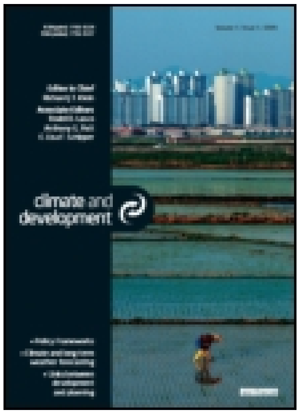

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REVIEW ARTICLE

The stress of climate change on water management in Cambodia with a focus on rice production

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As a least developed country, Cambodia has limited infrastructure to respond to the ongoing and anticipated stress imposed by climate change. This article uses existing publications to examine the potential impact of climate change on water resources and reviews possible adaptation and mitigation strategies, with particular emphasis on rice crop management. The development of agriculture and hydropower is proceeding quickly and it is critical that climate change be considered in such growth. The intensity of storms and severity of droughts appear to be increasing. The infrastructure must adapt for more extreme weather instability. To satisfy the increasing demands for food and to stimulate Cambodia's economy, rice production must increase and irrigation systems must be greatly improved. A more climate-change-resilient option for rice growing includes methods using less water, which result in oxic soils and much less release of methane, contributing less to greenhouse gas emissions. The required changes would be implemented more quickly by the mitigation approach of carbon trading of modified rice culture, which could augment food production, reduce greenhouse gases, and help poor rice farmers make a better living.

Keywords: agriculture; carbon trading; climate change; Southeast Asia; water management

1. Introduction

Cambodia is located in Southeast Asia with a tropical monsoon climate and two seasons: wet and dry. Severe fluctuations in weather currently result in the hardship from floods and droughts (Dany, Kamal, Vuthy, & Chanthoeun, 2010). Most Cambodians live in the floodplains of either the Mekong River or Tonle Sap Lake. The ecology and people who live here have adapted to annual floods that have resulted in soils that are well suited to rice growing. From the early ninth through the fifteenth century, the Khmer kingdom had developed extensive irrigation systems that in synchrony with a rich fishery supported the city of Angkor, the largest low-density urban complex of the pre-industrial world (Fletcher et al., 2003). Although many of the wetlands were modified to produce rice, the remaining wetlands are still the source of about 75% of the estimated 2 million tons of fish and other aquatic animals consumed in the lower Mekong River Basin annually (Millennium Ecosystem Assessment, 2005). Unfortunately, only 14% of Cambodia's rice paddies have irrigation and can only produce one crop of rice a year (Yu & Diao, 2011). Water management must not only be updated to increase irrigation in order to enhance agricultural production, but it must also reflect the major changes in hydrology from hydroelectric dams and anticipated effects of climate change. The impacts from climate change and other change factors such as hydroelectric development will likely seriously impair the Tonle Sap ecosystem (Keskinen et al., 2009). This article reviews some of the potential impacts and adaptation strategies for the water resources sector in Cambodia in association with climate change. We particularly focus on rice management practices as a mechanism to increase food security and reduce greenhouse gas emissions.

The watershed of Tonle Sap Lake is highly unusual in that during the wet season, the Tonle Sap River changes direction and floods the 'great lake', increasing its size four- to five-fold (Keskinen et al., 2009; Penny, 2006). The lake subsequently drains back towards the Mekong River during the dry season. This pulsing system hydrology results in the Tonle Sap Lake being one of the most productive inland fisheries in the world (SCW, 2006) and has a major effect on the fishery of the Mekong River. There is apparently only one other large river system with the unusual hydrology of the Tonle Sap River, the Athabasca River, part of the Mackenzie River in Northern Canada; its productivity was compromised by a large hydroelectric dam (Peter, Prowse, Pietroniro, & Leconte, 2005).

2. Paleoclimate changes

Since there is a relatively short history of weather recordings for this region, it is useful to review the paleoclimate. There is a strong prehistorical record of major climate changes in Cambodia. Large and relatively rapid changes

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in climate have been inferred from analysis of sediment cores taken in Cambodia. From a study in NE Cambodia, Maxwell (2001) observed an 'abrupt transition to a warmer, more humid climate' (p. 397) around 8400 ^{14}C years B.P. The early to mid-Holocene precipitation maximum was followed by a transition to drier conditions, usually involving stronger seasonality. By using sediment cores from the Tonle Sap Lake, Penny (2006 and 2008) confirmed Maxwell's observations of a mid-Holocene precipitation maximum. He also commented that 'dramatic changes are apparent in both the pollen record and particle size data at 5200 BP' associated with a more seasonal and seasonally drier environment (Penny, 2006). Penny also reviewed some of the effects of the 5-m rise in sea level above modern levels. As well as extensive flooding along the lower Mekong River, there were probably intrusions of saline water into the Tonle Sap River and more stable and higher than the present water levels in the Tonle Sap Lake.

More recent changes were discovered by Bishop, Penny, Stark, and Scott (2003). In the lower Mekong River floodplain, an abrupt change during the fifth to sixth century A.D. involved a dramatic reduction in grasslands and the expansion of secondary forest or re-growth taxa. Tree ring analysis has also shown relatively recent changes in historical climate. Analysis of tree cores in Southeast Asia discovered at least four mega-droughts dating back 722 years (Cook et al., 2010). Cambodia was hit by a severe and prolonged drought from 1415 until 1439, coinciding with the period during which many archeologists believe that the Kingdom of Angkor collapsed. Buckley et al. (2010) also reported in this same period extensive infilling of irrigation systems with earth and sand reflecting intense rainfalls. Hence, perhaps the Thai invasion and subsequent fall of Angkor in 1431 was in part set up by collapse of agricultural productivity caused by a long period of severe weather variability.

3. Recent and future changes in climate: implications for flooding

The normal weather in Cambodia varies seasonally from heavy rains to droughts. The dry season goes from November to mid-May, while the rainy season generally begins mid-May and lasts until October. The highest average temperatures are 26–30°C during early summer months and remain between 25 and 27°C throughout the rest of the year (McSweeney, New, & Lizcano, 2008). The same study also reported that the mean annual temperature has increased by 0.8°C since 1960 with a decadal rate of around 0.18°C. A more rapid increase occurred during drier months (December to May) at a rate of 0.20–0.23°C per decade while the rate in wet season temperature (June to November) was between 0.13 and 0.16°C. It was projected that the mean annual temperature will increase by 0.7–2.7°C by the 2060s and 1.4–4.3°C by the 2090s (McSweeney et al., 2008).

Keskinen et al. (2009) reported that rainfall in the first half of the last century fluctuated, while their model showed that rainfall increased in the second half of the century. Rainfall is predicted to increase markedly over mainland Southeast Asia and become more intense and more variable, leading to an increase in the frequency of flooding (AIACC, 2006), particularly after 2030 (Hu, Latif, Roeckner, & Bengtsson, 2000). An increase in the intensity of storms seems to be a global response to climate change (IPCC, 2011; Schiermeier, 2011). Projections suggest a gradual 4.3% increase in the annual average discharge of the Mekong at Kratie station from 2010 to 2049 compared to the 1980s (Keskinen et al., 2009) and a 25–40% increase in the discharge of the Mekong River is predicted by the end of this century (Falloon & Betts, 2006). A modeling review by Mainuddin et al. (2010) predicts interesting differences between the wet and dry seasons. In the wet season a combined effect of hydroelectric dam development and climate change may cause a decrease of up to 13% in discharge at one station, but an increase of 3% at another station. Whereas in the dry season they predict that the effect of both climate change and development may cause an increase of discharge of up to 40–76%. Their analysis indicates that higher flows in the dry season could result in an increase in the minimum level of Tonle Sap of 30 cm.

For Asia, water and agriculture are the most vulnerable sectors to climate change (IPCC Working Group II, 2001b). High temperatures, severe droughts, floods and associated soil degradation are projected to impair agricultural productivity in Asia (Vastila, Kummu, Sangmanee, & Chinvanno, 2010; Wassmann et al., 2004). Climate change will decrease food availability in other ways too. Partly because of the anticipated increase of fish diseases, aquaculture in Asia is also threatened (Dikitanan, 2009). Projections suggest that large deltas and low lands of Asia could be inundated by sea-level rise (IPCC Working Group II, 2001). Inundation of the lowest parts of the delta in Vietnam and more potent storm surges may lead to increased back-flooding higher in the delta. Saltwater intrusion further inland is expected but only the worst projections associated with complete melting of the ice caps in Greenland and Antarctica would result in the Tonle Sap River having pulses of brackish water as it was in the mid-Holocene (Penny, 2008).

The intensity of recent storms adds to natural flooding processes that are already difficult to manage. In the rainy season, the Tonle Sap Lake is four to five times larger than in the dry season with flooding in surrounding provinces moving the shoreline up to seven kilometers (Dany et al., 2010; Penny, 2006). Similarly in this season, the Mekong River can overflow its levees by four meters in some places with flooding occurring in areas from

Kratie to the Vietnamese border (Dany, Kamal, Vuthy, & Chanthoeun, 2010).

In 2009, the rainy season came several weeks early in Cambodia. Surprisingly, there was a drought in August which is normally the third to fourth wettest month. This drought damaged at least 2% of the rice crop (Sophal, 2009) and in parts of Pursat Province, 60% of the rice crop died (D. Emery, Sustainable Cambodia, personal communication). Later in September there was a series of heavy storms, including the worst on record (Ketsana). At least 54 people were killed in Typhoon Ketsana and related storms days after Ketsana (Channyda & Paynton, 2009). Moreover, over 40,000 ha of crops were damaged by Typhoon Ketsana (Channyda & Paynton, 2009).

In SE Asia, the monsoon season of 2011 produced massive damage. In the Bangkok region of Thailand, the World Bank estimated, as of 1 December 2011, 1425 billion baht (US$ 45.7 billion) in economic damages and losses due to flooding, and this ranked as the world's fourth costliest disaster (Koontanakulvong, 2012). In part because of the huge capital and human losses to Thailand, Cambodia received less world attention. The United Nations reported that Cambodia suffered 247 deaths by drowning during the monsoon season. As of 7 November 2011, 9.4% of the rice crop was destroyed (UNCS, 2011). Over a thousand schools were damaged, as were major highways and medical centers. Over 46,000 houses had to be evacuated and more than 300,000 houses were affected.

Figure 1 shows the flooding immediately north of Phnom Penh. Normally, the Mekong River will flood but not as extensively as shown in this picture. The tops of the levee of the Mekong River can be seen clearly in the bottom of the picture. However, the outline of the major tributary that joins the Mekong River in Phnom Penh, the Tonle Sap River, is only visible in the top of the picture as meandering parallel lines, the tops of the levees. Figure 2 illustrates the extremes of water elevation observed along the Tonle Sap River in the city of Phnom Penh. The major parts of the city escaped much of the flooding but most of the neighboring flood plains were inundated. About 3.3 million hectares were flooded (Figure 3). As serious as these problems were, the flood stage at MRC monitoring stations around Phnom Penh in 2011 was not significantly different from the last big flood in the Phnom Penh area in 2000 (http://ffw.mrcmekong.org/historical_data/2011/his_data11.htm). It is quite possible that neither the 2000 nor the 2011 floods were the scale of a potential 100-year flood, i.e. without any consideration of impending changes, the potential for a more serious future flooding exists. The predicted future includes the potential for more intense rainfall and associated increases in flooding depth and duration. The IPCC report on extreme weather that was released in November 2011 predicted a doubling of severe weather in SE Asia (IPCC, 2011). Mainuddin et al.'s report (2010) also predicts more frequent and more extreme high flows that may require consideration of flood mitigation.

Evaluation of flooding in the Bangkok region in 2011 is relevant to the development of Cambodia. Koontanakulvong (2012) stated that 'While the pattern and volume rainfall set up the floods', it was aggravated by 'water management for irrigation', 'unsystematic flood fighting system', and 'inefficient drainage/protective facilities'. The latter two problems were identified in a study conducted in 1998 (Golder Associates, BTG-Golder Co. Ltd., Murphy, Wastewater Technology International Corp. & Barbara Herring and Associates, 1998). These aspects must be considered in the development of water resources in Cambodia and changes in hydraulics associated with the development of the wetlands around Phnom Penh.

4. Anticipated hydraulic development

Irrigation, hydropower dams and drainage in Cambodia are in the process of rapid change and must avoid the mistakes that exacerbated the heavy rains around Bangkok into massive flooding. Since 2008 more than 7 million hectares of land in Cambodia have been granted as concessions to private firms with perhaps a third of this for agriculture (Titthara, 2011). In central Cambodia, large sections of the Siem Bok, Stung Chinit and Stung Sen rivers will be converted to irrigation dams to service large plantations (Forbes, 2011); these rivers are about 100 km long. The public review is often limited and there has been some international concern over how expropriations for developments have taken place (Amnesty International, 2008; BBC, 2009). There was little coordination in the development of large rice irrigation projects in the Tonle Sap Lowland. In 2010, the Fisheries Department started destruction of 113 rice irrigation reservoirs spanning in total 10,000 ha in Kampong Thom Province (Ana & Vrieze, 2010). The owners of these private irrigation reservoirs claimed support from local governments. Similar actions against illegal reservoirs were initiated in the other provinces around the Tonle Sap Lake. From an engineering viewpoint of irrigation it might seem more cost effective to build a reservoir on a drainage course but this would have much more impact on fisheries than reservoirs trapping rainfall in the limited water shed of an excavated pond with earthen berms around it. There is a trade off with fisheries and land area required for water retention and storage. A deeper pond would take less land but if placed on a drainage course would impact fisheries. A shallow (2 m) rainfall-filled pond would have minimal fisheries impact but take more land from agricultural production. There is a need for this simple hydrology to be evaluated in consultation with the Fisheries Department to determine what options are cost-effective for agriculture and have minimal fisheries impact.

Figure 1. Flooding on 13 October 2011 immediately north of Phnom Penh.

The effects of climate change need to be part of the planning of new developments and at times will influence the social and engineering aspects of such developments. Cambodia must prepare for more climate change. Development of new reservoirs and irrigation canals and diversification of agriculture are essential. Some new irrigation reservoirs will be built with a capacity for hydroelectric production which imposes another set of change factors. The theoretical hydropower potential of Cambodia was estimated by the World Bank (2006) at 10,000 MW. The largest dam site near Kratie on the Mekong River can potentially produce as much as 4700 MW. There will likely be massive losses of fish production and fish biodiversity due to dams on the Mekong River (Ziva, Baran, Nam, Rodríguez-Iturbe, & Levina, 2012). Once the transmission lines are built for power export, the construction costs for additional dams are less and it could be argued that once fish stocks are greatly damaged by an upstream dam such as in Laos, there is less to lose by further dam construction downstream in Cambodia. Once major fish migrations have stopped, fisheries will collapse and the people that depend on them will have to find another way to live (Baird, 2009a). Orr, Pittock, Chapagain, and Dumaresq (2012) predict that hydroelectric dams will result in Cambodia using 29–64% more water for agriculture to make up for protein supplies lost by the developing hydroelectric dams. However, development will have positive aspects for agriculture. At least in the Tonle Sap Basin and likely in many areas of Cambodia the electrical development would facilitate construction of pumping stations for water movement. Canada has done the equivalent to trap runoff from the Rocky Mountains to irrigate wheat and other cereal crops in areas with inadequate water supplies (Irrigation in Alberta, 2013). The technology for growing cereals with irrigation water from mountains is well established (or for that matter, from groundwater such as the Ogallala Aquifer in the US). However, the future economics of growing rice is unknown and other crops might become more profitable as a second crop in the dry season.

It has been argued that the Environmental Impact Assessments (EIAs) associated with the larger dam projects do not adequately address the complications of Tonle Sap hydrology and fisheries (Lamberts, 2008). A review by Grumbine, Dore, and Xu (2012) also agrees that EIAs in the region downplay ecological and social factors, but goes further to say that they are often focused solely on the country that carries them out, and upstream and downstream impacts are not considered cumulatively. Development of dams on the tributaries of the Mekong River has caused severe problems downstream of dams such as on the Sesan River (SWECO Grøner, NIVA, ENVIRO-DEV, & ENS Consult, 2006; Tiodolf & Stålnacke, 2009). Tiodolf and Stålnacke (2009) reported toxic algae including *Microcystis* and disturbing skin irritations apparently caused by water contact but originating in the upstream reservoir. Projections for the Sesan 2 hydroelectric dam include 100,000 people losing access to migratory fish, relocation of 4800 people and the destruction of 30,000 ha of forest (Baird, 2009b). The new hydroelectric dams will cause hydrologic and fisheries impacts that will exceed the current and anticipated changes from global warming (Keskinen et al., 2009). Mainuddin et al. (2010) state that climate change alone would probably not significantly reduce fish production, but concur that hydroelectric dams could probably impact fisheries. The summary EIA on hydroelectric dams done for the Mekong River Commission stated, ‘If all mainstream projects were to proceed, Viet Nam and Cambodia are likely to suffer net short to medium term losses because the combined effects on

Figure 2. (a and b) Views of the Tonle Sap River in Phnom Penh on 30 September 2011 (flooding) and 18 April 2010 (end of dry season).

fisheries and agriculture would outweigh power benefits' (ICEM, 2010, p. 11).

5. Social changes related to climate change

Cambodia is one of the most sensitive countries in Southeast Asia to climate change (Yusuf & Francisco, 2009). Cambodia lacks the infrastructure, trained professionals and finances to respond to changes. Cambodia is among the poorest countries in the world, ranking 139 of 187 countries in the 2011 Human Development Index (http://hdrstats.undp.org/en/countries/profiles/KHM.html, 2010data). The GDP per capita in 2010 was $760 (http://data.worldbank.org/country/cambodia). The problems in Cambodia go beyond the destruction of medical, educational and scientific agencies by the Khmer Rouge and time required to train a new generation.

A considerable portion of the economy of Cambodia is based on foreign aid or loans and climate change is typically a consideration in such support. To improve the finances of irrigation development, innovative solutions should be considered such as carbon trading. Moreover,

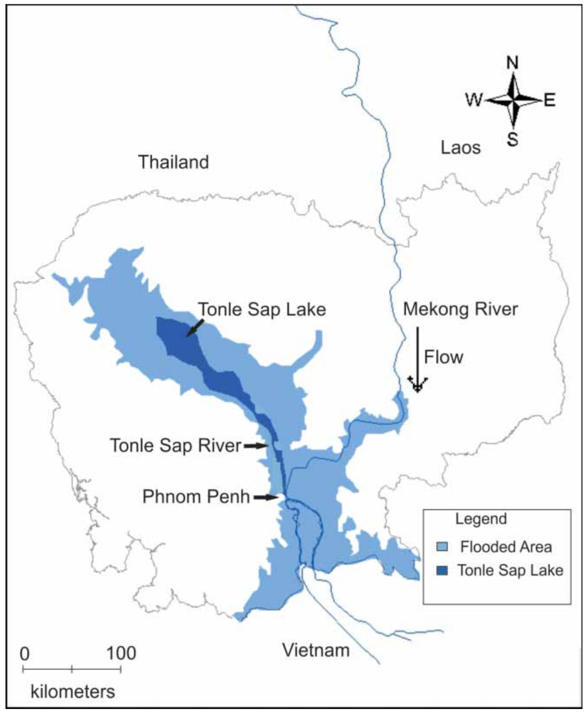

Figure 3. Map of the flooded area of Cambodia in 2011 (from UNCS, 2011).

any development must consider the ongoing changes in the countryside. Rice farmers are typically quite poor. 'Two thirds of the country's 1.6 million rural households face seasonal food shortages each year. Rice alone accounts for as much as 30% of household expenditures' (IFAD, 2007). Many farm families rely on support from the family members who have found employment either in the new factories in Phnom Penh or by working overseas. The farmers usually have neither funding nor labour for farm development (Tong, Hem, & Santos, 2011). The small size of rice farms limits their income and policies that encourage larger farms are an option; however, any push for rice plantations should consider the criticism of current farm consolidation since 'such approaches tend to dispossess, injure, or impoverish local communities, jeopardizing the viability of projects' (Shepherd, 2012).

6. Ongoing Clean Development Mechanism projects

The Clean Development Mechanism (CDM) is an arrangement under the Kyoto Protocol allowing industrialized countries with a greenhouse gas reduction commitment to invest in projects that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries. One of the five CDM projects approved by Cambodia's Designated National Authority (DNA) is for a hydroelectric dam in Kampot Province (Cambodia, 2009a; Gorin, 2011). It is currently undergoing validation. The following four CDM projects have been registered in the Cambodian CDM Executive Board: rice husk biomass cogeneration, biogas production, methane recovery at pig farm and cement waste heat power generation (IGES, May 2009). 'The main obstacle in developing more projects resides in the relative small size of projects which are not proportionate with the high transaction cost of CDM' (MOE and UNEP, 2010).

Development of wind power has been slow in part because of limited data on wind due to poor availability of monitoring equipment (http://www.recambodia.org/wind.htm). Williamson, McIntosh, Lopez, and Ponlok (2004) used model simulations to predict that 6% of the rural Cambodian population lives in areas with an annual average wind speed of 5–7 m/s at 30 m above ground level, which should be sufficient for village-scale wind energy. The two models that have been used to predict wind speeds deviate in a few important sites, such as the southern end of Tonle Sap Lake and Mount Aural (Cambodia, 2009b; CRCD, 2006). Studies have confirmed that the coast of Cambodia is suitable for wind power production and a commercial project was completed to supply wind power in Sihanoukville (Clean Energy Cambodia, 2011). Grants and loans have been available to builders of such power grids and they can own them (Cambodia, 2006). The lack of adequate wind greatly limits the potential to use wind power to pump groundwater for irrigation.

Much of the Tonle Sap Basin has adequate groundwater for irrigation but most, if not all, of this area has no wind power.

Solar power has been slow to develop because of the high initial investment. The first developments in Cambodia were a large assay of solar cells in Sihanoukville (Ponlok, 2004) and telecommunication installations. In part because of several funding initiatives, there are now over 12 vendors selling solar systems in Cambodia (Odrerir, 2009). Grants for 25% and loans for 50% of small projects with solar or mini hydroelectric power are available (REOREC, 2006). The United Nations Development Program and local organizations have, so far, cooperated with each other to install more than 500 solar electricity generators in rural areas of Cambodia, where electricity is not accessible in schools and referral hospitals (Bernama, 2009). We are unaware of any use of solar power systems in Cambodia to pump groundwater for irrigation. The capital cost would be beyond most farmers. However, we have often seen gasoline-powered pumps in Southern Cambodia (Kandal and Takeo provinces) for extraction of groundwater for rice culture. Bio-digesters, mini-hydroplants (MIME, 2011) and bio-gas generators (TTY Cambodia Biogas Project, 2007) are also being developed. Hopefully, new funding arrangements such as carbon trading can push these power developments. The supply of electricity in Cambodia is very unreliable and expensive and restricts business and the quality of life. The average price of Cambodian electricity is \$0.16/kWh but can be as high as \$0.90/kWh in remote rural areas (AsiaViews, October 2009). Outages and brown outs in Phnom Penh occur daily in most of the city (Open Development Cambodia, 2012). In 2005, only 12% of the Cambodian people had access to grid electricity supply (Chanthan & Mahe, 2005).

7. Management of rice agriculture and climate change

In spite of difficulties with implementation, some development, especially irrigation, is essential. The agricultural community in Cambodia is much less productive than its neighbors Thailand and Vietnam. Cambodia increased the proportion of rice paddies that produce two crops a year from 8% in 2004 (Samnang, 2004) to 14%, but this is only half of Thailand's irrigation (USDA, 2010) and a third of Vietnam's irrigation (Yu & Diao, 2011). Alternative crops and other methods of cultivating rice should at times be considered to reduce water use. Other rice culture options include direct seeding or drum seeding that can be done on dry land, albeit there are trade-offs from conventional transplanting of rice plants (IRRI, 2007). Cambodia has a significant capacity for development but it must consider climate change. Production of a second or third crop of rice a year with traditional methods will result in longer flooding of soils and more production of methane. One ton of methane produces about 21 times the effect of one ton of carbon dioxide on global warming (IPCC, 2007). Paddy rice farming produces roughly one-fifth to one-quarter of global methane emissions from human activities (Climate Change Information Sheet, 22) and this seems to be increasing. A decade ago, irrigated rice cultivation was estimated slightly lower at approximately 15–20% of the annual total of atmospheric methane (Sass & Fisher, 1997). Relative to carbon dioxide, methane contributes about half to a third as much global warming (Kiehl & Trenberth, 1997).

Other methods of cultivating rice should at times be considered to reduce methane release. Babu et al. (2005) found that additions of sulfate to rice paddies reduced methane emissions. This is basic redox biochemistry. Without oxygen, iron and manganese would be reduced before sulfate is reduced and in turn before methane is formed. Tropical soils such as laterites are highly weathered and often have low concentrations of sulfate, so the natural geochemistry favors methane formation. Midseason drainage (a common irrigation practice adopted in major rice growing regions of China and Japan) and intermittent irrigation greatly reduce methane emissions (Wassmann, Hosen, & Sumfleth, 2009). Mano et al. (2005) also observed a reduction in methane release associated with the seasonal drainage of water in midseason. Babu et al. (2005) also observed that increasing the length of midseason aeration reduced methane emissions. Yan, Akiyama, Yagi, and Akimoto (2009) call for midseason drainage of rice paddies to reduce methane release by 30%. Basically by using less water, soils can remain oxic, microbial metabolism changes and less methane is produced. In the dry season, midseason drainage would only be possible with irrigation water to rewet the field. In areas with modest irrigation supplies, midseason drainage would waste water. Moreover, in some situations the discharge of nutrient-rich water could impair downstream water quality.

The International Rice Research Institute developed a method of Alternate-Wetting and Drying (AWD) of fields that under saturated soil conditions on average used 23% less water with yield reductions of only 6% (Bouman et al., 2001; Tuong & Bouman, 2003). AWD potentially reduces methane emissions by 48% compared to continuous flooding of rice fields (FAO, 2010).

The rice culture method used in Cambodia that has a similar aerobic soil chemistry as AWD is the System for Rice Intensification (SRI). A collection of refereed publications and other reports on the SRI system can be found at http://sri.ciifad.cornell.edu/countries/. SRI is capable of producing more rice with 50% less water. However, the conversion to SRI is not seamless. It relies on a source of water for irrigation. Moreover, the farmers need control over the water supply, and frequent irrigation would take more time away from other potential income-earning activities. Also, the covering water layer of traditional rice culture suppresses weeds and more labor is required for weeding with SRI. Since farm incomes have not kept up with urban wages, farm labour is less available in Cambodia. SRI has been effective on larger systems but there is an ongoing debate on the suitability of SRI for large rice paddies. Mechanization of weeding in SRI has been proposed but is still simple (http://sri.ciifad.cornell.edu/countries/cambodia/index.html). SRI has been developed with the viewpoint of producing more food using less water but climate change and potential reductions of greenhouse gases and potential for carbon trading should also be considered in its management.

Initially, to conserve water the Ground Cover Rice Production System (GCRPS) was developed in China. Evaluations of GCRPS observed very modest levels of methane release (3–10 kg/hectare-year; Kreye aus Peine, 2004). Moreover, Kreye aus Peine (2004) found that there was no significant change in release of nitrous oxide, another greenhouse gas, under GCRPS as compared to regular rice paddy management. Such details are important in that nitrous oxide is 10 times more potent a greenhouse gas than methane (Li et al., 2004).

Complications arise when considering both methane and nitrous oxide release. Johnson-Beebout, Angeles, Alberto, and Buresh (2009) concluded that since methane forms under very reducing conditions and nitrous oxide forms under more oxic conditions, simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable only by redox control associated with flooding. However, they believe that appropriate water and residue management can reduce both greenhouse gas emissions. Advocates of SRI propose that by not watering as much, plants establish deeper roots, do not need any nitrogen fertilizer and would not release significant amounts of nitrous oxide (Uphoff, 2008). It remains to be determined how long nitrogen in deeper soils can sustain good production and what nitrogen applications might be required for rice production. Moreover, deeper roots are an important sink for carbon, and appropriate crop management that stimulated deeper roots would reduce atmospheric carbon dioxide (Kell, 2011).

Kimura (2008) validated Uphoff's ideas by showing that methane release was less under SRI management and that nitrous oxide emission was within the range of conventional field management. Similarly, Yang, Liu, Lai, and Liu (2003) found that intermittent irrigation in paddy fields significantly reduced methane emission and that conservative application of nitrogen fertilizers decreased nitrous oxide emission. McMillan, Goulden, and Tyler (2007) also showed that nitrous oxide emissions were associated with nitrogen fertilizers. Without better management of nitrogen fertilization, the benefits of SRI or other oxic rice culture methods producing less methane would be reduced. The degree of response of nitrous oxide and methane varies. In an evaluation of the effects of draining a rice field in mid-season to reduce methane release, Li et al. (2004) did observe lower methane release but they also observed increased nitrous oxide fluxes by 0.13–0.20 Tg N_2O-N/year, and that carbon dioxide fluxes were only slightly altered. Since nitrous oxide possesses a stronger radiative absorption than methane, the increase in nitrous oxide offset about 65% of the benefit gained by the decrease in methane emissions. Another important and related aspect is Zou, Liu, Qin, Pan, and Zhu's (2009) finding that sewage irrigation increased methane and nitrous oxide emissions from rice paddies in southeast China. Several factors such as degree of water coverage, rice genetics, soil chemistry and fertilizer use would influence redox and microbial biochemistry. This is particularly important since water reuse is a proposed climate change adaptation measure for periurban agricultural areas facing water shortages (Khai, Ka, & Oborn, 2007). Rice management requires technical regional management but it has global impact.

A recent synthesis of monitoring data suggests a mean reduction in greenhouse gas emission would be obtained by switching to SRI or its equivalent. Owing to improved water conservation in rice culture in northern Asia, the rate of increase of methane concentrations in the atmosphere has decreased (Kai, Tyler, Randerson, & Blake, 2011). More data are required on the amount of nitrous oxide released by SRI or its equivalent but there is no doubt that the basic redox biochemistry would result in substantial reductions of methane by switching to SRI, and the weight of evidence suggests that with appropriate use of fertilizers, nitrous oxide emissions will only slightly reduce the effect of lower methane release. Moreover, in 1992, the United Nations Framework Convention on Climate Change approved the precautionary principle which allows actions to be taken in the 'absence of full scientific certainty' (http://www.aph.gov.au/library/Pubs/ClimateChange/governance/international/unfccc/unfccc.htm). The fact that SRI and similar methods use substantially less water to grow as much or more rice should be enough to push for faster implementation of these systems at least with pilot-scale evaluations of carbon trading.

8. Rice management and disease

There are many other aspects that should be considered in management of rice production. Another factor that has to be considered with rice flooding is the potential for human disease. IPCC Working Group II (2001b) warned that climate change will enhance tropical diseases. The early monsoons in 2009 in Cambodia enhanced both malaria (Curtis, 2009) and dengue fever (Xinhua News, 2009). Certainly, malaria is enhanced by standing water with traditional rice culture (Lawler & Dritz, 2005). Since there is much less standing water with SRI and similar rice culture, these methods could reduce malaria and probably other diseases spread by mosquitoes, including dengue fever and Japanese encephalitis. This topic needs analysis but since mosquitoes feed by filtering water any action that disrupts this 'aquatic' life stage should suppress mosquitoes. A recent blog says data from Kenya supporting this concept are available but unpublished (SRI, 2012). Schistosomiasis (infection by a type of liver fluke) ranks second globally only to malaria among the parasitic diseases with regard to the number of people infected and those at risk (Steinmann, Keiser, Bos, Tanner, & Utzinger, 2006). Schistosomiasis requires snails as an intermediate host (Ohmae et al., 2004). Steinmann et al. (2006) observed that schistosomiasis can be three times more prevalent near fish ponds in Africa (21% vs. 7−8%) and it is often spread quickly by new irrigation systems. Cambodia has been known as an endemic area for schistosomiasis before 1988 with some villages having more than 70% of people infected (Lee, Bae, Kim, Deung, & Ryang, 2002; Urbani et al., 2002; Urbani et al., 2003). Still, because of a lack of resources, the infection status of intestinal parasites in Cambodia has not yet been thoroughly investigated (UNICEF, 2002). Hortle (2008) reviews liver flukes as 'an underrated health risk in the Mekong Basin'. Manures are frequently crudely managed. Touch, Komalamisra, Radomyos, and Waikagul (2009) found a mean infection rate of 17.5% with *Opisthorchis viverrini*, a fluke in 929 cyprinoid fishes in Cambodia, while Ngoenklan et al. (2010) reported a higher rate of infection for fishes sampled from a large wetland receiving wastewater in Phnom Penh. Hortle did not include schistosomiasis in his discussion of liver flukes which could reflect another underrated health risk. The distinction is important in that unlike other flukes, schistosomiasis can be caused by cercariae passing through the skin (Hardin, 2009). Hence, while cooking fish will control the spread of *Opisthorchis viverrini*, it will not stop schistosomiasis.

Sanitation is clearly important. In a study in Laos, Strandgaard, Johansen, Pholsena, Teixayavong, and Christensen (2001) found that 75.8% of pigs were infected with one or more helminth species and that pigs can act as a definitive host for *Schistosomiasis mekongi*. In some areas most Cambodians have parasites (UNICEF, 2002) but the databases and methods of analysis are modest. Breaking parasite cycles by controlling human wastes is the first step. In Southeast Asia, diarrhea is responsible for as much as 8.5% of all deaths (WHO, 2007). In Peru and the South Pacific it has been shown that admissions for diarrhea were strongly correlated to mean ambient temperature (Checkley et al., 2000; Reena et al., 2001). There are no similar data on the effect of temperature and diarrhea in Cambodia but the concerns are obvious, especially as the cold season warms. Probably, the effect of extreme storms on flooding of latrines has a greater effect than temperature and would extend to other diseases such as cholera and typhoid fever. Efforts to control human wastes have to consider changes in hydrology. As irrigation systems are built, without new management of parasites, the situation will get worse. To respond to climate change and associated threats of enhanced disease, lifestyle changes are required with improved sanitation, food preparation and rice management.

9. Rice management and carbon trading

Agriculture in Cambodia badly needs both more research and new management. SRI was introduced in 2000 to Cambodia and by the end of 2012 about 140,000 farmers on nearly 4% of Cambodian rice paddies were using SRI (http://sri.ciifad.cornell.edu/countries/cambodia/index.html). Although this is impressive, projections from this small percentage are very uncertain and the approximate growth rate of 10% in SRI from 2009 to 2012 is not sustainable without more irrigation. There is a lack of resources to develop irrigation that is required to grow a second or third crop of rice. SRI seems well suited for growing rice in the dry season in that it requires 50% less water. Of course more irrigation systems are needed but the reservoirs should be used conservatively. New management techniques for rice would be implemented faster if the reduction of greenhouse gases could qualify for carbon trading.

The potential for carbon trading could strongly influence Cambodian rice management. A thorough economic analysis is beyond the scope of this review, but at a simple planning level, let us calculate the relative carbon credits associated with stopping the release of methane. Zhuang et al. (2009) reviewed that methane formation in rice paddies can vary from 175 kg/hectare-year to 3500 kg/hectare-year or a mean of about 1840 kg/hectare-year. Since 1 kg of methane has about 21 times the impact of 1 kg carbon dioxide, the release of methane represents about 39 tons of carbon dioxide per hectare per year. If we then use the total area of rice cultivation in Cambodia of 2.4 million hectares (USDA, 2010) we can estimate the total equivalent production of carbon dioxide from methane released from rice fields to be about 94 million tons of carbon dioxide per year. To put this into a human scale, use the United States Environmental Protection Agency (USEPA) estimate term of 5.1 metric tons of carbon dioxide released per typical American car per year (USEPA, 2011). This converts the equivalent carbon dioxide from methane release from Cambodia rice fields to about 1.8 million American cars for one year.

The management of carbon trading is changing quickly. In early 2008, methane emissions from rice paddies could not qualify for Certified Emissions Reductions (CERs). The 18 November 2008 changes to the rules for carbon trading allowed land use projects including forestry and agriculture to be validated and verified against Voluntary

Carbon Standard (VCS), qualifying them for credits tradable in voluntary carbon markets (http://news.mongabay.com/2008/1118-vcs.html). The minutes of the meeting of the Methane to Markets Partnership (2009, p. 1) state, 'Methane emissions from enteric fermentation and rice cultivation cannot be captured and used. However, reduction options from these sources are possible and could be marketed as carbon credits under the Clean Development Mechanism (CDM) or a similar offset mechanism'. In the same meeting, King (2009) used three projected prices for carbon trading of methane from rice paddies in the year 2030: $20, $50 and $100 a ton. The EU price was about US$20/ton in late July 2009 (http://www.pointcarbon.com/). Any market value would have to reflect the uncertainties and the price might be determined in the voluntary carbon market. When the changes were approved in November 2008, the recession was reducing the prices of carbon trading, and slowing associated project development. For example, there had been no trade in CERs from the five approved CDM projects in Cambodia (IGES, May 2009). It remains to be seen if changes in rice management such as SRI or its equivalent can apply for carbon credits but they should. Both the Global Environment Facility (GEF) and the International Fund for Agricultural Development (IFAD) state that there is a need to suppress agricultural emissions of greenhouse gases including changing rice management as one option to control global warming (IFAD, 2008). GEF is an executing agency of IFAD, a UN agency. Interestingly, a GEF summary shows that nitrous oxide effects on global warming from agriculture are larger than methane releases. It underscores the importance of managing nitrogen fertilizers. SRI is capable of using less nitrogen fertilization. This does not detract from the basic principles already proposed earlier in this paper but it does flag the need for ongoing research as projects are implemented. For example, in some areas of Cambodia, such as Pursat, there is a firm plow pan that could act as a barrier to roots (White, Oberthuarn, & Sovuthy, 1997). One principle of SRI is that plants are forced to root deeper to seek water and thus indirectly find nitrogen. It is important to increase tillage from conventional practice to ensure that the roots can grow deeper.

When a proposal for modifying rice production is evaluated, any judgment in Cambodia should use the principle of 'financial additionality'. 'Financial additionality' is often defined as an economically non-viable project becoming viable as a direct result of CDM revenues. It could even be considered as an international subsidy to develop agriculture but with the special requirement that greenhouse gas emissions be significantly reduced. With today's lack of irrigation, it is difficult for farmers to grow a second crop of rice. Financing for improved infrastructure and SRI with carbon credits seems like a good fit. Whether it was SRI or AWD, rice farmers would need improvements in irrigation systems and control over the access to water.

In Cambodia, the closest relevant example might be the signing of an agreement on 24 June 2009 to develop and market carbon credits for Reduced Emissions from Degradation and Deforestation (REDD) under the VCS (PACT, 2009). As with forestry, carbon trading with rice paddies could provide the mechanism to help contain global warming while providing development opportunities. It would need the support, management and policing more commonly associated with banking than with environment. A number of NGOs are implementing REDD and the same activities could develop with carbon trading for rice growing protocols that do not release methane.

It is interesting to consider what costing would be required to entice a rice farmer to change his or her practice to SRI or its equivalent. In Cambodia currently the average farmer produces 2.6 tonnes of rice per hectare (Reuters, 2008; 1 tonne = 1.102 ton). In February 2009, rice in Cambodia was selling for $490–590/tonne (Socheata, 2009). Hence, the average farmer, without consideration for production costs, could at best make $1500/ha hectare. The primary reason for farmers to convert to SRI is the financial incentive associated with the mean increase of productivity of about half a ton of rice a year per hectare (http://sri.ciifad.cornell.edu/countries/cambodia/index.html) or about a gross of $270 a hectare. The net incentive after production costs would be closer to $200 a hectare. Likely, a carbon credit of $10 a tonne of carbon dioxide equivalents or $200/hectare to the farmer and an equivalent to an agency to administer the programme and provide irrigation systems would produce a rapid reduction in agricultural production of methane and enhance rice production for the country. The biggest boost to productivity could come from using some carbon credit funding to upgrade irrigation. Carbon trading will probably continue at times to be a form of foreign aid and irrigation development could be associated with carbon trading of rice culture that blocks methane formation. Higher prices for carbon trading have been forecast (King, 2009) and if achieved could transform Cambodia and similar developing countries.

The recession has resulted in record low pricing of both CERs and the volunteer market for carbon trading of Voluntary Carbon Units. There has been some rebounding in the USA with prices increasing to the $4–5 range per ton in early July 2009 (http://www.carbonpositive.net/viewarticle.aspx?articleID=1599). NGOs often work with very little money and this might be enough money to entice a farmer to cooperate and provide money for management. In 2011, California voluntary market prices for offsets were around $3–7 per metric ton of CO_2 emissions, and pre-compliance offsets approved by the California Air Resources Board were going for $7–10 per metric ton on the voluntary market (Bardelline, 2011).

Since the 'American Clean Energy and Security Act' was passed in June 2009, the adoption of carbon trading by the USA should increase the global value of carbon credits. In 2011, the USDA initiated grants of $1.1 million to groups testing greenhouse gas reduction projects at rice farms, which could help bring farmers revenue from selling offsets on California's carbon market (Bardelline, 2011). Furthermore, now that Australia has passed new laws on carbon emissions, carbon trading will be facilitated (Grubel, 2011). Although it is fiscally and technically possible to remodel rice management, implementation would require an integrated effort. The projects must be validated and verified to qualify for credits. There is a need for agencies to coordinate such services for farmers in developing countries. It would also require international accreditation and monitoring to ensure that farmers actually implemented SRI or its equivalent to avoid release of methane. With appropriate calibration, monitoring for methane release could be routinely done by eye to observe water levels, with occasional use of a simple redox probe. Furthermore, it would be necessary to determine which areas would be suitable for this approach. It seems unwise to sanction and encourage the use of arsenic-rich groundwater for any irrigation project in Cambodia (Murphy et al., 2010). Large areas along the Mekong River have high concentrations of arsenic in the groundwater (Sampson, Bostick, Chiew, Hagan, & Shantz, 2008). Several studies in Bangladesh and India have reported an up to 10-fold increase of bioaccumulation of arsenic into rice irrigated with arsenic-rich groundwater (Heikens, Panaulah, & Meharg, 2007; Mondal & Polya, 2008).

Since arsenic motility is controlled by redox, the effect of SRI on bioaccumulation of arsenic warrants analysis. With oxidized soils perhaps the arsenic would be bound to iron. Supervision of the process is also important. It would be essential to set up a management structure to suppress corruption without alienating the Cambodian government or any country where this was attempted.

Without extensive development of new irrigation systems, SRI (or AWD) could not be implemented in much of Cambodia now. However, it is already large enough to consider carbon trading. Using a conservative carbon credit of $10 a ton of carbon dioxide equivalent the current farmers using SRI in Cambodia are producing an annual carbon credit value of about $30,000,000. This calculation is based on the 2012 data provided by Cornell University (http://sri.ciifad.cornell.edu/countries/cambodia/index.html; in 2009, 59,785 ha with 110,530 farmers participating; in 2012, 140,000 farmers participating presumably on similar size farms).

10. Conclusions

Global methane emission estimates from paddies range from 29 to 61 Tg/year (Babu et al., 2005). It has been estimated that global rice production must almost double by the year 2020 in order to meet the growing demand and this may increase methane fluxes by up to 50%. However, the Intergovernmental Panel on Climate Change has recommended reductions of 8% in anthropogenic methane fluxes to stabilize atmospheric concentrations. As long ago as 2004, Li proposed that agriculture, especially rice management, is a likely target for greenhouse gases mitigation efforts. The technical database is stronger but still the concept of carbon trading for rice management has not gone forward.

Current weather in Cambodia suggests that climate change is taking place with more unstable weather, warmer temperatures and more rainfall. Paleoclimatological studies indicate that there were a number of earlier rapid changes in climate that forced large changes in how people lived. Perhaps the massive Bangkok floods are an illustration of the risks of similar events happening again in Cambodia in the future. Some diseases in Cambodia are still not well managed and without preparation some of them will become worse as climate change proceeds. To prepare for the expected changes, Cambodia must quickly improve its infrastructure and water management and, where possible, reduce its release of greenhouse gases.

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