with full water control, DMC systems are systematically managed with AWD approach combined with the improved soil storage capacity and the mulch limiting evaporation, contributing to higher water-use efficiency.

Diversification of double rice cropping systems with non-rice crops and cover/relay crops

Most of the double rice cropping systems of the Mekong River Delta and of the coastal plains are driven by the extent and occurrence of flood in the autumn (from September to early December). Diversification with cover/relay crops and particularly legumes should be tested after rice harvesting at the end of August and early September. Other options could be based on a ratoon (i.e., spring rice reshooting) based production in the summer in associations with cover crops. The use of the cover/relay crops are threefold : (i) increasing the diversification after rice with high quality fodder sources, (ii) improving the soil fertility through the biomass-C inputs (above and belowground) with Nfixing legumes, and (iii) decreasing, through an integrated pest management strategy, weeds and diseases pressure.

Several cover/relay crops can be tested alone or in association such as *Centrosema pascuorum*, *Sesbania* sp., *Stylosanthes guianensis*. Prior to the establishment of the spring cycle part of the cover/relay crops can be used as fodder sources using straw-balling machine available in southern Vietnam. This dynamic, with an increase of fodder sources, must be tested given the rise in cattle fattening, and dairy farms. The use of cover/relay crops gives also the opportunity to initiate DMC systems that can be split into 2 sub-groups:

- System based on dead-cover in which cover crops are terminated by combination of physical and chemical means prior to rice sowing.
- System based on alive cover-crop in which the cover is kept alive in association with the rice, in which competitions are controlled by irrigation and limited dose of herbicide.

Based on the extent of flooding, water flow and drainage, double rice cropping systems with non-rice crops before the summer rice cycle should be considered under no-till management. Crops with higher add-value such as pulse crops, sesame, amaranths, chia (*Silvia hispanica*), among others, should also be tested. In each context of flood regimes and water control, a large variety of systems based on crops successions (rice and diversification one), cover crops species and its management type could be introduced and rapidly tuned and adjusted in close contacts with farmers, farmers organizations and extension services.

In the meantime, diverse technologies can be used for the rice sowing. Rice can be direct-seeded through the biomass of cover/relay crops (previously desiccated or keep alive), using a no-till planter or dry rice seeds can be broadcasted on green mulch that will be mechanically controlled and terminated if needed. This latter system gives a higher flexibility and higher resources-use efficiency (lower production costs and energy use for sowing).

Figure 21: Thick mulch of *S. guianensis* and *C. pascuorum* (sowing time)

Figure 22: Broadcasting rice seed under no-till management

Figure 23: Rice direct seeded through a thick mulch of *S. guianenis* and *C. pascuorum* (Kampong Thom)

Figure 24: Jasmin rice broadcasted under DMC management, hydromorphic plains, no water control (Battambang)

Figure 25: Rice seed broadcasted on a green cover crops (mix of sorghum and sunnhemp, upland field)

Figure 26: Rolling of the cover crops after rice seed broadcasting

Figure 27: Emergence of rice on thick mulch of sorghum and sunnhemp

Figure 28: Rice well established under DMC (no ploughing, no soil disturbance, full soil cover, diversification, no planter)

In addition, the use of non-rice crops and cover/relay crops (legumes and others) will contribute to reducing the use of inorganic fertilizer and particularly urea that is also contributing to N_2O and CH_4 emissions. The N use-efficiency should be improved by strengthening the organic soil fertility (increased concentrations of organic C & N, soil biological activity, use of legumes ...). As emphasized previously, these cropping systems should also embed AWD approach plus a wide diversity of rice varieties with a particular emphasis on aerobic rice, tolerance to blast and other fungi. The use of rice variety with polygenic traits (or several monogenic traits) to fungi diseases will largely contribute to reduce the use of fungicides that are one of the main pesticides used in the Mekong River Delta and in others major rice production regions.

Systems flexibility, irrigations schemes management ... and design

As briefly introduced above, DMC enlarges flexibility in terms of crops choice (less anoxic soils' conditions) and management modalities. This flexibility can be mobilized to design cropping systems addressing specific hydraulic and hydrologic contexts characterized along the year by water flow control (from a zero-control of rain-fed context, to partial or complete irrigation possibility), drainage capacity and flooding occurrence.

The crop diversity based on the association, succession and rotation between irrigated or rain-fed crops with species – secondary grain or cover/fodder crops - able to grow on marginal rainfalls and/or soil's water reserves could be spatialized at the scale of the irrigation scheme. This "aggregation" of crops based on collective arrangements could ease for instance the organization, in case of water shortage, of seasonal water allocation between sectors, in advance split into irrigated or rain-fed / soil reserve regimes. It could also allow the development of fodder production and/or pasture management to serve better livestock integration.

Thus it can be understood how DMC could be adapted to multiple socio-economic and bio-physical conditions. How, also, in contexts marked by environmental hazards, the creation of innovative, flexible and diverse systems could feed the emergence of new collective organizations in order to optimize resource management through better integration between systems and schemes functioning and operations.

In longer perspectives, we can imagine that the emergence of DMC based management associated to new ways to operate irrigation (i.e., AWD, contour lines designed vs planning, subterranean micro-irrigation with dripper lines) will lead to conception of new scheme design. These new combinations should allow drastic improvement of water use efficiency and open new pathways to halt progressive soils' salinization.

Adaptation and mitigation options

Interdependencies exist between adaptation and mitigation and there are benefits from considering adaptation and mitigation in concert.

Adaptation	**Mitigation**
Diversified DMC Biomass-C inputs from non-rice crops and cover/relay, aerobic management Increasing soil biota abundance and diversity, improving nutrients cycling Crops diversification, buffering shocks, multiple options and possibility of choices Reducing production costs, increasing flexibility (no-till sowing or broadcasting) Increasing water (AWD, MSD) and nutrients-use efficiency (fertilizer type, application rate and placement)	**C**: soil organic C accumulation, increasing soil microbial communities and diversity, improving soil structure: from anoxic to aerobic soil profile **CH_4**: reducing emissions **N_2O**: emissions need to be assessed for contrasted rice cropping systems and time

The Table 2 summarizes existing approaches that can integrate rice-based cropping systems design in response to climate change induced alterations of the environment. It emphasizes on a distinction between "thematic" components that can integrate pre-existing cropping systems and "systemic" approaches leading to a complete redesign of cropping –and even- farming systems.

Alternative hydraulic infrastructures (nature-based solutions vs. hard engineering with dykes networks) (MDP, 2013; Ibanez et al., 2014; Chapman et al., 2016), water-saving strategies (Bouman et al., 2007), soil organic C and soil biota management and thematic adjustments (combining a large range of tools: rice varieties, organic and inorganic fertilizers and pesticides) should be designed through a systemic lens based on a close co-design process between infrastructures, water management and diversified rice cropping systems. These latter should restore soil life in order to re-establish and enhance the multiple soil-based biological processes (C and N cycling, soil structure, nutrient cycling, soil biota and water).

Assessing GHG

As emphasized by Smith et al. (2007) a practice affect more than one gas, by more than one mechanism, sometimes in opposite ways, so the net benefit depends on the combined effects on all gases. In addition, several studies, including those by Six et al. (2004) and Marland et al. (2003), observed that temporal pattern of influence may vary among practices or among gases for a given practice; some emissions are reduced indefinitely, other reductions are temporary (Six et al., 2004; Marland et al., 2003). The effect of DMC systems on N_2O emissions need to be evaluated. Chapuis-Lardy et al. (2007) emphasized that N_2O can be consumed by denitrifiers but probably also by nitrifiers, resulting on negative fluxes of N_2O at least temporary. Quantifying and assessing the magnitude of the impacts of carbon and GHG emissions on agro-ecosystems could facilitate a potential solution to mitigate climate change and further environmental issues, and be helpful in raising awareness and decision-making concerning environment-friendly technological development for the general public and policy makers. Analytical platform at different scales (i.e., field experiments, on-farm demonstrations, and pilot extension network) should be established integrating different topographic positions, different water management and a diversity of innovative cropping systems. This design should be used to assess the performances of the cropping system (agronomic, labor inputs, costs and profitability), the changes in soil fertility with an emphasis on soil organic C and N, nutrients cycling, water use efficiency and GHG (CH_4, N_2O and CO_2).

	Mitigation			Adaptation	state of art
	CO2	CH4	N2O		
***Thematic* - Level crops management**					
Variety development		var. with limited CH4 emission		selection / CC-induced alteration (resistance to drought, tolerance to submergence, tolerance to salinization ...)	on-going breeding program prospective for application rapid for salt tolerance
potential impact		-?-		-?-	
Nitrogen management	interdependance N and SOC dynamics		Balance Ammonium / Nitrate as N-source, fractionation, nitrification inhib., dose ...		research to validate impact / analyze pathways - high transferability
potential impact	-?-		-?-		
Biochar					
potential impact					
AWD		reduction emission		reduced water consumption	operational - high transferability
potential impact		+++		+	
Straw management	reduction emission (no burn, positive SOC balance)				operational - high transferability, via livestock integration
potential impact	+++				
***Systemic* - level cropping / farming systems management**					
SRI	to be evaluated	reduction emission via integration of AWD in the system	to be evaluated / likely to be significant with increased rely on O.M. based fertilization	reduced water consumption	operational -transferability function of the context-, based on simple message
potential impact	-?-	+++	-?-	+	
CA	strong stimulation of positive SOC balance	water and soil management lead to aerobic condition	to be evaluated / likely to be significant with increased rely on O.M. based fertilization	Context-based design, multi-functionnality of cover-c.	methodology and technique references for systems design and up-scale (initiated by R&D approach)
potential impact	+++	+++	-?-	+++	

Table 2. “Thematic” and “systemic” approaches for Climate Smart Rice systems design and potential contribution to the adaptation / mitigation of climate change

Climate Smart Rice production in response to CC in Mekong Delta

Agrochemical-based Green Revolution in front of CC challenges

Rice farming in Vietnam largely relies on the foundations of the agrochemical-based green revolution (Nguyen Huu Dung and Tran Thi Thanh Dung, 2003; Pingali et al., 1997). It is undeniable that intensive rice farming has provided huge productivity gains under conditions of intensive resource use and a controlled, predictable environment.

In brief, the green revolution thrived on high-yielding monoculture crops and based on a close interaction of means of production as irrigation, mineral fertilizers and pesticides with two cross-links:

- Irrigation, water control, and engineered infrastructures are the safeguard of the high use efficiency of the chemical and rice genetic investments.
- In the same time, the profitability of the irrigation scheme is largely related to the level of agricultural intensification with massive use of inorganic fertilizers, pesticides and high yielding rice varieties.

It is however essential to recognize the inherent limits and contradictions of agrochemical-based rice production. The green revolution exhibits intrinsic limits with (i) a massive use of mineral fertilizers and pesticides generating water and soil pollution but also health concern from the users and consumers (Chau et al., 2015), and (ii) a marked soil fertility depletion (i.e., soil organic matter, soil biota activity among others) and the generation of specific cultivation characteristics as compaction and anoxic soil ecosystem largely responsible of CH_4 emissions. Regarding most intensive area, mineral fertilizers applications reach up to 800-900 kg/ha on each rice cycle and pesticides (i.e., herbicides, fungicides and insecticides combined) up to 12-15 kg/ha of active ingredient.

The process of agricultural intensification has increased the systemic dependency of smallholder farmers on fossil fuels for both energy-intensive production and agrochemical inputs (Fortier and Thi Thu Trang, 2013). By relying on water-controlled infrastructure, agro-chemical inputs, rice genetic and mechanization (land preparation: ploughing, harrowing, rotary tiller), rice farming is trapped into a constant need for maintenance and thematic adjustments to environmental attributes that are becoming unstable, and changing at an accelerating rate. Engineered landscapes that have been reclaimed from the flood plains and wetlands of the Mekong Delta are increasingly threatened by sea level rise, unexpected river flows and aquifer depletion (Mekong River Commission, 2010). As the resulting floods and salinization become more frequent, intense and damaging, the Delta's extensive hydraulic systems require increasing levels of maintenance, while becoming less and less effective. It has also to be noted that current rice farming systems have driven an erosion of crop diversity, a depletion of soil fertility and of soil biota diversity that directly threaten the resilience of the system.

In addition, the nature and amount of pesticides applied increased rapidly from the end of the 1980s to 2010s (Ut, 2002). While 77 different active ingredients (a.i.) were legally applied in 1991, nearly 300 a.i. were in use in 2010 (Vien and Hoi, 2009; MARD, 2010). As a result, the amount of imported pesticides increased from 20,300 to 72,560 t (Huan, 2005; MARD, 2010). Van Toan et al. (2013) observed residues (12 out of 15 a.i. monitored) of currently used pesticides (i.e., buprofezin, butachlor, cypermethrin, difenozonazole, α-endosulfan, β-endosulfan, endosulfan-sulfate, fenobucarb, fipronil, hexaconazole, isoprothiolane, pretilachlor, profenofos, propanil, and propiconazole) in considerable concentrations in water, soils, and sediments of fields, field ditches and canals in the Mekong delta. These environments are the most exposed to potential pesticide pollution due to their proximity to application places. However, these results also show that this pollution partially persists and reaches larger canals which are used by people for drinking and other domestic purposes (7 out of the 15 studied pesticides in some samples of drinking water) as well as for aquaculture production. A recent study from Chau et al. (2015) confirmed these previous findings and observed that all investigated water sources in the Vietnamese Mekong Delta have been shown to be contaminated by pesticides.

Irrigated rice production is facing systemic problems. In terms of cropping systems, these constraints are inherent to the soil and crop management that are based on the principles of the green revolution: depletion of the soil fertility, use of inorganic fertilizers to maintain the soil chemical fertility, high weeds pressure and high dependence to the herbicides. Therefore, these investments on irrigation scheme are capital intensive generating a high sensitivity to externals shocks (increasing production costs, decreasing price …). In addition, these systems are more and more criticized for their local (soil fertility depletion, high dependence to inorganic fertilizers and pesticides, health of farmers …) and global (GHG) environmental footprint, and demands of the society to have access to better nutritious food.

The magnitude and pace of climate change will depend partly on the uncertain unfolding of biophysical changes, and partly on adaptation and mitigation measures which national policy-makers, donors, agro-industries and farmers will (or will not) undertake. With over 3,200 km of coastline, two major deltas (Mekong and Red river deltas), monsoon rains and strong typhoons, Vietnam is exposed to sea-level rise, coastal and hillside erosion, floods, inundations, salinization, cold spells, and droughts which subject local ecosystems to increasingly severe stress (Nguyen Van Viet, 2011; Yu et al., 2010). Carew-Reid (2008) reports that a SLR of 1-m by 2100 would submerge up to 31% of the Mekong Delta.

The floods cause serious problems for rice and other crops because of the poor or non-existent drainage and the topography of the land prevents fast water movement to drain flooded fields. Flooding is therefore considered a major challenge for rice production in some coastal provinces of Vietnam (Ha Tinh province for example with the severe flood in 2010). Salt intrusion is also one of the main concerns of the impacts of climate changes in the coastal and delta regions. In early 2016, *the Mekong Delta has been hit by a double blow of prolonged drought and salt intrusion due to the impacts of El-Nino. The region delta has seen the water level in Mekong River continuously decrease during several recent years. The level fell by 3 m from 2000 to 2015. The underground water source in the region has also dropped at an annual rate of 40 cm* (Mekong Delta struggling with drought, salt intrusion, Vietnam Pictorial, 29/03/2016).

Climate change repercussions and damages to rice agro-ecosystems might be severer on the large extent of acid sulfate soil in both deltas. Consequences of climate changes, with the alternate period of drought, flood and possible saline intrusions on such soil type, regulated by redox driven biogeochemical processes remain difficult to predict (Bush et al., 2010) ; prolong drought periods would trigger oxidation and acidifying processes while inundation will allow a return to reductive and neutralizing trends.

Over the last thirty years, rice production orientations have been able to meet the growing demand for food due to an increase on rice productivity growth. In the last decades, while improved cultivars (including hybrids), and new generation of pesticides have been released, the rate of growth in yields has been stagnating. In addition, the adverse weather conditions in the recent years have also contributed to emphasize the sensitivity of rice farming to climate variability and climate changes in the main basins of production of Vietnam.

The green revolution has *in fine* a low capacity to adapt and to mitigate the effects of climate variability and climate changes. A range of constraints can be described with higher flood and/or drought, depleted soil fertility, soil compaction and anoxic soil profile that do not allow crop diversification without a massive use of inputs and an investment in land preparation (ploughing, hilling/ridging, bed planting…).

The time has come to rethink rice farming systems that ensure that enough nutritious food is produced to fit with local demands and market strategies and that are able to adapt to climate change and to contribute to its mitigation.

Climate Change and impacts patterns on rice based farming systems in Mekong Delta

Several extensive works (Jica, 2013, Ngo and Wassmann, 2016) have developed models to foreseen what will be the impacts of climate change scenarios on cropping and farming systems in Mekong River Delta. These models highlight key evolution trends notably (i) flood regime in upper regions (figure 29) that will be enhanced by heavier rainfalls in October and November and, (ii) accentuated and extended saline intrusions figure 30), under the combined influences of SLR and dryer dry season with delayed rainfalls onset, in coastal regions and upward, along major Mekong distributaries. Consequences of these evolutions are crossed with contrasted climatic year, corresponding to hydrological anomalies of El Niño (drought of 1998 or 2015-2016) or La Niña ("exceptional" Mekong discharge and flood like e.g. in 2000) to integrate the large inter-annual variation observed along the last decades (Räsänen and Kummu, 2013). These models integrate also upstream development with hydropower dams construction (China, Laos, Cambodia mainly) and extension of irrigated areas in Thailand and Cambodia; dams' constructions can be seen as a factor of discharge regulation (Ngo and Wassmann, 2016) capable to partly offset CC impacts like salinity intrusions in dry season and flood in rainy season but also impacting sediment deposition rate and a flush capacity for salt and acidity in the early phase of the flood, in June - July. These modeling approaches help also to prospect the impact of hardware development like major and medium/small-scale sluice gates on estuaries and canals as well as sea-dykes upgrades to control saline intrusions and floods.

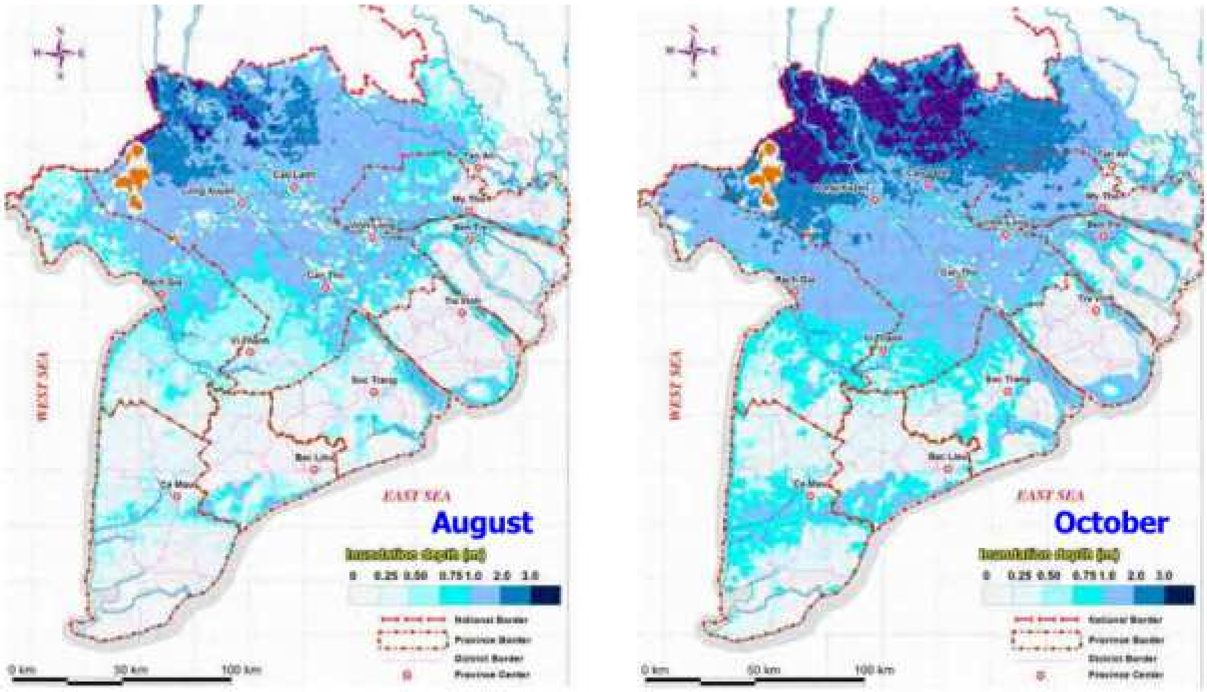

Figure 29: Evolution of the inundation depth between August and October in a year of high flow with a SLR of 30 cm (2050) (in JICA, 2013).

Furthermore, the model-based prospective allow to test the effect of civil engineering constructions to counteract saline intrusions linked to SLR and drought expected to be more frequent. According to scenario of more or less intensive "hard" constructions, including sluice gates and up-grading of sea-dykes network, models delineate hot spot zones of changes, notably from fresh to brackish and from brackish to saltwater (Smajgl et al., 2015).

This zoning indicates the evolution trends that most affected regions will undergo, especially in extreme climatic years (decrease in upstream flows). It is then foreseen patterns of change among rice-based agroecosystems, inspired by what have been observed, in recent years, in affected regions by salinity: abandon of one irrigated rice cycle, integration of upland crops (short term veggies, annual or perennial) and integration of brackish shrimp culture in rotation with summer – autumn rice (CGIAR, 2016). These areas, where systemic changes will occur, will be fringed by interface zones where paddy production will continue through unchanged cropping systems pattern but under increasing risk of saline intrusion (water with 4 to 10 g/l) in February (end of the winter – spring cycle) or in June (early stage of summer-automn cycle).

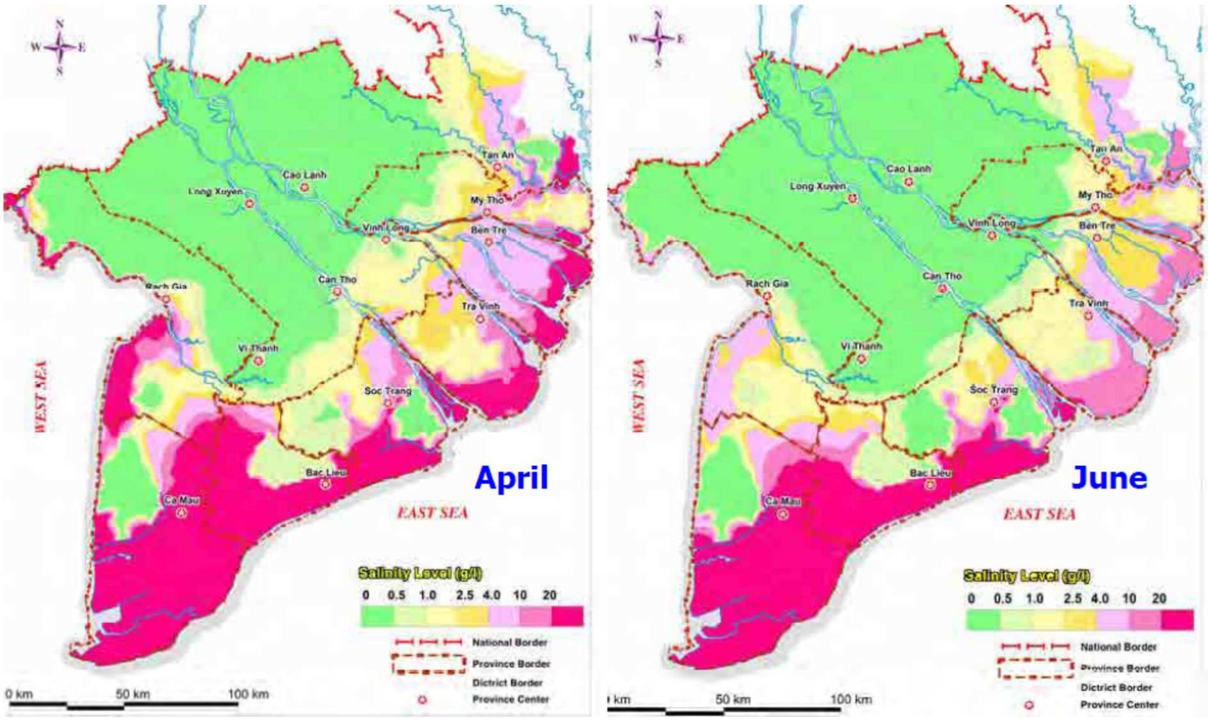

Figure 30: Evolution of the saline intrusions between drier month (April) and beginning of the flood (June) in a year of low with a SLR of 30 cm (2050) (in JICA, 2013).

Accompanying transitions in the different “hot spot” zones, for both accrued risks of inundation and saline intrusions, should mobilize participatory R&D works on systems design. In addition, developed innovations will remain under pressure of the abiotic risks evolution and this work should take the form of medium-long term and dynamic innovation platforms. For instance brackish shrimp aquaculture, in rotation with rainy season rice, developed by farmers in response to saline intrusion in dry season are also threaten by excessive salt which induces reduced growth rates and diseases outbreaks.

Cropping systems design in response to CC induced challenges and potential DMC inputs

As already mentioned, CC will induced two major types of challenge in Vietnamese MRD, on one hand and in upstream regions, more frequent and pronounced flood events occurring in the 2nd half of the rainy season, and, on the other hand, in coastal provinces, saline intrusions impacting crops productivity in extended zones.

In each of these areas, CC induced problems will present local gradients of gravity according to position in the “micro-topography” and salinity concentration, those site specificity being influenced by upstream development (hydropower, irrigation) and downstream protection (sea-dykes, sluice gate). In addition to these local characteristics, severity of stresses will greatly vary from year to year according to local and river catchment climate; transboundary coordination being needed, in the future, to plan regulation of water discharge in El Niño event.

These evolutions patterns require an array of adaptation measures to adjust cropping and farming systems. A first group of measures will consist in an adjustment of the existing systems, through for instance the development and integration of high yielding varieties with improved tolerance to salinity. Several breeding programs are in progress, some mobilizing markers (Ngo and Wassmann, 2016) and some varieties can maintain productivity superior to 5 t/ha despite episodic irrigation with water with salt concentration of up to 3 g/l. In the same perspective, some measures will focus on stress-avoiding tactics by harnessing cropping systems calendars with cut-off dates; this approach will call for the development of varieties offering a range of cycle lengths, including short one, to secure harvest before flood (summer-autumn cycle) or saline intrusion (counter season cycles). It is probable that these adjustments will benefit soon of support tools for decision based on improved El-Niño Southern Oscillation and related weather predictions (Räsänen, 2013; CGIAR, 2016).

A second group of evolutions will introduce structural evolution of the cropping systems; it will generally consist in replacing one or two rice cycles in the annual succession by other type of production; these alternatives could consist in other crops, upland annual and/or perennial species, or integration with aquaculture or other breeding activities. The recent soaring of the annual succession between summer-autumn rice with brackish shrimp culture in place of a double rice cycle is an exemplary illustration of this type of innovation process (Photo 1 and 2).

Thus, the elaboration of adaptive pathways should mobilize in sequence, marginal adjustments of the existing practices and structural shifts, breakthrough innovation, with integration of complete novelty.

But both types of evolutions might be eased and acquire improved resilience capacity through the integration of CA principles. Furthermore, CA could help, through the mobilization of agroecological services, in recuperation process of the agro-ecosystems after extreme events like flood, drought or severe salt intrusion (high tides, storms).

The complex mosaic of agroecosystems in MRD, some marked by very specific features (cf. the large extension of acid sulfate soils), will request to conduct on-field works to adjust CA based proposal in key situations representatives of the most challenging situations.

Regarding the complex biogeochemical processes occurring in acid sulfate soils, driven by oxido-reduction under humidity fluctuation, CA could contribute to favor regulation process. For instance, mulch could help to maintain appropriate soil moisture and delay oxidation / acidification processes in case of dry spell; mulch could also contribute to limit salt injury by limiting soil temperature and process of sodium concentration in soil and plant. Progressive accumulation of soil organic matter in upper horizon could act as electron donor and contribute to balance oxidation / acidification process with an appropriate and minimum moisture control. On the contrary, O.M. in excess under flooding conditions could accentuate yet too low Eh and lead to complete anaerobiosis. In the meantime, it is hard to anticipate what would be the impact of a progressive change in soil structure of superficial horizons, the evolution of the exchangeable cationic capacity and its progressive saturation by O.M. supply. These evolutions will be site-specific and most likely vary with water control and occurrence of drought as well as salinity intrusion and their possibility of regulation by hardware.

Some techniques can be easily introduced in CA based management of the crops and give flexibility in the overall management of the crops sequence. We can list the possibility of broadcast sowing in standing mulch before its control, the “ratoon” rice production (secondary harvest on regrowing rice stalks). This latter option should be tested and compare to currently proposed action to introduce a double summer-autumn crop by transplanting a short cycle variety after 30-40 days in nursery, right after a first short cycle rice harvest. In addition, “ratoon rice” is a low / no risk option that could be conducted with the implementation of a cover crop species (hydromorphic / high water tolerant species to be selected).

Such alternative should be progressively built up and adjusted through participatory approaches mixing farmers groups and extension services and researchers. These platforms developed in key agro-ecosystems, selected for their importance and sensibility to foreseen changes could become central tools to support complex and collective transition processes that involved multilevel and coordinated decisions. These platforms could serve in the meantime of reference point to assess GHG emissions and CC attenuation potential of the designed innovations.

Photo 1 and 2: Illustration of a transition from double rice to rice – brackish succession in 3 years.

Photo 1: 11th February 2013 (south permanent aquaculture; North: maturing or harvested winter-spring rice
Photo 2: 29th February 2016 (south unchanged; North dominant of shrimp culture, few harvested rice)
9°04'43 N and 104°55'49 E / # 3,4 km altitude (© Google Earth)

Agricultural policies and institutional supports

Inducing systemic changes require greater flexibility but also different extension approach, necessarily bottom-up, combining training to understand new principles and access to attached know-how and requested technical production factors (i.e., agricultural implements, seeds …). By contrast, technical message attached to thematic adjustment (i.e. new rice varieties, fertilizer use, water management …) are simpler, and more easily exposed and diffused.

Shifting to DMC systems require a set of conditions that most of the time are not in place when starting the process of co-designing cropping systems with smallholders. Some could be related to technical difficulties and the need to have access to specific tools (i.e., seeds of cover crops, roller crimper, no-till planter ...). Others difficulties could be related to the level of understanding among farmers to keep the crop residues on field to improve soil fertility, diversifying their crops and using key cover crops. Perception of the positive effects of DMC by farmers and further appropriation of a new rationale for fertility management could be slow. Practicing DMC is an iterative learning process where smallholders will progressively improve their knowledge and skills. Cash disposal is also one of the main constraints that smallholder farmers face. Financial tools should be in place addressing both the usual households' deficit of cash flow and the investment capacity. These series of remarks highlight the complex elaboration of the DMC-based technical pattern. The cropping systems design process has to progress with the triggered biological transformations of the agro-ecosystems at field and landscape levels; it has also to evolve through and under an evolutionary perception and appropriation of the new practices by farmers supported by financial and institutional supports.

Agricultural policies need to account for the needs of both mitigation and adaptation. Investing substantially in **adapting rice farming to climate change** can result in substantial mitigation co-benefits. Economic incentives (*e.g.*, special credit lines for low-carbon rice farming, sustainable agriculture, payment for ecosystem services) and regulatory approaches (e.g., enforcement of environmental law controlling air and water pollution) should be implemented to foster the dissemination of climate smart cropping systems. Investments in scientific knowledge (assessing GHG for a range of rice farming systems and practices), development (designing alternative rice cropping systems), and diffusion (increase of resource use-efficiency) are of paramount importance to build synergies between adaptation and mitigation. By contrast a lack of investment will result in limited scientific and policy knowledge, as well as institutional and farmers' own financial and cognitive constraints.

Adaptation and mitigation to climate changes should be integrated in strategic plans to address complexed challenges in various regional rice production contexts. There is a need to bring together a large range of stakeholders and particularly joining water management and agricultural institutions with:

- policy-makers to deal with changes linked to multiple drivers such as socio-economic evolutions (i.e., urbanization, population growth, new trade-offs around water resource) and environmental changes (i.e., climate change, its immediate impact on weather variability, medium and long term impacts on average temperature and sea level rise),
- civil engineers to design new forms of infrastructures facilitating sediment deposition recognized as a potential adaptation strategy and incorporated recently into the management plans of the Mekong delta (MDP, 2013),
- farmer's organizations and agronomists to design alternative and innovative diversified rice farming systems **to first adapt** these systems to environmental attributes that are becoming unstable and changing at an accelerating rate.

Acknowledgments

This report was developed with funding from the Agence Française de Développement.

References

Ahn, J., Choi, M., Kim, B., Lee, J., Song, J., Kim, G., Weon, H., 2014. Effects of water-saving irrigation on emissions of greenhouse gases and prokaryotic communities in rice paddy soil. Environ. Microbiology 68: 271–283

Arai, H., Hosen, Y., Van Nguyen, P. H., Nga, T. T., Chiem Nguyen, H., Inubushi, K., 2015. Greenhouse gas emissions from rice straw burning and straw-mushroom cultivation in a triple rice cropping system in the Mekong Delta, Soil Science and Plant Nutrition, 61 (4): 719-735, DOI: 10.1080/00380768.2015.1041862

Bossio D.A., Horwatha W.R., Mutters R.G., van Kessel C., 1999. Methane pool and flux dynamics in a ricefield following straw incorporation, Soil Biology and Biochemistry 31: 1313–1322

Boulakia, S., Trang, S., Leng, V., Kou, P., 2013. Primary Development of DMC based cropping systems for irrigated lowland rice on poor Sandy Soil 2011 – 2012. Report GDA/PADAC. 24 pp

Bouman, B.A.M., Lampayan, R.M., Tuong, T.P., 2007. Water Management in Irrigated Rice: Coping with Water Scarcity. International Rice Research Institute, Manila, Philippines, pp. 53

Bush, R., Sullivan, L., Johnston, S., Burton, E., Wong, V., Keene, A., 2010. Climate change: a frontier for acid sulfate soil research. 19th World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia

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

Carew-Reid, J., 2008. Rapid Assessment of the Extent and Impact of Sea Level Rise in Viet Nam. Brisbane: International Centre for Environmental Management (ICEM). http://www.icem.com.au/documents/climatechange/icem_slr/ICEM_SLR_final_report.pdf (accessed 24 July 2017)

CGIAR Research Centers in Southeast Asia, 2016. The drought and salinity intrusion in the Mekong River Delta of Vietnam. Assessment Report. 54 p.

Chapman, A., Darby, S., 2016. Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. Science of the Total Environment 559: 326–338

Chapuis-Lardy, L., Wrage, N., Metay, A., Chotte, J.L., Bernoux, M., 2007. Soils, a sink for N_2O? A review. Global Change Biology 13: 1–17, doi: 10.1111/j.1365-2486.2006.01280.x

Chapuis-Lardy, L., 2016. Assessing N_2O emissions in rice farming systems. Atelier de travail COSTEA sur la riziculture et le changement climatique Montpellier, 9/6/2016.

Chau, N.D.G., Sebesvari, Z., Amelung, W., Renaud, F.G., 2015. Pesticide pollution of multiple drinking water sources in the Mekong Delta, Vietnam: evidence from two provinces. Environ Sci Pollut Res 22: 9042–9058

Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenberg, N. Sampson, D. Sauerbeck, and Q. Zhao, 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutrient Cycling in Agroecosystems, 49, pp. 221-228.

COSTEA, 2016. Atelier de travail COSTEA sur la riziculture et le changement climatique Montpellier, 9/6/2016. 8pp

Coulon, C., Dim, W., Bouarfa, S., Bernoux, M., Poirier-Magona, E., Rossin, N., Jamin, J.Y., Boulakia, S., Gilard, O., Hofmann, A., Rollin, D., 2016. Notes de synthèse Riziculture et changement climatique. Comment quantifier et réduire les impacts de la riziculture irriguée sur le changement climatique ?

Davidson E.A., Keller M., Erickson H.E., Verchot L.V., Veldkamp E., 2000. Testing a conceptual model of soil emissions of nitrous and nitric oxides. BioScience, 50: 667–680

FAOSTAT (2013). FAOSTAT database. Food and Agriculture Organization of the United Nations. Available at: http://faostat.fao.org/.

Fortier, F., and Tran Thi Thu Trang, 2013. Agricultural Modernization and Climate Change in Vietnam's Post-Socialist Transition. Development and Change, 44 (1): 81–99

Fukuoka, M., 1978. The One Straw Revolution, an Introduction to Natural Farming. Ed by Larry Korn, Rodale Press, 33 E Minor St., Emnaus, PA 18049

Gadde B., Bonnet S., Menke C., Garivait S., 2009. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ. Pollut., 157/ 1554–1558. doi:10.1016/j.envpol.2009.01.004

Hoang, T.X., Cong, S.P., Ulubaşoğlu M.A., 2016. The role of rice in poverty dynamics in rural Vietnam: 2002–2008. Journal of the Asia Pacific Economy, 21 (1): 132-150. DOI: 10.1080/13547860.2015.1068600

Hong Van N.P., Nga T.T., Arai H., Hosen Y., Chiem N.H., Inubushi K., 2014. Rice straw management by farmers in a triple rice production system in the Mekong Delta, Vietnam. Trop. Agr. Develop., 58: 155–162

Houghton R. A., House, J. I. , Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9, 5125 – 5142. doi: 10.5194 / bg-9 - 5125 - 2012, ISSN: 1726-4189

Huan N.H., 2005. Review on pesticide use in pest management in Vietnam. Plant Protection Department, Ministry of Agricuture and Rural Development. p 10

Husson O., Tran Quoc H., Boulakia S., Chabanne A., Tivet F., Bouzinac S., Lienhard P., Michellon R., Chabierski S., Boyer J., Enjalric F., Rakotondramanana, Moussa N., Jullien F., Balarabe O., Rattanatray B., Castella J.C., Charpentier H., Séguy L., 2016. Co-designing innovative cropping systems that match biophysical and socio-economic diversity: The date approach to Conservation Agriculture in Madagascar, Lao PDR and Cambodia. Renewable Agriculture and Food Systems, 31 (5): 452-470. DOI: 10.1017/S174217051500037X

Ibáñez, C., Day, J.W., Reyes, E., 2014. The response of deltas to sea-level rise: natural mechanisms and management options to adapt to high-end scenarios. Ecol. Eng. http://dx. doi.org/10.1016/j.ecoleng.2013.08.002

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Available online at http://www.ipcc-nggip.iges.or.jp (verified on March 20, 2016)

IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Janzen, H.H., 2004. Carbon cycling in earth systems - A soil science perspective. Agriculture, Ecosystems and Environment, 104: 399-417

JICA, 2013. The project for climate change adaptation for sustainable agriculture and rural development in the coastal Mekong Delta in Vietnam. Final Report. Japan International Cooperation Agency. p. 425

Ladha J.K., Tirol-Padre A.C., Punzalan M., Watanabe I., 1987. Nitrogen-fixing (C2H2 reducing) activity and plant growth characters of 16 wetland rice varieties, Soil Sci. Plant Nutr. 33: 187–200

LaHue, G.T., Chaney, R.L., Adviento-Borbe, M.A., Linquist, B.A., 2016. Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. Agriculture, Ecosystems and Environment 229: 30–39

Lampayan, R.M., Rejesus, R.M., Singleton, G.R., Bouman, B.A.M., 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Research 170: 95–108

Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: A review. Eur. J. Soil Biol. 37: 25−50

Lienhard P., Tivet F., Chabanne A., Dequiedt S., Lelièvre M., Sayphoummie S., Leudphanane B., Prévost-Bouré N.C., Séguy L., Maron P.-A., Ranjard L. 2013. No-till and cover crops shift soil microbial abundance and diversity in Laos tropical grasslands. *Agronomy for sustainable development*, 33 (2): 375-384. dx.doi.org/10.1007/s13593-012-0099-4

Linquist, B.A., van Groenigen, K.J., Adviento-Borbe, M.A.A., Pittelkow, C., van Kessel, C., 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob. Change Biol. 18: 194–209.

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

Lu, W.F., Chen W., Duan B.W. et al, 2000. Methane emissions and mitigation options in irrigated rice fields in Southeast China. Nutrient Cycling Agroecosystem 58(1): 65–73

Ly, P., Jensen, L.S., Bruun, T.B., Neergaard, A., 2013. Methane (CH_4) and nitrous oxide (N_2O) emissions from the system of rice intensification (SRI) under a rain-fed lowland rice ecosystem in Cambodia. Nutr Cycl Agroecosyst 97:13–27

MARD, 2010. Lists of pesticide permitted, restricted and banned for use in Vietnam (in Vietnamese). The circular of the Ministry of Agricultural and Rural Development, promulgated in April 2010. p. 231

Marland, G., R.A. Pielke Jr., M. Apps, R. Avissar, R.A. Betts, K.J. Davis, P.C. Frumhoff, S.T. Jackson, L.A. Joyce, P. Kauppi, J. Katzenberger, K.G. MacDicken, R.P. Neilson, J.O. Niles, D.S. Niyogi, R.J. Norby, N. Pena, N. Sampson, and Y. Xue, 2003. The climatic impacts of land surface change and carbon management, & the implications for climate-change mitigation policy. Climate Policy, 3, pp. 149-157

Mayer H.P., Conrad R., 1990. Factors influencing the population of methanogenic bacteria and the initiation of methane production upon flooding of paddy soil, FEMS Microbiol. Ecol. 73: 103–112

MDP, 2013. Mekong Delta Plan: Long-term vision and strategy for a prosperous and sustainable delta

Miura Y., Kanno T., 1997. Emissions of trace gases (CO2, CO, CH4, and N2O) resulting from rice straw burning. Soil Sci. Plant Nutr., 43: 849–854. doi:10.1080/ 00380768.1997.10414651

Mekong River Commission, 2010. 'Assessment of Basin-wide Development Scenarios Technical Note 8: Impacts of Changes in Salinity Intrusion'. Vientiane: Mekong River Commission.

Mosier, A.R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami, and D.E. Johnson, 1998. Mitigating agricultural emissions of methane. Climatic Change, 40: 39-80

Nazaries L, Murrell JC, Millard P, Baggs L, Singh BK, 2013. Methane, microbes and models: fundamental understanding of the soil methane cycle for future predictions. Environmental Microbiology, 15: 2395–2417

Neue, H.U., Wassmann, R., Kludze, H.K., et al, 1997. Factors and processes controlling methane emissions from rice fields. Nutr Cycl Agroecosyst 49 (1): 111–117Ngo D.P. and Wassmann R., 2016. Climate change affecting land use in the Mekong Delta: Adaptation of rice- based cropping systems (CLUES) SMCN/2009/021. Final report. ISBN 978-1-925436-36-5. ACIAR, Canberra, Australia

Nguyen Huu Dung and Tran Thi Thanh Dung, 2003. 'Economic and Health Consequences of Pesticide Use in Paddy Production in the Mekong Delta, Vietnam'. Ottawa: IDRC

Nguyen Thi Thu Ha, C. A. J. M. De Bie , Amjad Ali , E. M. A. Smaling & Thai Hoanh Chu, 2012. Mapping the irrigated rice cropping patterns of the Mekong delta, Vietnam, through hyper-temporal SPOT NDVI image analysis, International Journal of Remote Sensing, 33:2, 415-434, DOI: 10.1080/01431161.2010.532826

Nguyen Van Viet, 2011. 'Climate Change and Agricultural Production in Vietnam', in W. Leal Filho (ed.) Climate Change Management: Economic, Social and Political Elements of Climate Change, pp. 227–43. Berlin and Heidelberg: Springer.

Pandey, A., Mai, V.T., Vu, D.Q., Bui, T.P.L., Mai, T.L.A., Jensen, L.S., de 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

Pingali, P.L., T.K. Nguyen, R.V. Gerpacio and T.X. Vo, 1997. Prospects for Sustaining Vietnam's Reacquired Rice Exporter Status. Food Policy 22(4): 345–58.

Van Toan, P., Sebesvari, Z., Bläsing, M., Rosendahl, I., Renaud, F.G., 2013. Pesticide management and their residues in sediments and surface and drinking water in the Mekong Delta, Vietnam. Science of the Total Environment 452–453: 28–39

Räsänen,T.A., Kummu, M., 2013. Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. Journal of Hydrology 476 (2013) 154–168. doi:10.1016/j.jhydrol.2012.10.028

Richards, M., Sander, B.O., 2014. Alternate Wetting and Drying in Irrigated Rice: Implementation Guidance for Policymakers and Investors. Internet Resource. https://cgspace.cgiar.org/bitstream/handle/10568/35402/info-note_CCAFS_AWD_final_A4.pdf.

Savant, N.K., Stangel, P.J., 1990. Deep placement of urea supergranules in transplanted rice: principles and practices. Fertil. Res. 25, 1–83

Schimel, J., 2000. Rice, microbes and methane. Nature 403: 375–377

Séguy, L., S. Bouzinac, A. Trentini, and N. Cortes, L'agriculture brésilienne des fronts pionniers (Brazilian frontier agriculture). Agriculture et Développement, 1998. Special Issue (12): p. 1-74.

Séguy L, Bouzinac S, Husson O. 2006. Direct-seeded tropical soil systems with permanent soil cover: Learning from Brazilian experience. In: Uphoff N, Ball AS, Fernandes E *et al.* (eds) *Biological approach to sustainable soil systems,* pp 323-342. CRC Press, Taylor and Francis.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K. Paustian, 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biology, 10: 155-160

Smajgl, A., Toan, T.Q., Nhan, D.K., Ward, J., Trung, N.H., Tri, L. Q., Tri, V. P. D., Vu, P. T., 2015. Responding to rising sea levels in the Mekong Delta. *Nature Climate Change* 5: 167–174. doi:10.1038/nclimate2469

Smith, K.A. and F. Conen, 2004. Impacts of land management on fluxes of trace greenhouse gases. Soil Use and Management, 20, pp. 255-263

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Streets D.G., Yarber K.F., Woo J.H., Carmichael G.R., 2003. Biomass burning in Asia: annual and seasonal estimates and atmospheric emissions. Global Biogeochem. Cycles, 17, 1099–1118. doi:10.1029/2003GB002040

Tivet F., Sá J.C.M., Lal R., Briedis C., Borszowskei P.R., Bürkner dos Santos J., Farias A., Eurich G., Da Cruz Hartman D., Nadolny Junior M., Bouzinac S., Séguy L., 2013. Aggregate C depletion by plowing and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Soil and tillage research, 126: 203-218. [20121113]. dx.doi.org/10.1016/j.still.2012.09.004

Tyagi, L., Kumari, B., Singh, S.N., 2010. Water management: a tool for methane mitigation from irrigated paddy fields. Sci Total Environ 408(5): 1085–1090

Ut Tran Thi and K. Kajisa, 2006. The Impact of Green Revolution on Rice Production in Vietnam. Developing Economies 44(2): 167–89

Ut T.T., 2002. The impact of Green Revolution on rice production in Vietnam. Green Revolution in Asia and its transferability to Africa. p. 32. [Tokyo].

Vidal, A., Sander, B.O., Wasmann, R., 2016. Alternate Wetting & Drying (AWD), a climate smart practice. Atelier COSTEA sur la riziculture et le changement climatique Montpellier, 9/6/2016

Vien T.D., Hoi P.V., 2009. Pesticide dependence in agriculture: policy for productivity and policy for security in Viet Nam. In: Umegaki M, Thiesmeyer L, Watabe A, editors. Human insecurity in East Asia. United Nations University Press. p. 22.

Wang, J., Zhang, X., Xiong, Z. et al., 2012. Methane emissions from a rice agroecosystem in South China: effects of water regime, straw incorporation and nitrogen fertilizer. Nutr Cycl Agroecosyst 93(1):103–112

Wassmann, R., Lantin, R.S., Neue, H.U., Buendia, L.V., Corton, T.M., Lu, Y., 2000. Characterization of methane emissions from rice fields in Asia. III. Mitigationoptions and future research needs. Nutr. Cycl. Agroecosyst. 58, 23–36

Weis, A., 2010. The Accelerating Biophysical Contradictions of Industrial Capitalist Agriculture; Journal of Agrarian Change 10(3): 315–41

WRI, 2016. World Resources Institute World greenhouse gas emissions in 2005. Available at: http://www.wri.org/publication/world-greenhouse-gas-emissions-2005 (accessed August 2016).

Xu, Y., Ge, J., Tian, S., Li, S., Nguy-Robertson, A.L., 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. Sci. Total Environ. 505, 1043–1052.

Yu,B., T. Zhu, C. Breisinger and N.M. Hai (2010) 'Impacts ofClimate Change on Agriculture and Policy Options for Adaptation: The Case of Vietnam'. IFPRI Discussion Paper. Washington, DC: International Food Policy Research Institute (IFPRI).

Zou J, Huang Y, Zheng X, Wang Y (2007) Quantifying direct N2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmospheric Environment, 41, 8030–8042.