Climate Change and Rice Cropping Systems:
Potential adaptation and mitigation strategies

Report[1] by the
International Rice Research Institute (August 2006)

In many Asian countries, rice production represents the most significant activity of the agricultural sector and also constitutes a sizable portion of the national greenhouse gas budget. Although some 'generic' mitigation technologies have been identified in recent years, the immense variability of environmental factors in the 144 million ha of annually harvested rice fields defies blanket strategies to reduce emissions.

Moreover, technological options in rice production have to remain economically viable under a rapidly changing environment – both in terms socio-economic development as well as environmental changes. In this synopsis, we compile examples of 'robust' approaches that have a promising potential to reduce greenhouse gas (GHG) emissions and at the same time, maintain – or even increase --rice production under climate change.

Approach #1: Improving rice plants

Rising global temperatures may pose major threats to rice production in Asia due to yield losses that may result from heat-induced spikelet sterility or increased crop respiration losses during grain filling. Such reductions in the grain filling capability (termed as crop 'sinks') also have feedbacks on GHG emissions from rice paddies and the utilization efficiency of fossil fuel-based nitrogen fertilizer. Preliminary studies conducted at IRRI have demonstrated that removing or reducing the crop sink mechanism for assimilates results in enhanced methane (CH_4) emissions.

Wetland rice agriculture is a major source of atmospheric CH_4 due to extended flooding periods resulting in anaerobic decay of organic material. The composition of the organic material in the soil depends on residue management and manure application, but – in most rice systems -- the most important carbon source for CH_4 production is the rice plant actually growing in the field which supplies carbon for methanogenesis through root exudates and debris. For the rice plants, however, release of carbon represents a loss of valuable assimilates that would have otherwise been incorporated into plant tissue or grain. High-yielding plants use assimilates more efficiently and thus, supply less organic material for microbial methane production.

Plant breeding aiming at new rice cultivars that can maintain spikelet development under higher temperatures and have less wasteful maintenance respiration losses is likely to have mutual benefits for sustaining food production and reducing GHG emissions from rice paddies. Specific potential impacts may include (i) increased and more stable yield potential and better response to current atmospheric CO_2 levels, (ii) increased net removal of atmospheric CO_2 due to increased net assimilation, (iii) reduced methane emissions due to increased sink size and reduced below-ground C release for methanogenesis, and (iv) reduced fossil fuel use due to increased N use efficiency (see below). To achieve this, research needs to identify the genetic controls and physiological processes involved in rice adaptation to heat.

Approach #2: Improving fertilizer management

---

[1] Written by R. Wassmann, IRRI, and A. Dobermann, University of Nebraska

Nitrogen fertilizers are a significant direct source of greenhouse gases through N_2O emissions in the field and an indirect source through fossil fuel energy consumption associated with manufacturing and transport of fertilizers. Rice accounts for nearly 20% of the global N fertilizer consumption. In terms of GHG emissions, the annual amount of N applied to rice represents about 100 million tons CO_2 equivalents, with roughly one half embedded in fossil fuels used to manufacture and distribute the N fertilizer and another half in the form of N_2O emissions from field-applied fertilizer. Well-tailored fertilization – both in space and time – ensures high yields and a rapid take-up of N by the plants. Subsequently, less external N input is required to achieve the same crop yield, the amount and residence time of N in the soil is reduced and less N_2O or other reactive nitrogen compounds are released to the atmosphere or water.

Recent research conducted by IRRI and its partners in various countries of Asia has resulted in a new approach for site-specific nutrient management (SSNM). Demonstrated benefits include (i) increase in rice yields and thereby increased CO_2 net assimilation and (2) 30-40% increase in nitrogen use efficiency. This offers significant potential for decreasing GHG emissions associated with N fertilizer use in rice systems. Moreover, higher CO_2 concentrations in the future will result in temperature stress for many rice production systems (see above), but will also offer a chance to obtain higher yield levels in environments where temperatures are not reaching critical levels. The so-called 'CO_2 fertilization' effect, however, can only be tapped under sufficient nutrient supply. Phosphorus (P) deficiency, for example, not only decreases yields, but also triggers high root exudation and increases CH_4 emissions. Balanced fertilizer application, as developed in the new SSNM approach, may thus have a dual benefit, i.e. reducing greenhouse gas emissions as well as improving yields under future CO_2 levels. Future research needs to be conducted to fully develop and disseminate such new management concepts widely in Asia and elsewhere, including rainfed lowland rice areas, which are particularly prone to large nitrogen losses, including N_2O emissions.

Approach #3: Improving water management

Several field studies conducted by IRRI and other research institutions have shown that CH_4 can substantially be reduced by modified water management such as mid-season drainage or alternate wetting and drying. There is also a potential to combine the aims of (i) reducing CH_4 emission and (ii) saving irrigation water – in line with the expected shortages of available irrigation water in many rice growing regions. Likewise, significant potential exists for diversifying rice-based cropping systems in Asia, i.e., replacing lowland rice monoculture with rice – upland crop systems that can better meet emerging demands for food and feed and offer new opportunities to reduce water and/or nitrogen fertilizer consumption.

However, little is know how such changes will affect the sustainability of rice systems and their overall global warming potential. A key problem is that modifications of the water management also affect the emission of N_2O, an even more potent greenhouse gas than CH_4. There is an inverse relationship between CH_4 and N_2O emission rates; while drainage and wetting-drying cycles reduce CH_4 emissions they increase N_2O emissions. This intricate relationship requires a site-specific analysis of the baseline emissions as well as the impact of water management or crop diversification options – a task that cannot be accomplished by field studies for a wider range of locations. Likewise, such management changes will also affect soil biological processes, the population dynamics of weeds, insects and pathogens in ways that are little understood at present.

Simulation models may help to achieve reliable *a priori* assessments of management impacts on greenhouse gas emissions. These modelling tools will be especially powerful for future decision making as long as they supply – in addition to emissions – yield forecasts and regional water balances, so that the diverse impacts of rice production can be juxtaposed under different management scenarios.

Approach #4: Utilizing crop residues for renewable energy and carbon sequestration
More than 600 million tons of rice straw are produced worldwide and large amounts of the CO_2 fixed in these crop residues are currently re-released into the atmosphere through burning and other inadequate residue management practices. The residues of rice production offer an enormous potential as a source of renewable energy and could play a major role to substitute fossil fuel consumption in several Asian countries. Technological options in rice-growing areas include (i) biogas and recycling of biosolids to rice fields, (ii) co-generation of heat and electricity from rice husks at milling facilities, (iii) bio-char technology and (iv) conversion of rice and wheat straw to ethanol. In addition to offsetting fossil fuel consumption, most of these technologies may also recycle large portions of carbon and nutrients to the rice soils and may improve soil fertility alongside with energy generation and the associated reduction in net global warming potential

The traditional option to utilize crop residues for energy generation is biogas technology in which plant biomass is typically combined with animal excrements. The abundance of biogas plants has been declining in some countries, e.g. China, but higher fuel prices may re-stimulate biogas programs in the near future. When fermented biogas slurries are used as manure in wetland rice fields, emissions of CH_4 are lower than under application of fresh organic material.

Bio-char can be produced by controlled pyrolysis (smoldering) of farm residues and can be applied to soils with long-term benefits on soil fertility. Char soils ('terra preta' soils) show better water and nutrient retention improving the resilience of the cropping systems towards droughts. As compared to conventional crop management, char techniques reduce net greenhouse gas emissions because of (i) potential energy generation through the combustion process and (ii) carbon sequestration in the soil. However, this technique has only recently been discussed as mitigation technology. At present, there is no solid field data available allowing a complete accounting of greenhouse gas savings – neither a definite assessment of agronomical benefits of char soils under climate change scenarios. Nevertheless, this technique can be seen a promising mitigation/ adaptation technology for some cropping systems, e.g. rainfed lowland and upland rice which comprise nearly half of the global rice area and are primarily found on carbon-poor soils.

Efficient technologies to produce cellulosic ethanol from bulk crop biomass are not yet commercially available, but they will ultimately offer great potential for offsetting fossil fuel use. Potentially, 250 to 350 liters ethanol can be produced from each metric ton of dry crop biomass. If only 20% of the world's rice straw could be used in this process, the resulting annual ethanol production would amount to about 40 billion liters, sufficient to replace about 25 billion liters of fossil fuel based gasoline. This would result in an annual net GHG reduction of about 70 million tons CO_2 equivalents. Use of rice residues for ethanol production may be of particular interest at village scales to provide fuel for households, transportation and farm machinery as well as byproducts for other uses. Affordable small-scale technologies need to be developed for this.

All of the discussed approaches have in common that their real impact is currently difficult to predict with existing models because of the complexity of the induced changes. Likewise, there is a lack of research on integrated food production - renewable energy systems for rice environments, particularly those in which attempts are made to close the C and N cycles. Complete life cycle analyses and greenhouse gas accounting at field, landscape and regional scales is required and suitable metrics need to be developed for this.

Addendum[2] to the Report

“Climate Change and Rice Cropping Systems: Potential adaptation and mitigation strategies”

by the International Rice Research Institute

The previously identified adaptation and mitigation strategies in rice production, namely the approaches #1 (improving rice plants) and #2 (improving fertilizer management), are now assessed regarding costs for implementation.

For both approaches, the required costs can only be assessed within very broad ranges of uncertainty. In either case, we can here only provide budget figures for a project stage, i.e. research and development projects designed to provide suitable germplasm (approach #1) and new fertilization technologies (approach #2). This one-time investment could be seen as ‘seed money’ to stimulate the dissemination of mitigation/ adaptation technologies in close cooperation with national partners. Any attempt to estimate the implementation costs as a whole would require a thorough assessment of a multitude of factors (e.g. current baseline technologies, country-specific settings of extension services etc.) which has not been done so far and which is beyond the scope of such a report.

Approach #1: Improving rice plants

This mitigation approach #1 is based on the assumption that new rice cultivars with increased tolerance to heat can be developed so that net uptake of CO_2 from the atmosphere is increased and less substrate is available for methane production. Impact assessment studies consistently show that the benefits generated by plant breeding are large, positive and widely distributed. High yielding rice varieties with improved resistance and superior grain quality developed by IRRI and its collaborators are grown on 60% of the world’s rice land. One variety alone, IR36 released in 1976, was planted on 11 million hectares in Asia in the 1980s, yielding an additional five million tons of rice a year, boosting rice farmers’ incomes by US$1 billion, and, because of its resistance to pests, saving an estimated $500 million a year in insecticide costs.

The plant breeding effort for a new rice variety can be thought of as a two stage process. The first stage will involve basic research, primarily at IRRI and other advanced research centres, with an emphasis on molecular biology, plant physiology and screening of promising germplasm with regard to heat tolerance and associated traits. During the second stage, the locus of the research will shift to national agricultural research centres and the focus will shift to adaptive breeding. The costs for the second stage are especially difficult to estimate, but in previous cases the national systems have considerably contributed to this process through substantial in-kind contribution limiting the externally required costs.

<u>Cost estimate for a research project:</u>

---

[2] Written by R. Wassmann, IRRI, and A. Dobermann, University of Nebraska, USA

In IRRI's Rice and Climate Change Consortium, we have identified a project titled "Securing rice yield potential and grain quality under high temperatures resulting from global warming" which is estimated to require 5 million US$ over a 5-year period. The expected output will be germplasm with stable yield and grain quality under high temperatures together with a molecular marker system to be distributed to IRRI's partners in the national systems. Additional lab research and field testing of CH_4 emissions from new varieties is required to include it as an additional criterion for selection. Incorporating the new heat tolerance traits into national breeding programs would entail additional costs, so that the total costs are likely to be about US$ 10 million for an overall period of 7-8 years.

Approach #2: Improving fertilizer management

Fertilizers are direct and indirect sources of greenhouse gases, so that an increase in fertilizer use efficiency would translate into reduced emissions of both CO_2 (fossil fuel embedded in the fertilizer) and N_2O. The most advanced approach to optimize fertilizer application in high yielding rice production systems is termed 'site-specific nutrient management' (SSNM) which includes a range of field-specific management options and simple tools needed for implementing them. SSNM is a technology that can be tailored to local needs and requires no significant upfront investments by farmers. At farm level, SSNM only implies low extra costs, mainly in the form of slightly increased time requirements for decision making and fine-tuned crop management, but it also entails significant cost savings (less fertilizers) and higher returns (more rice produced). Most of the research on developing and evaluating SSNM has already been done by IRRI and its national partners. Long-term evaluations in a large number of farmers' fields around Asia have demonstrated high profitability of SSNM over a wide range of rice and fertilizer prices and significant environmental benefits.

Moreover, many rice growing countries subsidize fertilizers at present, so that successful campaigns to increase efficiency will also yield financial benefits at the national level. One example for this is Indonesia, where the government currently spends approximately US$300 million for fertilizer subsidies. The minister of agriculture requested a roll-out of best practices for fertilizer use, and the subsidy will be reviewed on the basis of subsequent usage patterns. SSNM is now being rolled-out in all major rice areas of Indonesia.

Broad adoption of SSNM is primarily impeded by lack of information. It will be important to conduct information campaigns to educate farmers in the principles of SSNM and disseminate the required tools through public and private sector chains. Production-scale demonstrations that are well-publicized and encourage active participation by farmers will be an important part of such information dissemination. The costs required for such information campaigns will vary from country to country.

Cost estimate for a research and extension project:

Through the Irrigated Rice Research Consortium (http://www.irri.org/irrc/default.asp), IRRI and its partners have conducted ground-breaking research on SSNM and are currently disseminating this technology in various regions of Asia. To have significant and lasting impact, these efforts will require further investments of about US$ 5 million for the next five years to (1) spread the SSNM technologies into all major rice areas of Asia, (2) continue fine-tuning and evaluating them as part of an overall new approach for rice management, and (3) conduct a full impact assessment with regard to mitigation of greenhouse gas emissions. An additional US$5 million will be required to expand the previous research on SSNM towards developing integrated technologies for an agro-ecological intensification of rice cropping systems, with an emphasis on integrated food and bioenergy production systems that optimize the use of resources such as fertilizer, water and energy and could represent even greater greenhouse gas mitigation potential.

Appendix:

Selected literature referring to individual approaches:

Approach #1:

BBC News World Edition, Monday, 19 August (2002) Better rice, less global warming (by Richard Black)

Denier van der Gon HAC, Kropff MJ, van Breemen N, Wassmann R, Lantin RS, Aduna E, Corton TM, van Laar HH. 2002. Optimising grain yields reduces CH_4 emissions from rice paddy fields; Proc. Natl. Academy of Science 99: 12021-12024.

Mitra S., Aulakh M.S., Wassmann R., Olk D.C. 2005. Triggering of Methane Production in Rice Soils by Root Exudates: Effects of Soil Properties and Crop Management, Soil Sci. Soc. Am. J. 69: 563–570.

Peng, S.B., J.L. Huang, J.E. Sheehy, R.C. Laza, R.M. Visperas, X.H. Zhong, G.S. Centeno, G.S. Khush, and K.G. Cassman. 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Academy of Science 101:9971-9975.

Sheehy, J.E., A. Elmido, G. Centeno, and P. Pablico. 2005. Searching for new plants for climate change. J. Agric. Met. 60:463-468.

Sheehy, J.E., P.L. Mitchell, D.J. Beerling, T. Tsukaguchi, and F.I. Woodward. 1998. Temperature of rice spikelets: thermal damage and the concept of a thermal burden. Agronomie 18:449-460.

Approach #2:

Dobermann, A., C. Witt, D. Dawe, G.C. Gines, R. Nagarajan, S. Satawathananont, T.T. Son, P.S. Tan, G.H. Wang, N.V. Chien, V.T.K. Thoa, C.V. Phung, P. Stalin, P. Muthukrishnan, V. Ravi, M. Babu, S. Chatuporn, M. Kongchum, Q. Sun, R. Fu, G.C. Simbahan, and M.A.A. Adviento. 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res. 74:37-66.

Lu, Y., Wassmann, R., Neue, H.U., and Huang, C. 1999. Impact of Phosphorus Supply on Root Exudation, Aerenchyma Formation and Methane Emission of Rice Plants, Biogeochemistry 47. 203-218

Peng, S.B., R.J. Buresh, J.L. Huang, J.C. Yang, Y.B. Zou, X.H. Zhong, G.H. Wang, and F.S. Zhang. 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crops Res. 96:37-47.

Ziska, L.H., W. Weerakoon, O.S. Namuco, and R. Pamplona. 1996. The influence of nitrogen on the elevated CO_2 response in field-grown rice. Aust. J. Plant Physiol. 23:45-52.

Approach #3:

Abao, E.B., K.F. Bronson, R. Wassmann, and U. Singh. 2000. Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rainfed conditions. Nutr. Cycling Agroecosyst. 58:131-139.

Bouman, B.A.M., H. Hengsdijk, B. Hardy, P.S. Bindraban, T.P. Tuong, and J.K. Ladha. 2003. Water-wise rice production. International Rice Research Institute, Manila.

Cai Z.C., Sawamoto T., Li C.S., Kang G.D., Boonjawat J., Mosier A., Wassmann R. 2003. Field validation of the DNDC model for greenhouse gas emissions in East Asian cropping systems, Global Biogeochemical Cycles 17, NO. 4, 1107, doi:10.1029/2003GB002046

Matthews, R.B., Wassmann' R. 2003. Modelling the impacts of climate change and methane emission reductions on rice production: a review. European Journal of Agronomy 19: 573-598

Wassmann R., Pathak H. (submitted) Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: II. Cost-benefit assessment for different technologies, regions and scales, submitted to ‘Agricultural Systems’

Wassmann R, Lantin RS, Neue HU, Buendia LV, Corton TM, Lu YH (2000) Characterization of methane emissions from rice fields in Asia. 3. Mitigation options and future research needs. Nutrient Cycling in Agroecosystems 58: 23-36.

Approach #4:

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. Science 311:506-508.

Marris, E. 2006. Black is the new green, Nature 442: 624-626

Prasertsan, S, Sajjakulnukit, B 2006. Biomass and biogas energy in Thailand: Potential, opportunity and barriers. Renewable Energy (5): 599-610

Wassmann R., Wang M.X., Shangguan X.J., Xie X.L., Shen R.X., Papen H., Rennenberg H., Seiler W. 1993. First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China). Geophysical Research Letters 20: 2071-2074