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AILEG Analysis and Investment for Low-Emission Growth

DESIGN OF A MONITORING, REPORTING AND VERIFICATION (MRV) SYSTEM FOR RICE GHG EMISSIONS IN VIETNAM

THE AILEG PROJECT

CONTRACT NO. EEM-I-00-07-00004-00
TASK ORDER: AID-OAA-TO-00041

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ACRONYMS AND ABBREVIATIONS

AGS	Applied GeoSolutions
AILEG	Analysis and Investment for Low-Emission Growth
AWD	Alternate Wetting and Drying
CH_4	Methane
DNDC	DeNitrification-DeComposition Model
EVI	Enhanced Vegetative Index
FAO	Food and Agriculture Organization
GHG	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LSWI	Land Surface Water Index
MARD	Ministry of Agriculture and Rural Development
MODIS	Moderate Resolution Imaging Spectroradiometer
MRV	Monitoring, Reporting and Verification
NDVI	Normalized Difference Vegetation Index
N_2O	Nitrous Oxide
SAR	Synthetic Aperture Radar
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development

1. EXECUTIVE SUMMARY

Agricultural lands cover 9.3 million hectares which is just over 28% of the land area in Vietnam. Rice is the largest cultivated area covering 7.6 million hectares.[1] In 2009, the greenhouse gas (GHG) emissions from agriculture were estimated to be 76 million tCO2e, or 35% of total emissions, second only to the energy sector.[2] Vietnam has developed a goal to enhance agricultural yields and to reduce agricultural GHG emissions. The Ministry of Agriculture and Rural Development (MARD) Climate Change Action Plan (CCAP) targets a 20% reduction in GHG emissions from rice production. Decision support systems are needed to develop agricultural management practices that are sustainable, enhance crop yields and reduce GHG emissions, to monitor progress in reaching Green Growth Strategy goals[3], and to improve sector level GHG reporting for Nationally Appropriate Mitigation Actions (NAMAs), national communications, and inventories.

This report summarizes the design of such a decision support system, or a Monitoring, Reporting and Verification (MRV) System for Rice GHG Emissions tool. This MRV system consists of 3 main components: remote sensing algorithms for mapping and monitoring rice, DeNitrification-DeComposition (DNDC) model for quantifying GHG emissions, and a geospatial data delivery and visualization system. The system allows users to compile rice GHG inventories, assess the mitigation potential of various mitigation strategies by changing rice management, and track progress over time. In addition to just querying the data, the system enables the user to see results in a graphical format, run 'what if' analyses by comparing net GHG emissions for various management strategies at user-defined spatial scales. The pilot MRV system was developed and demonstrated using data for Thai Binh Province. There are several take home messages from this pilot project:

There is a large potential for mitigation of greenhouse gas emissions from rice. Within the agricultural sector, rice—Vietnam's dominant crop—is the leading source of agricultural sector emissions (50 percent), followed by agricultural soils (e.g., from fertilizer use) (29 percent) and livestock (17 percent).[4] Implementation of alternative water management, such as intermittent wetting and drying, can reduce methane emissions significantly (~50%).

Integration of optical and synthetic aperture radar (SAR) remote sensing can be used for extensive mapping and monitoring of rice in Vietnam. Operational remote sensing applications can generate and deliver high resolution, georeferenced rice maps and rice production maps with sufficient accuracy to support a rice MRV system.

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[1] Ministry of Natural Resources and Environment, *Viet Nam's Second National Communication under the United Nations Framework Convention on Climate Change,* Hanoi, Vietnam, 2010

[2] World Resources Institute. CAIT 2.0 http://www.wri.org/project/cait. The sectors include: energy, industrial processes, agriculture, waste, land use and forestry, and bunker fuels. Accessed September 2013.

[3] Vietnam 2012. Vietnam National Green Growth Strategy. Decision on the Approval of the National Green Growth Strategy No. 1393/QĐ-TTg.

[4] RCEE Energy and Full Advantage, for the World Bank Carbon Finance Assist Program – Vietnam, *Potential Climate Change Mitigation Opportunities in the Agriculture and Forestry Sector in Vietnam,* Background Paper, November 2009.

Integrative research and development of well calibrated decision support tools are needed for quantifying emissions and evaluating mitigation opportunities in the Vietnam. A coordinated field measurement and model calibration and validation program will provide the backbone of a quantification system that is rigorous, based on state of the art science and can support low emissions growth for rice production in Vietnam.

A Monitoring, Reporting and Verification (MRV) System for Rice GHG Emissions can serve as an important decision support tool for Vietnam to enhance their strategy and progress for low carbon rice development. This project successfully demonstrated the feasibility and value of this MRV system for Thai Binh Province. The pilot system was designed so that it could easily be scaled up from a single province to national or regional scale. Given the importance of rice globally and the recent re-assessment of methane's global warming potential[5], the reduction of methane from rice production is an important mitigation opportunity. Investment in the following next steps are needed to transition this pilot MRV tool to an operational decision support tool to support GHG inventory and mitigation goals:

- ✓ **Compile field data on rice GHG emissions and identify gaps in measurements.** These independent field data are critical for rigorous evaluation and testing of DNDC model to improve estimates of uncertainty. There are several on-going programs[6] that are collecting rice GHG measurements. Coordination and synthesis of these efforts is needed.
- ✓ **Perform extensive model validation for better quantification of uncertainty of the DNDC model.** Additional testing and calibration will improve the quantification of the model accuracy and precision.
- ✓ **Build capacity for DNDC modeling.** DNDC is a detailed soil biogeochemical model that historically has been used as a basic research tool. However, recent developments have made the model easier to calibrate and to integrate into decision support tools. DNDC is now the quantification tool for several GHG offset protocols.
- ✓ **Build capacity for operational remote sensing for mapping and monitoring rice.** International space agencies (NASA, ESA, JAXA, etc) have or will be launching a constellation of satellites that will provide data at low or no cost that can be used for operational mapping of rice production. This constellation includes sensors that can image through clouds to provide all-weather capability for rice mapping and monitoring.
- ✓ **Coordination with MARD, MONRE and GSO for data collection, implementation of the MRV system and support for rice based Nationally Appropriate Mitigation Actions.** There is a need for setting standard operating procedures for collecting rice management data to support baseline setting and assessment of mitigation opportunities. Mechanisms for crediting GHG reductions are needed.

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[5] See http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

[6] For example, IRRI projects like MIRSA, Mitigation in Irrigated Rice Systems: Guidelines from Measurement, Reporting, and Verification; LUCCi project; CLUES; EDF Vietnam Low Carbon Rice Project; etc

2. BACKGROUND

Agricultural activities are responsible for approximately ~50% of global atmospheric inputs of methane (CH_4) and agricultural soils are responsible for ~75% of global nitrous oxide emissions.[7] Thus, agriculture representz a significant opportunity for greenhouse gas (GHG) mitigation through reductions of CH_4 and nitrous oxide (N_2O) emissions, as well as through soil carbon sequestration[8]. For irrigated rice, in season methane emissions can be reduced by changing residue management through altering the timing of incorporation, by composting crop residues prior to field incorporation or by reducing the time of flooding by draining and reflooding the fields during the growing season.[9]

Agricultural lands covering 9.3 million hectares which is just over 28% of the land area in Vietnam.[10] Rice is the largest cultivated area covering 7.6 million hectares. In 2009, the emissions from agriculture were estimated to be 65 million tCO_2e, or 35% of total emissions, second only to the energy sector.[11] Within the agricultural sector, rice—Vietnam's dominant crop—is the leading source of agricultural sector emissions (50 percent), followed by agricultural soils (e.g., from fertilizer use) (29 percent) and livestock (17 percent).[12]

The importance of agricultural mitigation has recently been affirmed by the Government of Vietnam through Decision 3119/QD-BNN-KHCN of Dec 16, 2011, which aims to reduce, by 2020, 20% of total GHG emissions in the agriculture and rural development sector (~19 million tons of CO_2 equivalent), while reducing poverty and increasing agricultural GDP by 20%. Rice is a unique agricultural system due to the use of flooding to meet the plant physiological demands. As a result, the per hectare GHG emissions can be quite high, primarily due to high CH_4 emissions since N_2O emissions tend to be low due to highly anaerobic soils. However, due to a lack of integrative research and availability of decision support tools for quantifying emissions and evaluating mitigation opportunities in Vietnam, it is difficult to assess current emissions and prospects for mitigation.

This report summarizes the design of a Monitoring, Reporting and Verification (MRV) System for Rice GHG Emissions for Thai Binh Province in Vietnam. This MRV system consists of 3 main components: a set of remote sensing tools/algorithms for mapping and monitoring rice, DeNitrification-DeComposition

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[7] Scheehle, E. A. and Kruger, D. 2005. Forthcoming. "Global Anthropogenic Methane and Nitrous Oxide Emissions," Energy Journal; US-EPA. 2005. Forthcoming. Global Emissions of Non-CO2 Greenhouse Gases: 1990-2020. Office of Air and Radiation. US Environmental Protection Agency (US-EPA), Washington, D.C.

[8] Oenema, O., G. Velthof, and P. Kuikman (2001) Technical and policy aspects of strategies to decrease greenhouse gas emissions from agriculture. *Nutr. Cycl. Agroecosys., 60,* 301-315; Cole, V., C. Cerri., K. Minami, A. Mosier, N. Rosenberg, and D. Sauerbeck. 1996. Agricultural options for mitigation of greenhouse gas emissions. in Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, edited by R.T. Watson, M.C. Zinyowera, and R.H. Moss, pp. 745-771. Cambridge University Press. Cambridge.

[9] Yan, X., Z. Cai, T. Ohara, and H. Akimoto (2003), Methane emission from rice fields in mainland China: Amount and seasonal and spatial distribution, J. Geophys. Res., 108, 4505, doi:10.1029/2002JD003182, D16.

[10] Ministry of Natural Resources and Environment, *Viet Nam's Second National Communication under the United Nations Framework Convention on Climate Change,* Hanoi, Vietnam, 2010

[11] World Resources Institute. CAIT 2.0 http://www.wri.org/project/cait. The sectors include: energy, industrial processes, agriculture, waste, land use and forestry, and bunker fuels. Accessed September 2013.

[12] RCEE Energy and Full Advantage, for the World Bank Carbon Finance Assist Program – Vietnam, *Potential Climate Change Mitigation Opportunities in the Agriculture and Forestry Sector in Vietnam,* Background Paper, November 2009.

(DNDC) model for quantifying GHG emissions, a geospatial database system and a WebGIS data delivery and visualization system (Section 3.5). The linked DNDC biogeochemical model and geospatial database form the basis of the MRV decision support system to compile improved inventory of emissions and perform a comprehensive analysis for rice mitigation strategies that are regionally appropriate and effective.

The MRV allows users to compile rice GHG inventories; assess the mitigation potential of various mitigation strategies by changing water management, fertilizer, rice residue and organic amendment; and track progress toward reaching green growth goals. The MRV tool can be used to:

- ✓ Enhance rice GHG reporting for National Communications using Tier 3 methodology[13]
- ✓ Develop Tier 2 emission factors[14] for rice at provincial or national scales.
- ✓ Evaluate the impact of policies for reducing GHG emissions at field, district, province or national scales.
- ✓ Develop targeting strategies for rice GHG mitigation.
- ✓ Monitor and verify progress to meeting Green Growth goals.
- ✓ Support the development and implementation of a rice carbon offset program.

In addition to querying the data, the webGIS tool enables the user to see results in a graphical format, run what if analyses by comparing net GHG emissions for various management strategies at user-defined spatial scales.

[13] Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Eds). Institute for Global Environmental Strategies (IGES). Hayama, Japan 2006. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/

[14] Ibid.

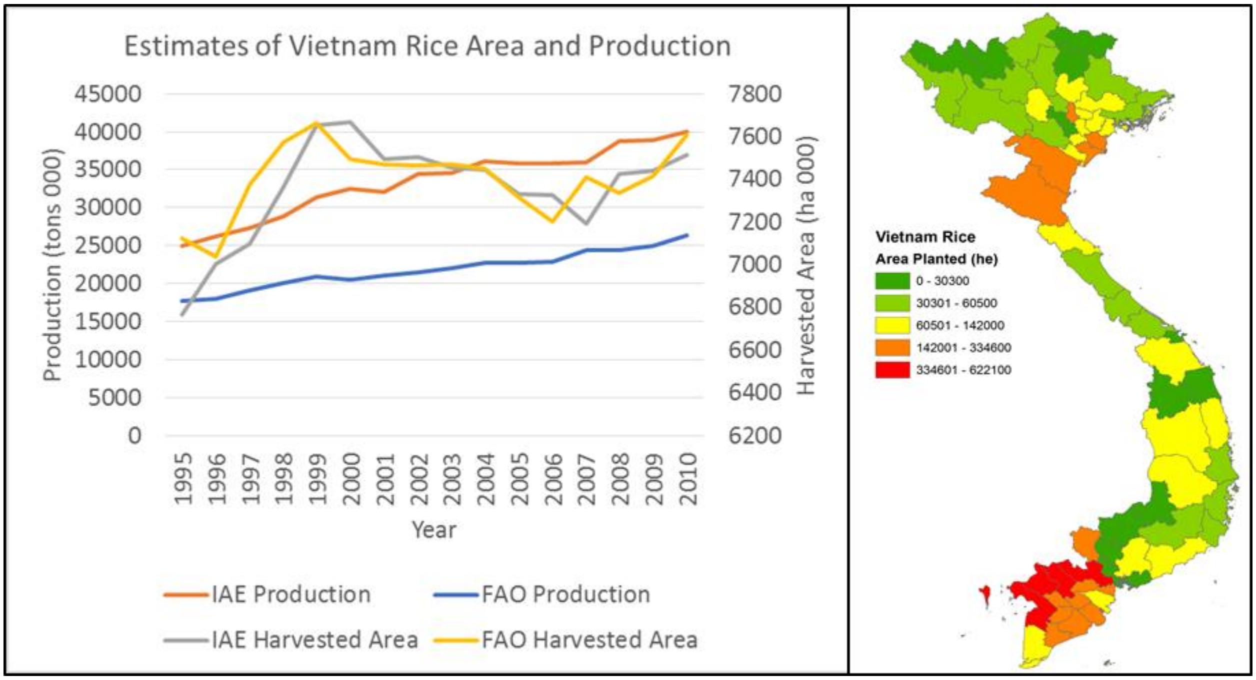
3. REMOTE SENSING

Component 1: Remote Sensing Rice Production in Thai Binh Province

Vietnam harvests approximately 7,753km^2 of rice to produce ~43.6 million tons of unmilled rice annually. Production has continued to rise steadily with between 35 – 45% increases in tonnage since 1995 (Figure 1)[15]. The steady increase in production has occurred while total harvested area has fluctuated as a result of land use change, shifts in cropping intensity, and government policies. Drivers of area and production include weather variability and extremes, water resources, and economic conditions. Compound these factors with varying management practices and monitoring rice production and quantifying greenhouse gas emissions becomes a challenge. The discrepancy between estimates and fluctuating production due to weather and economic conditions highlights the need for accurate and timely spatial information on rice paddy status to improve production forecasts, monitoring tools, and estimate GHG emissions.

[15] FAOSTAT 2013. www.faostat.fao.org

Figure 1: Vietnam Rice Statistics



Rice statistics for the past 15 years (left) show increasing production and year to year variability in total hectares planted and harvested and primary regions of rice production across Vietnam (right).
Source: Graphic created by Applied Geosolutions using FAO STAT data[16]

The use of satellite remote sensing for mapping rice systems has been shown to be powerful tools to support decision making and GHG accounting protocols. All satellite platforms have strengths and limitations that are determined by spectral, spatial, and temporal resolutions. *Spectral resolution* is the particular wavelengths, or bands, that measures energy from objects or the land surface that are used to identify unique signatures for classifying into categories of interest such as land use classes. *Spatial resolution* determines the pixel size, or minimum mapping unit, that can be effectively resolved for a given satellite instrument. *Temporal resolution* is the overpass repeat frequency, or how often a satellite observes the same location. Typically, there is a tradeoff in spatial and temporal resolution, as fine (<5m) and moderate-scale spatial (<30m) sensors have longer time spans between observations compared to coarser spatial resolution sensors with high frequency (eg, daily - 3 days) overpass cycles. By combining the strengths of different sensors, a more thorough characterization of rice paddy attributes is possible, enabling a comprehensive monitoring system.

3.1. MAPPING RICE WITH OPTICAL PLATFORMS

Optical satellite remote sensing platforms such as Landsat, MERIS, or MODIS, can be used as cost effective tools for mapping rice as these data are free and useful for mapping rice paddy conditions. One

[16] Ibid.

established technique for efficient mapping and monitoring of rice paddies uses the dynamic relationship among the Land Surface Water Index (LSWI), Enhanced Vegetative Index (EVI), and Normalized Difference Vegetation Index (NDVI) which can be generated from optical imagery such as Landsat or MODIS[17]. LSWI is an indicator of equivalent water thickness, or indicator of the presence of water, that is generated by ratioing spectral bands that are sensitive to vegetation, moisture, and water properties. NDVI is a well-established index that is sensitive to green vegetative vigor and health. EVI builds upon NDVI by incorporating additional spectral information to normalize soil and background effects[18]. The LSWI requires spectral information from the shortwave infrared band which is available on instruments such as Operational Land Imager and MODIS flown onboard Landsat 8 and Terra, respectively. By using EVI and LSWI, effective measures of rice growth and an indicator of paddy inundation is feasible with high accuracies (>85%). Figure 2 shows one Landsat image from January 2009 with the panel on the right showing the LSWI index for the period. The dark blue areas are open water and lighter blue area are vegetated are with standing water (rice paddies).

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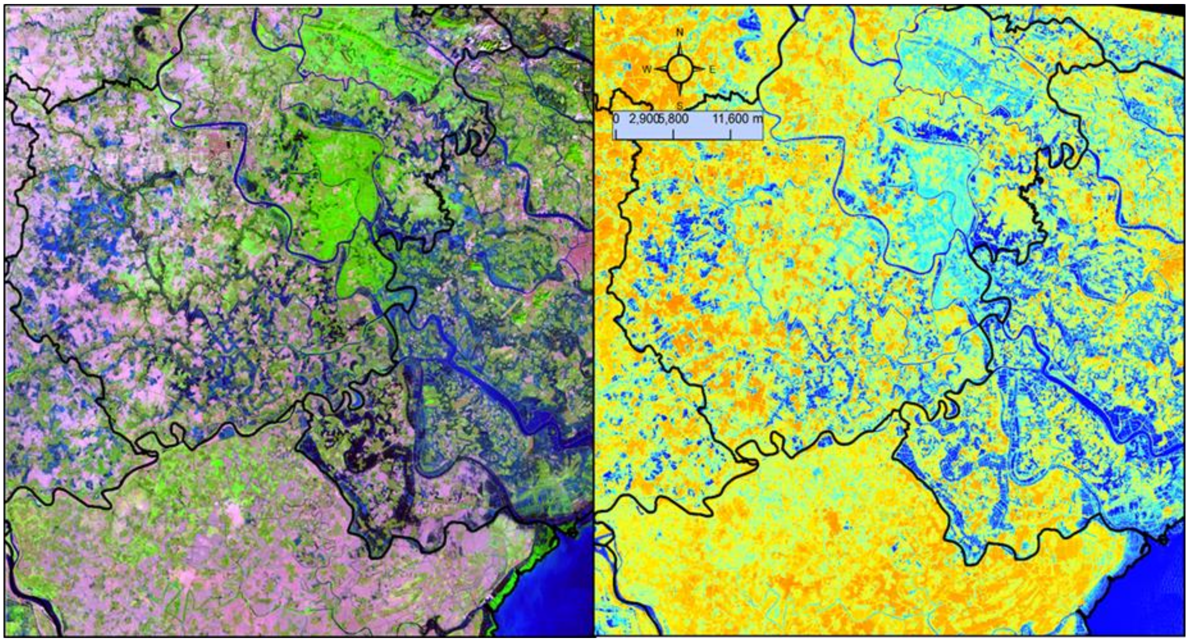
[17] Biradar, C., & Xiao, X. (2011). Quantifying the area and spatial distribution of double- and triple-cropping croplands in India with multi-temporal MODIS imagery in 2005. International Journal of Remote Sensing, 32, 367-386; Torbick, N. et al 2011a. Integrating SAR and optical imagery for regional mapping of paddy rice attributes in the Poyang Lake Watershed, China. Canadian Journal of Remote Sensing. 37(1); Xiao, X. M., Boles, S., Liu, J. Y., Zhuang, D. F., Frolking, S., Li, C., et al. 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. Remote Sensing of Environment, 95, 480– 492.; Xiao, X., Boles, S., Frokling, S., Li, C., Badu, J., Salas, W., Moore, B. 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. Remote Sensing of Environment, 100, 95-113.

[18] Xiao, X. M., Boles, S., Liu, J. Y., Zhuang, D. F., Frolking, S., Li, C., et al. 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. Remote Sensing of Environment, 95, 480– 492; Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., & Ferreira, L.G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment, 83, 195-213.

Figure 2: Landsat Imagery of Thai Binh Province



Landsat 5 TM false color (left) RGB (7:4:3) showing portions of Hai Duong and Thai Binh Provinces on 1/14/2009 (green showing dense vegetation and pink showing dormant fields) with LSWI (right) highlighting rice paddy and fish pond inundation (blue) that is underway before spring rice preparation.
Graphic created by Applied Geosolutions using Landsat imagery available from USGS.

Primary advantages of MODIS and MERIS measurements are the frequent repeat intervals of the satellite platform. The MODIS and MERIS Science Teams provide a suite of products including surface reflectance with bands that are sensitive to water and vegetation at no charge using near real time geospatial data servers. These high temporal frequencies observations enable daily and weekly monitoring of rice paddy status which allows for near real time characterization of flood dynamics, crop calendar such as planting and harvest dates, and assessment of rice plant growth. For example, Xiao et al. used 8-day MODIS indices to map rice and agro-ecological attributes across large regions to support food security and climate change programs. The algorithm, based on multi-temporal MODIS, has been successfully employed in several regions in South and Southeast Asia and California for mapping rice and rice hydroperiod over large areas[19].

3.2. MAPPING RICE WITH SAR PLATFORMS

Over the past decade several countries have begun utilizing Synthetic Aperture Radar[20] (SAR) instruments for rice monitoring programs. SAR is one type of active sensor that can take measurements through clouds with sensitivity to vegetation structure and surface conditions such as flooding. Often

[19] Xiao, X., Boles, S., Frokling, S., Li, C., Badu, J., Salas, W., Moore, B. 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. Remote Sensing of Environment, 100, 95-113; Torbick, N., Salas, W., Hagen, S., & Xiao, X. (2010). Mapping rice agriculture in the Sacramento Valley, USA with multitemporal PALSAR and MODIS imagery. IEEE J. Selected Topics in Remote Sensing, 4, 451-457.

[20] Synthetic Aperture Radar is a type of remote sensing sensor. SAR is an active sensors that send microwave radiation to the Earth surface and measures the amount that the scattered back to the sensor.

highlighted is the all-weather capability of SAR satellite imagers. In the tropics and Monsoon Asia this is critical as crops are often centered on the rainy season, which limits the application of optical sensors. Research has shown that SAR observations are sensitive to rice growth stages, soil moisture, and paddy inundation frequency and duration[21]. SAR can be particularly useful for mapping rice extent and cropping intensity. Inundation timing and duration, referred to as the hydroperiod, is another rice paddy attribute that can be mapped from satellite data Therefore, by timing overpass satellite observations a thorough characterization of rice paddy conditions and management practices is feasible[22].

SAR satellite observations over the length of the rice growing season change which makes mapping possible. During rice transplanting periods, the surface contribution of a paddy causes a low backscatter measurements by the SAR sensor (basically radiation scatters forward off water with little radiation scatter back to the sensor). As plant tillering, biomass, and haulm develop the backscatter response (dB) increases with more interaction, but volume scattering tends to cause a decrease in backscatter as the crop peaks and approaches harvest (Figure 3). Overpass dates can thus be timed with these growth patterns and inundation periods to extract the unique SAR signature of rice and estimate biogeophysical attributes such as biomass, leaf area, and plant height. Kuenzer and Knauer [23]highlight that the utility of SAR for rice mapping can vary depending on incident angles, wavelength, and overpass timing. Due to the complexities of rice stages, plant spacing, roughness, incident angle, and hydroperiod[24] there is no one single SAR instrument that surpasses all other sensors. When cost and data availability are factors the selection of data becomes more complex. While many SAR sensors have been utilized for rice mapping (i.e., ERS-1, ENVISAT ASAR, TerraSAR-X, Radarsat), only a few programs provide large area coverage with consistent observation strategies for cost-effective rice monitoring and near-real time forecasting. Two SAR satellites that carry the spectral bands useful for rice mapping and planned for orbit for the next decade include Sentinel-1[25] and ALOS-2[26]. Sentinel-1 is scheduled for launch in early 2014 with the objective of providing 2-3 images per week in four modes over the next decade. Alos-2 is planned for launch by JAXA by April 2014 and will provide 14-day repeat L-band observations using a collection strategy that will support monitoring of important rice regions such as Vietnam and Southeast Asia.

[21] Chen, C., & McNairn H. (2006). A neural network integrated approach for rice crop monitoring. International Journal of Remote Sensing, 27(7), 1367-1393; Inoue, Y., Kurosu, T., Aeno, H., Uratsuka, S., Kozu, T., Dabrowska-Zielinska, K., & Qi, J. (2002). Season-long daily measurements of multifrequency (Ka, Ku, X, C, and L) and full-polarizaiton backscatter signatures over paddy rice field and their relationship with biological variables. Remote Sensing of Environment, 81, 194-204; Le Toan, T., Ribbes, F., Wang, L. F., Floury, N., Ding, K. H., Kong, J. A., & Fujita, M. (1997). Rice

Crop Mapping and Monitoring Using ERS-1 Data Based on Experiment and Modeling Results.

IEEE Geoscience and Remote Sensing, 35, 41–56.

[22] Torbick, N., Salas, W., Hagen, S., & Xiao, X. (2010). Mapping rice agriculture in the Sacramento Valley, USA with multitemporal PALSAR and MODIS imagery. IEEE J. Selected Topics in Remote Sensing, 4, 451-457.

[23] Kuenzer, C., & Knauer, K. (2012). Remote sensing of rice crop areas. International Journal of Remote Sensing, 34, 2101-2139.

[24] Hydroperiod in this case refers to flooding and draining of rice paddies. Specifically it is the length of flooding.

[25] http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1

[26] http://www.jaxa.jp/projects/sat/alos2/index_e.html

Figure 3: SAR Rice Backscatter Model

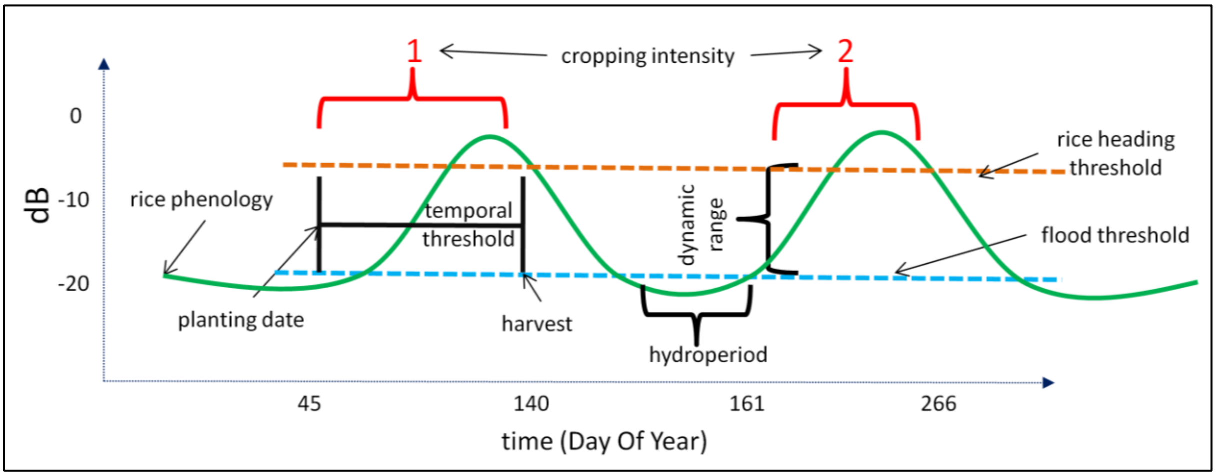
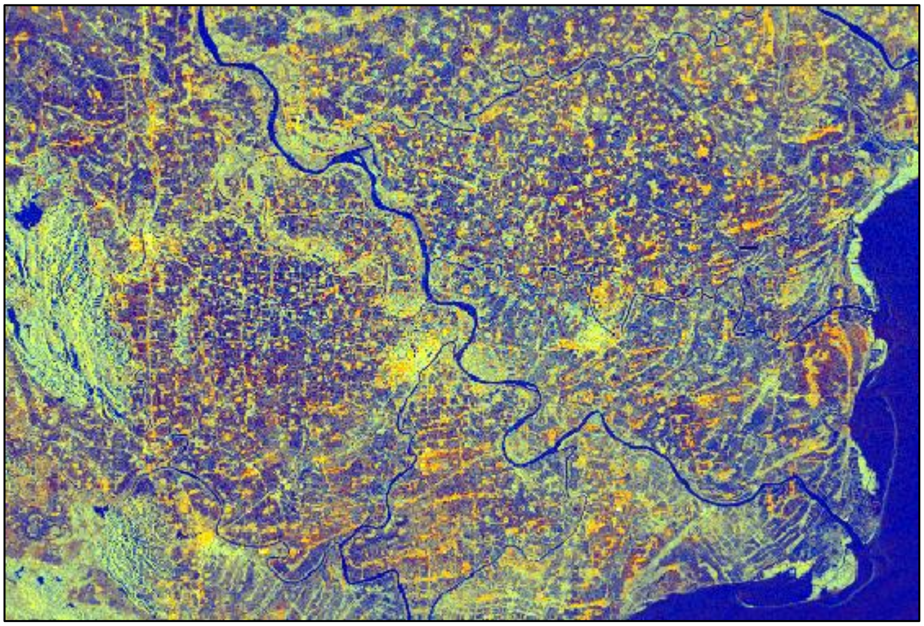


Illustration of key rice stages, such as planting date and rice heading, for a double crop system. Here, PALSAR sigma nought (dB) response at 34.3 incidence angle is shown over Day Of Year during key paddy attributes that can be used for effective mapping and identification of flooding, management, and crop calendar.
Source : Graphic created by Applied Geosolutions

3.3. PILOTING VIETNAMESE MRV TOOLS IN THAI BINH

As part of our Vietnam MRV pilot project we obtained and tested multi-temporal, SAR satellite imagery using RadarSat-2 imagery (Figure 4). SAR was tested due to its particular sensitivity to rice and capability of mapping through clouds. Use of multi-temporal data enables us to examine changes in surface conditions (open water, followed by rice growth, drainage of fields and crop harvests) as a strong indicator of land use. We coordinated this overpass with our partners at Institute of Agricultural Environment and then trained them to collect basic measurements of GPS, rice growth stages, inundation status, plant height, and geophotos. We collected multi-temporal imagery to have observations of rice at multiple growth stages in order to monitor crop development and distinguish from others land cover types (such as forest or grassland). The multi-temporal satellite imagery was used to map cultivated rice paddies, estimate irrigated extent and planting area, and identify crop calendar. These products help form spatial databases that serve end users with GHG model parameterization, support crop forecasting, and help with risk management and decision making. We coordinated the timing of the field work to coincide with the Radarsat imaging dates and with rice transplanting, midseason growth, and near harvest periods. We carefully measured rice paddy conditions to calibrate the satellite images.

Figure 4: Multi-temporal Radrasat-2 imagery



False color RadarSat-2 imagery of Thai Binh targeting rice paddies approximately 45 days into the growing period, inundated areas, and other land cover types . The color composite shows a traditional color scheme (Red represents the HH polarization Green represents the – HV polarization, Blue represents the HH/HV ratio) to highlight the landscape features.
Graphic created by Applied Geosolutions

The imagery was classified into board classes following a standard classification scheme. First, we employed a Classification And Regression Tree (CART) algorithm to classify the remote sensing imagery into rice maps and spatial data. The CART algorithm uses rules for assigning/classifying the imagery into land types based on the training data we collected in the field.

In this pilot application, training data were used to "teach' the imagery about rice fields and other landscape cover types (forest, water, urban, etc). Then the CART algorithm maps all the data into the classes. Next, we use the satellite imagery over time to map how rice paddies develop. With the SAR data we monitor the growth stage of rice in order to distinguish rice from other cover types and assess the condition of the crop.

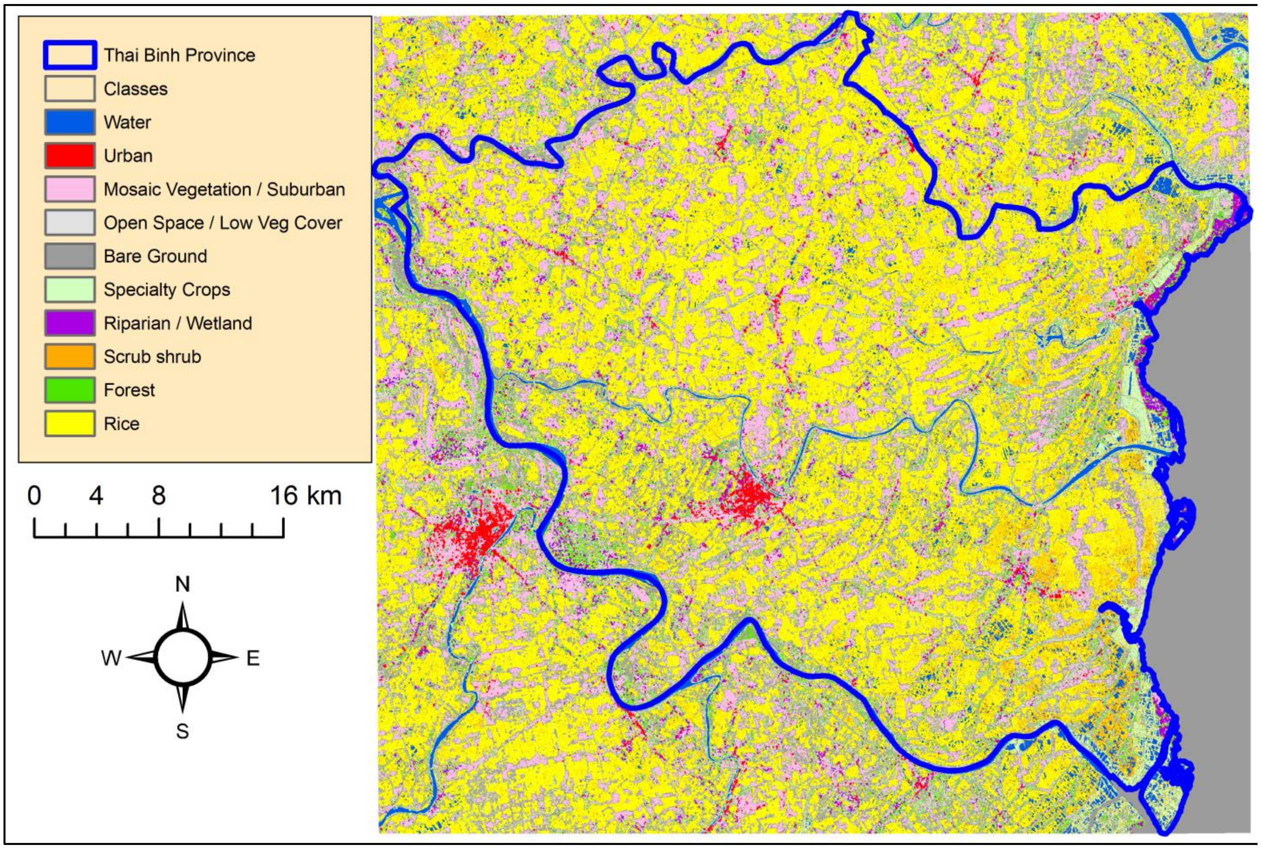
3.4. REMOTE SENSING RESULTS

The overall accuracy for the classification was of 79%, while the rice class had a high overall accuracy with 90% specificity. This means the rice mapping was very accurate. Open space low density vegetation and scrub shrub classes had the most confusion in the classification which resulted in the lower overall accuracy. Combining these two classes substantially improves the mean overall accuracy. The final decision tree approach delineated ~866 km^2 of rice land use in the Province (Figure 5). This total rice extent value is very near the Provincial statistics collected by the

> Remote sensing can be used to create high quality and accurate maps of rice production, cropping intensity and management practices for Vietnam. This approach can be implemented in an operational system.

Institute of Agricultural Environment which estimated 839.38 km^2 using traditional survey techniques. We used a 10-year average of spring rice area as 2013 data are not available. If using an average of ~6.69 tons per hectare an average of ~579,534 tons is generated, which is very near the 10 year running average. In short, the mapping products accurately classified the extent and location of rice across the Province. The mapping routine can be executed in near real time, making these information products useful components of an MRV tool.

Figure 5: Thai Binh Province land use map



Map of land use in Thai Binh. Rice is dominant.
Source Graphic created by Applied Geosolutions

3.5. REMOTE SENSING OUTCOMES AND TAKE HOME MESSAGES

- Satellite radar data accurately mapped rice for the pilot study area – Thai Binh Province.
- The spatial and temporal resolution of radar are adequate for mapping rice in the region.
- Coordination with field work is important for calibrating the satellite data.
- Spatial information is useful for GHG model parameterization, food security assessment, and real time rice monitoring and forecasts.

- New data from Sentinel-1 and ALOS-2 will provide radar data for the next decade. These sensors are effective at mapping rice in Vietnam and should be considered in an MRV tool.

4. DNDC MODELING

Component 2: DNDC Modeling of Rice GHG Emissions

In consideration of the complexity of GHG emissions from rice paddies, a process-based model, **D**e**N**itrification-**D**e**C**omposition or DNDC[27], has been utilized to cope with the relationships between GHG emissions and farming management practices. DNDC has been widely tested and utilized for rice ecosystems worldwide, with an emphasis on Asia[28]. To estimate the impacts of alternative management practices and policies on GHG mitigation at regional scales, the DNDC model must be driven by spatially differentiated data on climate, soil properties, rice ecological attributes, and other cropping management practices such as tillage, fertilization, manure amendment, irrigation, and grazing.

We simulated rice agro-ecosystem processes in Thai Binh (Red River Delta) and An Giang (Mekong River Delta) Provinces using the Denitrification-Decomposition (DNDC) model. We assembled climate, nitrogen (N) deposition, soils, and crop management data from various sources (Section 4.1). We reported crop yield for numerous management scenarios as well as net greenhouse gas emissions, including methane (CH_4), nitrous oxide (N_2O), and changes to soil organic carbon ($dSOC/CO_2$), and .

The DNDC model performs process-based simulations of nitrogen and carbon dynamics in agroecosystems. Based on environmental drivers (inputs like soil characteristics, temperature and precipitation data, crop characteristics, and crop management) the model predicts crop growth and yield, GHG emissions (such as carbon dioxide, CH_4, and N_20), and other environmental effects (like nitrogen leaching and runoff). DNDC is used widely around the world and has been tested against many field datasets in the US and abroad.

> Once calibrated, the DNDC model is a valuable tool for modeling nitrous oxide and methane emissions from rice in Vietnam and for decision support.

4.1. DNDC INPUTS

Climate

We used the National Centers for Environmental Prediction (NCEP) climate reanalysis product to generate daily meteorological data (minimum and maximum temperature, °C, and total precipitation, cm) for the modeling timeframe (1995-2012).

[27] DNDC, 2012. DeNitrification-DeComposition Model, version 9.5. URL: http://www.dndc.sr.unh.edu/

[28] Li, C., J Qiu, S. Frolking, X. Xiao, W. Salas, B. Moore III, S. Boles, Y. Huang, and R. Sass, 2002. Reduced methane emissions from large-scale changes in water management in China's rice paddies during 1980-2000, Geophysical Research Letters, 29(20), doi:10.1029/2002GL015370, 2002.; Li, C., W. Salas, B. DeAngelo, and S. Rose, 2006. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next 20 years. Journal of Environmental Quality 35:1554-1565, doi:10.2134/jeq2005.0208.

To estimate nitrogen deposition, we used data from the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics. To derive 2012 N deposition for this site, we calculated a year-weighted average from the 1993 and 2050 Global Maps of Atmospheric Deposition datasets[29].

Soil

Soil characteristics were extracted from the Harmonized World Soils Database.[30] We use top soil attributes for clay fraction (a proxy for soil texture), bulk density, soil organic carbon fraction, and pH. Each HWSD soil map unit includes one or more soil types of varying fractions. Soil types (see "HWSD ID" in Annex A) within soil map units were the base modeling unit for this simulation – this included 15 soil types for Thai Binh province and 18 soil types for An Giang province. Annex A summarizes the soil attributes used in the simulations.

4.2. CROP MANAGEMENT

Crop management was based on an analysis on the results of the AILEG rice management survey.[31] We used DNDC to simulate all permutations of the following aspects of rice management (Table 1). For flooding, the two practices other than continuous flooding are considered alternate wetting and drying (AWD).

Table 1: Rice Management Systems Modeled with DNDC

Category	Management
Flooding	Continuous flooding from plant date to harvest date, paddy drained 20 days before harvest
	Flood from plant date to 35 days, drain for 2 days, flood for 14 days, repeat until harvest date, paddy drained 20 days before harvest (AWD)
	Flood from plant date to 35days, drain for 6 days, flood for 6 days, repeat until harvest date, paddy drained 20 days before harvest (AWD 50%)
Variety	Long duration (120 days – or 120d[32])
	Short duration (90d)
Fertilizer rate	80 kgN/ha/crop
	100 kgN/ha/crop
	120 kgN/ha/crop
	170 kgN/ha/crop

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29 Dentener F.J. 2006. Global Maps of Atmospheric Nitrogen Deposition, 1860, 1993, and 2050. Data set. Available on-line from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/830. URL: http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=830. Accessed October 2012

30 http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

31 Abt Associates Inc., Vietnam Data Collection to Support LEDS for the Agricultural Sector, prepared for USAID under the AILEG Project, Washington, DC, forthcoming.

32 This refers to the length of the growing of the rice variety. The abbreviation d is used throughout for days when discussing rice varieties.

Fertilizer Form	Ammonium sulfate
	Urea
Manure	Manure
	No manure*

* Manure was never applied in An Giang province.

A list of scenarios is provided in Appendix B.

Data on all other aspects of rice management was provided by Dr. Mai Van Trinh (Institute of Agricultural Environment) and are summarized in Table 2.

Table 2: Rice Management Assumptions

		Thai Binh	**An Giang**
1st Rice Crop (Spring)	*Tillage*	30d before plant date @ 30cm	20d before plant date @ 30cm
	Fertilizer	plant date	
	Plant Date	5-Feb	25-Jul
	Flood	plant date	
	Fertilizer	plant date and after 25d	plant date and after 25d
	Drain	20d before harvest date	20d before harvest date
	Harvest date	variety-dependent	variety-dependent
	Crop residue	2%	2%
	Yield	2,213 kgC/ha	2,213 kgC/ha
2nd Rice Crop (Summer)	*Tillage*	1d before plant date @ 30cm	1d before plant date @ 30cm
	Fertilizer	plant date	plant date
	Plant Date	20-Jun	5-Dec
	Flood	plant date	
	Fertilizer	20d before harvest date	20d before harvest date
	Drain	plant date and after 25d	
	Harvest date	variety-dependent	variety-dependent
	Crop residue	2%	2%
	Yield	2,213 kgC/ha	2,213 kgC/ha
	Tillage	5d after harvest @ 20cm	5d after harvest @ 20cm

d = days

4.3. CALIBRATION

To simulate nitrogen and carbon dynamics and other soil processes accurately, DNDC requires precisely calibrated crop parameters. We calibrated the following rice crop parameters independently for Thai Binh and An Giang:

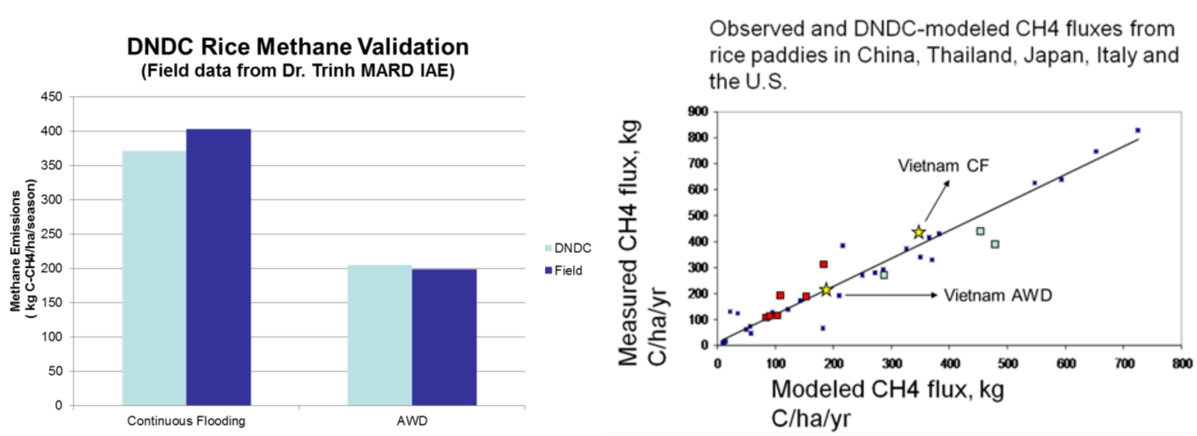
- Total growing degree-days (TDD): the sum of mean temperature (°C) for days during the growing season (plant date to harvest date) greater than or equal to 10°C
- Maximum biomass (yield): grain biomass (kgC/ha)

We calibrated TDD based on an analysis of climate for each province. We chose the mean annual TDD which allowed the rice crop to mature within 1 week of harvest on average across all years in the simulation. We calibrated yield based on the national yield figure for 2011 as reported by FAOSTAT (2,213 kgC/ha) for both the short duration (90 day) and long duration (120 day) varieties.[33] We assumed a baseline scenario for each variety (continuous flooding, 120 kg urea N/ha/crop, no manure) and iteratively adjusted the maximum biomass parameter across successive model runs until modeled yield was within 10% of reported. Crop parameters are shown in the Appendix B.

4.4. DNDC VALIDATION

DNDC has been extensively validated for rice GHG emissions. As part of this pilot project, we extended the validation with new datasets collected near Hanoi. Dr. Mai Van Trinh at MARD's Institute of Agricultural Environment provided methane flux measurements for two water management systems: continuous flooding and AWD. These data were used to independently validate DNDC. Figures 6a and 6b shows the results of the two water management systems and summary of DNDC validation across a range of rice systems.

Figure 6: DNDC Validation



(a) DNDC validation results for continuous flood and AWD for rice fields near Hanoi and (b) Vietnam results compared with independent validation for sites worldwide. Results indicate that DNDC does a good job of simulating methane emissions from rice paddies worldwide

4.5. SIMULATIONS

For each region and for each soil type we simulated all scenarios.[34] We differentiated between two phases in the simulation: to allow soil carbon to equalize over the presumed life of the rice paddy, we ran the model for 15 years (1995-2009) prior to the 3-year reporting timeframe (2010-2012). We assume consistent management over the entire 18 year simulation. Results are only reported for the 2010-2012 timeframe.

[33] www.faostat.fao.org

[34] In An Giang Province, manure application was not simulated.

4.6. RESULTS

DNDC model results were provided to generate marginal abatement cost curves for rice management.[35] The results were summarized for each region, for each site, for each scenario, and for each of the three reporting years (2010, 2011, and 2012), as well as annual means for the timeframe. The principal statistics we report from the model output are yield, change in soil organic carbon (dSOC[36]), CH_4, and N_2O. GHG results are reported both in native units and in CO_2e. Yield (for spring and summer rice) and GHG emissions were simulated for each of the 50 different management scenarios for An Giang and Thai Binh (See Appendix C for scenarios). Table 3 shows the estimate of the baseline results for both provinces and for long and short duration rice varieties. The 100 year Global Warming Potentials used in these calculations are from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report[37] with CH_4 and N_2O values of 21 and 310, respectively. It is important to note that the IPCC Fifth Assessment Report[38] updated these numbers to 34 and 298 for CH_4 and N_2O, respectively. This indicates that the assessment of the GWP for rice methane has increased by over 50% - enhancing the need for rice methane mitigation strategies.

Table 3: DNDC Model Results for Thai Binh and An Giang

Site and Management	spring yield (kgDM/ha)	summer yield (kgDM/ha)	dSOC (kgCO2e/ha)	CH_4 (kgCO2e/ha)	Total N_2O (kgCO2e/ha)	Total GHG (kgCO2e/ha)
Thai Binh baseline / long variety	4,971	5,025	234	16,404	6,839	23,476
Thai Binh baseline / short variety	4,846	5,023	311	9,038	9,636	18,985
An Giang baseline / long variety	5,023	4,622	337	18,368	4,450	23,155
An Ginag baseline / short variety	5,021	3,134	456	7,115	5,900	13,471

Broadly speaking, alternate wetting and drying (AWD) scenarios saw large GHG reductions when compared to baseline flooding (continuous flooding)(approximately 70%), largely due to a large decrease in CH_4 emissions (67% / 14,284 kgCO_2e/ha on average). Scenarios with reduced fertilizer N applications saw decreases to both yield (~18%) and GHG emissions (~35%), principally due to decreases in N_2O (~65%) but also because of reduced CH_4 emissions (~20%) due to decreased soil C inputs. When fertilizer N applications were simulated as ammonium sulfate, CH_4 emissions were

[35] As reported in Abt Associates Inc.. 2013. Vietnam Data Collection to Support LEDS for the Agricultural Sector, The AILEG Project. USAID. Washington, DC, October.

[36] dSOC is the modeled change in soil organic carbon over a one year period. A positive dSOC value in units of CO_2eq represents a loss of soil carbon

[37] 2001 IPCC Third Assessment Report (TAR) page on Global-Warming Potentials

[38] See http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

reduced by approximately 20% leading to comparable decreases in combined GHG emissions when compared to baseline applications of urea. The long duration rice variety had increased GHG emissions when compared to the short duration variety (23% for An Giang; 8% for Thai Binh), principally due to increased CH_4 emissions over the longer flood period. Manure applications in Thai Binh (no manure was ever applied in An Giang), lead to marginal increases in yield (~2%) and soil carbon (substantially decreased soil CO_2 emissions from 315 to -468 $kgCO_2e/ha$ on average), but increased N_2O emissions (due to increased soil N, such that GHG emissions increased slightly over scenarios with no manure applications.

<u>An Giang, long duration variety</u>
The AWD-50% scenarios with low fertilizer N saw the largest reductions to total emissions (75% / 17,255 $kgCO_2e/ha$ on average) largely due to substantially reduced CH_4 emissions (~80%), but had an accompanying average yield decrease of 28%. The AWD-14d practice with high ammonium sulfate applications saw a comparably large reduction in GHG emissions (67% / 15,523 $kgCO_2e/ha$) but only a 9% decrease to yield. Only the continuous flooding scenarios with high fertilizer applications saw increases in yield (~8%), but had accompanying increases (~30%) in GHG emissions.

<u>An Giang, short duration variety</u>
The AWD-50% scenario with low fertilizer N applied as ammonium sulfate had a large reduction in GHG emissions (64% / 8,611 $kgCO_2e/ha$) with only a 1% decrease to yield. The AWD-50% scenarios with high fertilizer N applied as ammonium sulfate had smaller GHG reductions (41% on average) but saw increases in yield of approximately 22%.

<u>Thai Binh, long duration variety</u>
The AWD scenarios (either 50% or 14d) with low N (in either form, with or without manure) saw a 82% GHG reduction on average (19,237 $kgCO_2e/ha$) with an average reduction to yield of 31%. The CF scenario with high N applied as ammonium sulfate with no manure application saw a 10% reduction in GHG emissions (2,459 $kgCO_2e/ha$), but had no appreciable change to yield.

<u>Thai Binh, short duration variety</u>
As with the long variety comparison, the AWD scenarios with low N (either form, with and without manure) saw reductions to GHG emissions of 70% on average (13,300 $kgCO_2e/ha$) with an average reduction to yield of 21%. The AWD-14d scenario with high N (either form, with or without manure) saw GHG reductions of 55% on average (10,670 $kgCO_2e/ha$) with marginal yield reductions of ~3%.

In conclusion, AWD results in significant reductions in GHGs, but the impact on yield is a function of the rice variety, fertilizer practices and province-specific factors.

4.7. DNDC OUTCOMES AND TAKE HOME MESSAGES

- DNDC model was calibrated for rice system in Thai Binh Province.
- DNDC was applied to quantify emissions using remote sensing derived maps of rice production. Data can be used to assess emissions at scales ranging from field to commune to province.
- DNDC captured variability in GHG emissions when compared against field data for continuous flooding and AWD.
- Additional field data will enhance the quantification of DNDC model uncertainties for quantifying changes in GHG emissions associated with a practice change (e.g. shift from traditional production to reduced water use.

- DNDC model is an important component of the MRV system and can be linked with remote sensing products and GIS data layers to form the quantification basis of a decision support system.

5. WEB-GIS MRV TOOL

We developed a pilot 'Vietnam Rice Emissions MRV' (VMRV), a website that will be used for visualizing and reporting on GHG emissions. The VMRV can be used to plot and analyze emissions geospatially, and compare different regions and different agricultural practices and scenarios. By using these tools for different time periods, progress toward meeting goals can be evaluated and reported on. The VMRV tool is basically a decision support system to serve comprehensive analysis for rice mitigation strategies. The system allows users to compile rice GHG inventories, assess the mitigation potential of various mitigation strategies by changing water management, fertilizer, rice residue and organic amendment. The VMRV tool can be used by Vietnam to:

- ✓ Enhance rice GHG reporting for National Communications using Tier 3 methodology[39]
- ✓ Develop Tier 2 emission factors[40] for rice at provincial or national scales.
- ✓ Evaluate the impact of policies for reducing GHG emissions at field, district, province or national scales.
- ✓ Develop targeting strategies for rice GHG mitigation.
- ✓ Monitor and verify progress to meeting Green Growth goals.
- ✓ Support the development and implementation of a rice carbon offset program.

5.1. VMRV BACKGROUND

VMRV is based on open-source project GeoNode, utilizing a stack of software, most notably Django and PostGIS (a geospatial database). It is a fully featured WebGIS system that supports spatial visualization and analysis that allow searching, viewing, editing, and uploading of data, analysis and reporting tools, and also facilitates communication with other users through forums, news and announcements, and the use of comments.

The stack of software that VMRV uses includes:

- *The Website*: VMRV is a Django (a popular Web Framework) based project that includes tools to handle user registration and accounts, avatars, news, forums, and helper libraries.

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[39] Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Eds). Institute for Global Environmental Strategies (IGES). Hayama, Japan 2006. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/

[40] Ibid.

- *The Geospatial Publisher*: GeoServer manages and serves up rendered images of the geospatial data that is usually stored in a geospatial database (i.e., PostGIS).
- *The Metadata Catalogue*: Pycsw stores all the metadata for data, including abstract, revision history, author, notes, data source, etc, which facilitates searching available data using a variety of criteria.
- *The Map Viewer*: This is the main map interface used for viewing and interacting with geospatial data. It is built on top of GeoExt and uses OpenLayers and GXP and talks to the other components via HTTP and JSON as well as standard OGC services.
- *The Database*: PostgreSQ (with PostGIS extension) is the database used to store the geospatial vector data (that is then accessed by the other components). Geospatial raster data is stored on disk, although the metadata is stored within the database.

The development version of the VMRV system is located at http://vmrv.appliedgeosolutions.com. See Figure 7 for screenshot of VMRV homepage.

5.2. GEOSOLUTION FRAMEWORK

The VMRV development site is running on Applied GeoSolution's 'GeoSolution' platform. GeoSolution hosts multiple GeoNode powered websites that utilize a central database and web mapping service, coupled with site-based permissions. This sharing of base data, such as country and province boundaries, allows for more efficient data management as data layers are invariably updated for fixes or new additions. End users have access to a larger amount of data layers for ancillary data to use along with viewing model output results. GeoSolution is hosted on a virtualized machine, allowing flexibility in scaling the server specs to meet the demands of the projects.

5.3. DATA LAYERS AND MAPS

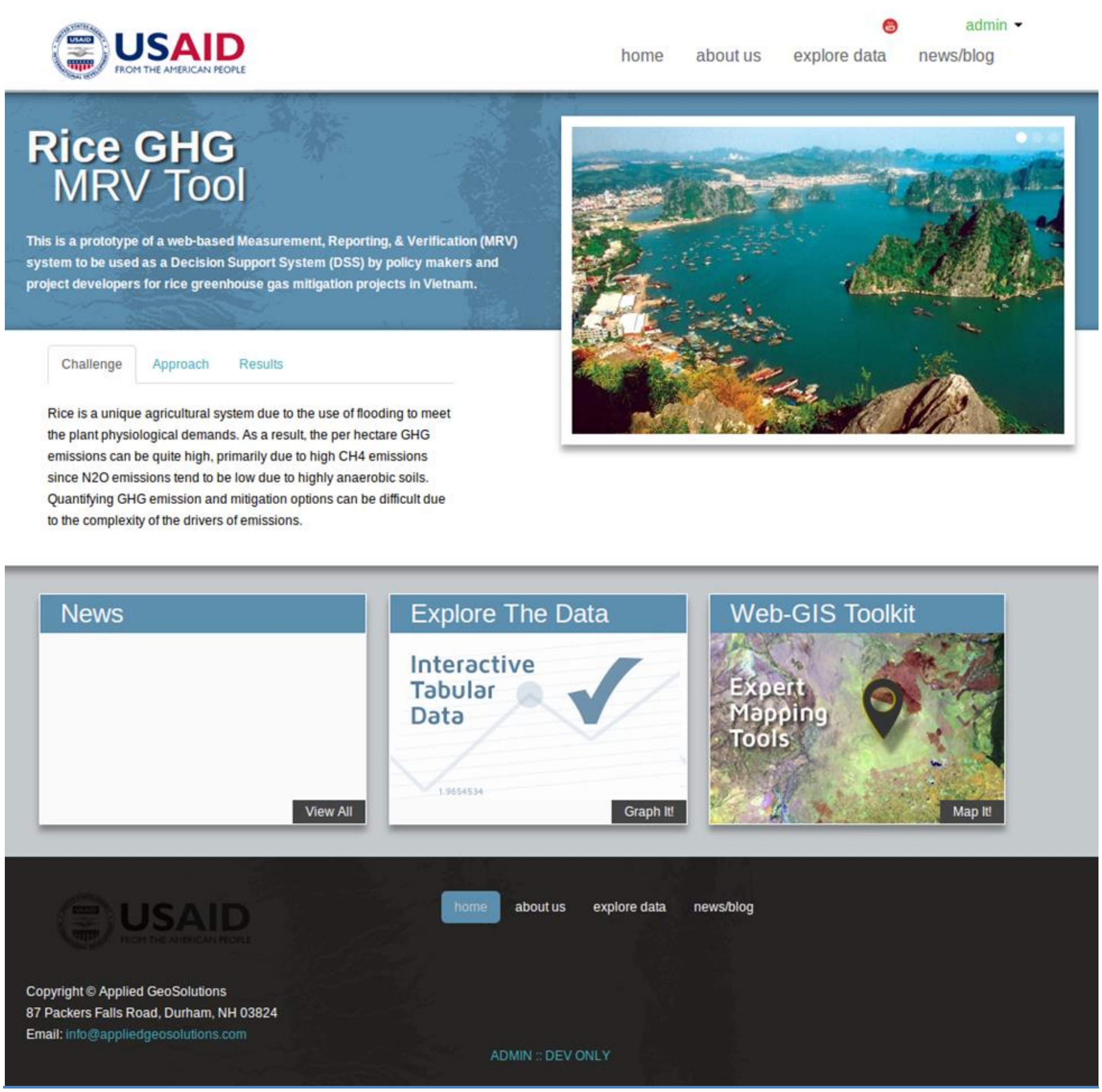
VMRV uses the term data layers to signify a single layer of data (e.g., vector file, multi-band raster, group of photos or other geocoded documents), while maps signify a collection of data layers along with additional metadata such as an abstract, links to reports, etc. Data layers can be browsed or searched on a variety of metadata. See Figure 8.

GeoNode allows users to organize various layers together into collections, which can be styled (via a web-based styler app) and saved. These collections are called "Maps", such as province boundaries, greenhouse gas emissions, and field photos overlayed on top of a Google satellite base layer.

VMRV allows the user to upload vector and raster data in their original projections using a web form. After the upload is finished, the user is presented with a form to fill in any additional metadata, such as description, abstract, etc. Once the data has been uploaded, GeoNode lets the user search for it geographically or via keywords and create maps.

All the layers are automatically reprojected to web Mercator for display, making it possible to use different popular base layers, like Open Street Map, Google Satellite or Bing layers. Once maps are saved, it is possible to embed them in any webpage or get a PDF version for printing.

Figure 7: WebGIS MRV Tool



5.4. GEONODE AND VMRV FRAMEWORK

GeoNode supports a hierarchal accounts system and control over setting permissions for any function users can perform. These permissions can be set for a group of users, such as a small workgroup, or for all users of a site. Default permissions are set such that the world can view user data but only the owner can change it. Users may optionally grant layer editing permissions to all registered users or to specific users they choose. Editors can modify layer styles, edit metadata records, and upload new versions of the data. Similarly, users can grant layer management permissions to other users or groups. In addition to editing capabilities, managers can modify layer permission settings or delete the layer entirely.

The VMRV portion of the site adds several additional capabilities on top of GeoNode's geospatial features. Django models for DNDC data are implemented as a Django app. The model outputs and different management scenarios for different fields are stored in the database and allow for interactive selecting, plotting, and analysis of emission results (See Figure 9). Fields can be compared against different management scenarios for the same field, or compared against other fields with common management practices.

In the future, data could collected and transferred to VMRV by locals in the field via mobile-device applications customized for this project (example red dots in Figure 8: photos and locations). These applications will make data collection faster and will reduce errors associated the transcribing of paper-based records. The applications will also be rich with easily accessible resources to guide the field team in gathering consistent field data. Field observations will be uploaded to the central database for integration with remotely sensed observations.

Figure 8: WebGIS data layers

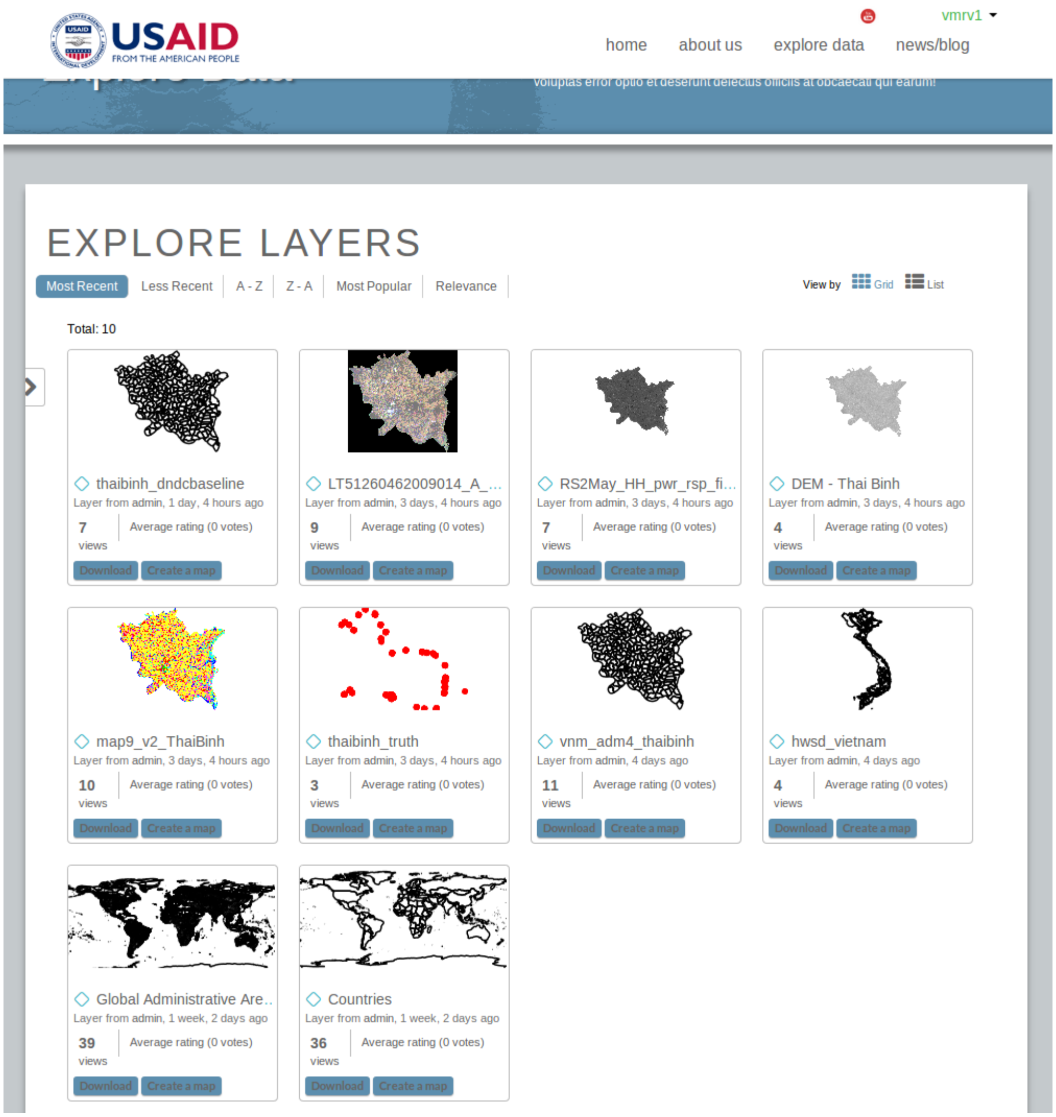
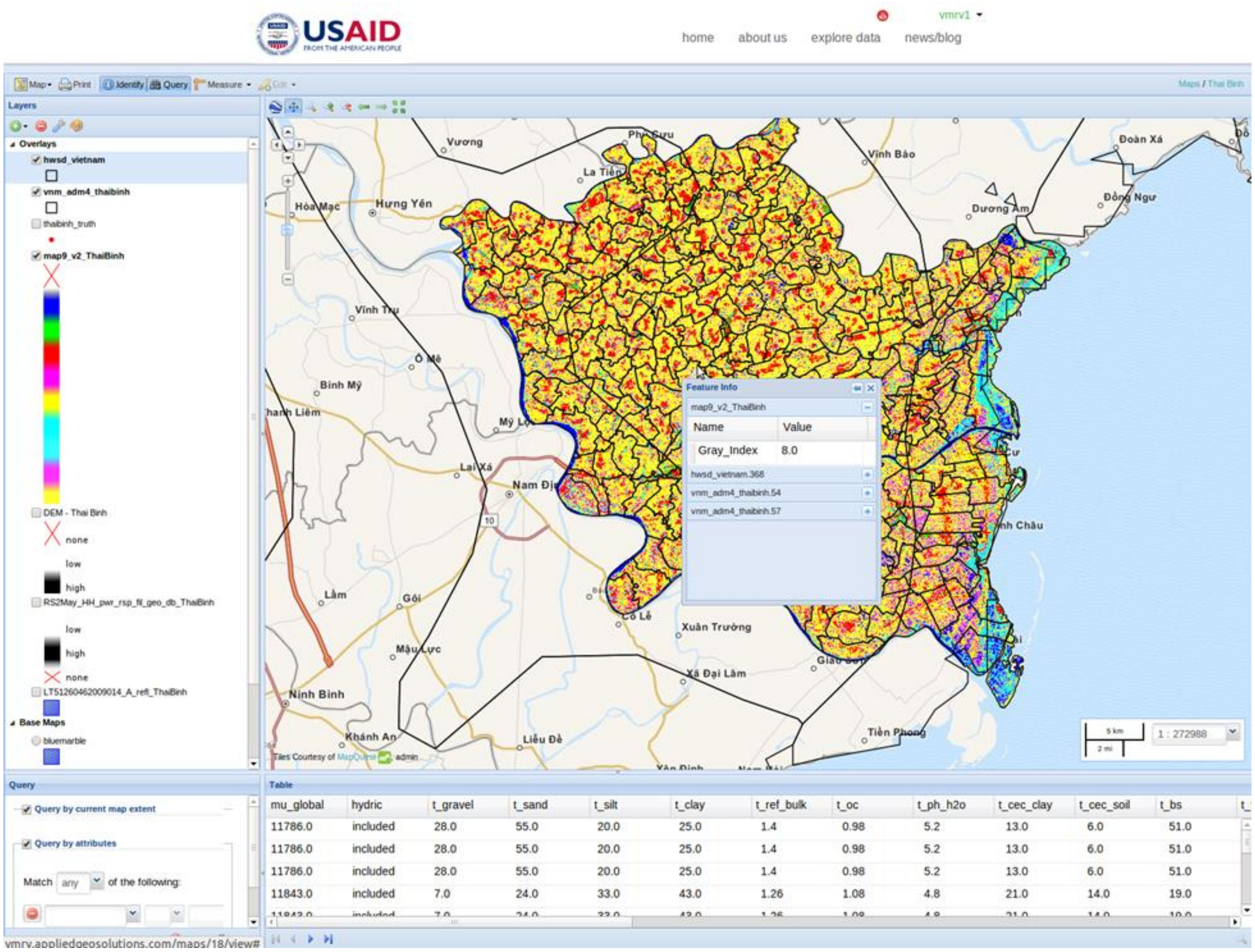


Figure 9: Spatial GHG data viewer



WebGIS tools to query DNDC modeled GHG emissions and create maps on the fly.

5.5. WEB-GIS MRV TOOL: OUTCOMES AND TAKE HOME MESSAGES

- A pilot 'Vietnam Rice Emissions MRV' (VMRV) system was successfully designed and piloted to illustrate the power of integrating remote sensing, DNDC modeling, field surveys and the GeoNode open-source project.
- VMRV system is flexible and is easily scaled to include additional provinces up to national level or even regional scale (e.g. multiple SE Asian countries).
- VMRV system can be customized to support specific measurement, report and verification needs for carbon emissions trading or NAMAs to facilitate access to climate finance like the Green Climate Fund.
- A dialogue is needed with relevant stakeholders (e.g. MARD, MONRE, and others) to customize the VMRV system for their institutional needs.
- Investment is required to move the VMRV system from this pilot phase to implementation.

6. CONCLUSIONS AND RECOMMENDATIONS

There is a large potential for mitigation of greenhouse gas emissions from rice. Within the agricultural sector, rice—Vietnam's dominant crop—is the leading source of agricultural sector emissions (50 percent), followed by agricultural soils (e.g., from fertilizer use) (29 percent) and livestock (17 percent).[41] Implementation of alternative water management, such as intermittent wetting and drying, can reduce methane emissions significantly (~50%).

Integration of optical and synthetic aperture radar (SAR) remote sensing can be used for extensive mapping and monitoring of rice in Vietnam. Operational remote sensing applications can generate and deliver high resolution, georeferenced rice maps and rice production maps with sufficient accuracy to support a rice MRV system.

Integrative research and development of well calibrated decision support tools are needed for quantifying emissions and evaluating mitigation opportunities in the Vietnam. A coordinated field measurement and model calibration and validation program will provide the backbone of a quantification system that is rigorous, based on state of the art science and can support low emissions growth for rice production in Vietnam.

A **Monitoring, Reporting and Verification (MRV) System for Rice GHG Emissions** tool can serve as an important decision support tool for Vietnam to enhance their strategy and progress for low carbon rice development, national communications to the UNFCC and development and tracking of NAMAs. The central components of the MRV system should consists of 3 main components: a remote sensing based Rice Management Observatory, DNDC Modeling and field measurement system, and a WebGIS Data Delivery, Visualization and Tracking System.

This project successfully demonstrated the feasibility and value of this MRV system. The pilot system was designed so that it could easily be scaled up from a single province to national or regional scale. Given the importance of rice globally and the recent IPCC increase of methane's global warming potential to 34 in the Fifth Assessment Report[42] reduction of methane from rice production is an important mitigation opportunity. Investment/funding from USAID or other donors in the following next steps are needed to transition this pilot MRV tool to an operational decision support tools to support GHG inventory and mitigation goals:

A Monitoring, Reporting and Verification (MRV) System for Rice GHG Emissions can serve as an important decision support tool for Vietnam to enhance their strategy and progress for low carbon rice development. This project successfully demonstrated the feasibility and value of this MRV system for Thai Binh Province. The pilot system was designed so that it could easily be scaled up

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[41] RCEE Energy and Full Advantage, for the World Bank Carbon Finance Assist Program – Vietnam, *Potential Climate Change Mitigation Opportunities in the Agriculture and Forestry Sector in Vietnam,* Background Paper, November 2009.

[42] See http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

from a single province to national or regional scale. Given the importance of rice globally and the recent re-assessment of methane's global warming potential[43], the reduction of methane from rice production is an important mitigation opportunity. Investment in the following next steps are needed to transition this pilot MRV tool to an operational decision support tool to support GHG inventory and mitigation goals:

- ✓ **Compile field data on rice GHG emissions and identify gaps in measurements.** These independent field data are critical for rigorous evaluation and testing of DNDC model to improve estimates of uncertainty. There are several on-going programs[44] that are collecting rice GHG measurements. Coordination and synthesis of these efforts is needed.
- ✓ **Perform extensive model validation for better quantification of uncertainty of the DNDC model.** Additional testing and calibration will improve the quantification of the model accuracy and precision.
- ✓ **Build capacity for DNDC modeling.** DNDC is a detailed soil biogeochemical model that historically has been used as a basic research tool. However, recent developments have made the model easier to calibrate and to integrate into decision support tools. DNDC is now the quantification tool for several GHG offset protocols.
- ✓ **Build capacity for operational remote sensing for mapping and monitoring rice.** International space agencies (NASA, ESA, JAXA, etc) have or will be launching a constellation of satellites that will provide data at low or no cost that can be used for operational mapping of rice production. This constellation includes sensors that can image through clouds to provide all-weather capability for rice mapping and monitoring.
- ✓ **Coordination with MARD, MONRE and GSO for data collection, implementation of the MRV system and support for rice based Nationally Appropriate Mitigation Actions.** There is a need for setting standard operating procedures for collecting rice management data to support baseline setting and assessment of mitigation opportunities. Mechanisms for crediting GHG reductions are needed.

[43] See http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

[44] For example, IRRI projects like MIRSA, Mitigation in Irrigated Rice Systems: Guidelines from Measurement, Reporting, and Verification; LUCCi project; CLUES; EDF Vietnam Low Carbon Rice Project; etc

ANNEX A: SOIL ATTRIBUTES

TABLE: Soil attributes for Thai Binh and An Giang Modeling.

region	soil ID (HWSD_ID)	rice area (ha)	FAO-74 soil type	texture class	clay (%)	SOC (%)	bulk density	pH
An Giang	43055	8,966	Gleyic Acrisols	sandy clay loam	23	1.7	1.4	4.9
An Giang	43056	5,977	Orthic Acrisols	sandy clay loam	24	2.0	1.4	4.6
An Giang	43057	5,977	Gleyic Luvisols	loamy sand	22	1.9	1.4	6.1
An Giang	43058	2,989	Plinthic Acrisols	sandy clay loam	23	2.3	1.4	4.8
An Giang	43059	2,989	Dystric Gleysols	loamy sand	21	2.5	1.4	5.1
An Giang	43060	2,989	Gleyic Solonetz	sandy clay loam	23	1.4	1.4	7.2
An Giang	43170	43,554	Eutric Gleysols	silty clay	52	2.5	1.2	5.8
An Giang	43171	26,132	Mollic Gleysols	loamy sand	22	3.5	1.4	6.5
An Giang	43172	8,711	Humic Gleysols	loamy sand	22	7.4	1.4	5.5
An Giang	43173	8,711	Dystric Fluvisols	loamy sand	20	1.8	1.4	7.3
An Giang	43236	73,116	Dystric Fluvisols	loamy sand	20	1.8	1.4	7.3
An Giang	43237	36,558	Eutric Gleysols	sandy clay loam	23	2.1	1.4	6.2
An Giang	43238	12,186	Mollic Gleysols	loamy sand	22	3.5	1.4	6.5
An Giang	43248	48,376	Thionic Fluvisols	clay	58	5.2	1.2	5.0
An Giang	43249	5,375	Humic Gleysols	loamy sand	22	7.4	1.4	5.5
An Giang	43599	35,876	Thionic Fluvisols	clay	58	5.2	1.2	5.0
An Giang	43600	17,938	Humic Gleysols	loamy sand	22	7.4	1.4	5.5
An Giang	43601	5,979	Dystric Gleysols	loamy sand	21	2.5	1.4	5.1
Thai Binh	43170	20,529	Eutric Gleysols	silty clay	52	2.5	1.2	5.8

Thai Binh	43171	12,317	Mollic Gleysols	loamy sand	22	3.5	1.4	6.5
Thai Binh	43172	4,106	Humic Gleysols	loamy sand	22	7.4	1.4	5.5
Thai Binh	43173	4,106	Dystric Fluvisols	loamy sand	20	1.8	1.4	7.3
Thai Binh	43236	11,042	Dystric Fluvisols	loamy sand	20	1.8	1.4	7.3
Thai Binh	43237	5,521	Eutric Gleysols	sandy clay loam	23	2.1	1.4	6.2
Thai Binh	43238	1,840	Mollic Gleysols	loamy sand	22	3.5	1.4	6.5
Thai Binh	43248	1,063	Thionic Fluvisols	clay	58	5.2	1.2	5.0
Thai Binh	43249	118	Humic Gleysols	loamy sand	22	7.4	1.4	5.5
Thai Binh	43271	2,322	Eutric Regosols	loamy sand	6	1.0	1.7	6.6
Thai Binh	43272	1,548	Albic Arenosols	sand	4	0.8	1.7	5.9
Thai Binh	43273	1,548	Ferralic Arenosols	loamy sand	6	0.8	1.7	5.6
Thai Binh	43274	774	Gleysols	loamy sand	22	2.5	1.4	5.8
Thai Binh	43275	774	Dystric Fluvisols	loamy sand	20	1.8	1.4	7.3
Thai Binh	43276	774	Podzols	sand	4	4.2	1.7	4.4

ANNEX B: DNDC CALIBRATED CROP PARAMETERS

Table: DNDC Calibrated Crop Parameters

crop variey	Thai Binh, short	Thai Binh, long	An Giang, short	An Giang, long
crop code	1	2	3	4
Maximum biomass (kgC)*	6,161	5,817	3,918	3,553
Grain fraction†	0.41	0.41	0.41	0.41
Leaf fraction	0.27	0.27	0.27	0.27
Stem fraction	0.27	0.27	0.27	0.27
Root fraction	0.05	0.05	0.05	0.05
Grain C:N‡	45	45	45	45
Leaf C:N	85	85	85	85
Shoot C:N	85	85	85	85
root C:N	85	85	85	85
Water demand (g water / g dry matter produced)	508	508	508	508
Optimum temperature (°C)	25	25	25	25
Total degree days to maturity (TDD) +	1,999	2,762	2,214	3,045
Nitrogen fixation index#	1.05	1.05	1.05	1.05

* maximum total biomass production (grain + leaf + stem + root) under optimal growing conditions
† fractions allocate plant production to the various plant parts (grain, leaf, stem, and root)
‡ ratio of carbon to nitrogen for each plant part
+ determines the cumulative degree days from the start of plant growth to maturity; a degree day is any day where the mean temperature meets or exceeds 10°C
# the N fixation index is equal to the ratio of plant N to N taken up from the soil (for non-N-fixing plants, the index is equal to 1.0; for N-fixing plants the index will exceed 1.0).

ANNEX C: RICE MANAGEMENT SCENARIOS

Table: DNDC Rice Management Scenarios

name	water management	rice variety	N application	fertilizer type	manure
AWD14d / 120d / 100 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	long (120d)	100 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 120d / 100 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	long (120d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 120d / 100 / urea / manure	AWD, 2d drain, 14d flood	long (120d)	100 kgN/ha/crop	urea	manure
AWD14d / 120d / 100 / urea / no manure	AWD, 2d drain, 14d flood	long (120d)	100 kgN/ha/crop	urea	no manure
AWD14d / 120d / 120 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	long (120d)	120 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 120d / 120 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	long (120d)	120 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 120d / 120 / urea / manure	AWD, 2d drain, 14d flood	long (120d)	120 kgN/ha/crop	urea	manure
AWD14d / 120d / 120 / urea / no manure	AWD, 2d drain, 14d flood	long (120d)	120 kgN/ha/crop	urea	no manure
AWD14d / 120d / 170 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	long (120d)	170 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 120d / 170 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	long (120d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 120d / 170 / urea / manure	AWD, 2d drain, 14d flood	long (120d)	170 kgN/ha/crop	urea	manure

AWD14d / 120d / 170 / urea / no manure	AWD, 2d drain, 14d flood	long (120d)	170 kgN/ha/crop	urea	no manure
AWD14d / 120d / 80 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	long (120d)	80 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 120d / 80 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	long (120d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 120d / 80 / urea / manure	AWD, 2d drain, 14d flood	long (120d)	80 kgN/ha/crop	urea	manure
AWD14d / 120d / 80 / urea / no manure	AWD, 2d drain, 14d flood	long (120d)	80 kgN/ha/crop	urea	no manure
AWD14d / 90d / 100 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	short (90d)	100 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 90d / 100 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	short (90d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 90d / 100 / urea / manure	AWD, 2d drain, 14d flood	short (90d)	100 kgN/ha/crop	urea	manure
AWD14d / 90d / 100 / urea / no manure	AWD, 2d drain, 14d flood	short (90d)	100 kgN/ha/crop	urea	no manure
AWD14d / 90d / 120 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	short (90d)	120 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 90d / 120 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	short (90d)	120 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 90d / 120 / urea / manure	AWD, 2d drain, 14d flood	short (90d)	120 kgN/ha/crop	urea	manure
AWD14d / 90d / 120 / urea / no manure	AWD, 2d drain, 14d flood	short (90d)	120 kgN/ha/crop	urea	no manure
AWD14d / 90d / 170 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	short (90d)	170 kgN/ha/crop	ammonium sulfate	manure

AWD14d / 90d / 170 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	short (90d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 90d / 170 / urea / manure	AWD, 2d drain, 14d flood	short (90d)	170 kgN/ha/crop	urea	manure
AWD14d / 90d / 170 / urea / no manure	AWD, 2d drain, 14d flood	short (90d)	170 kgN/ha/crop	urea	no manure
AWD14d / 90d / 80 / ammonium sulfate / manure	AWD, 2d drain, 14d flood	short (90d)	80 kgN/ha/crop	ammonium sulfate	manure
AWD14d / 90d / 80 / ammonium sulfate / no manure	AWD, 2d drain, 14d flood	short (90d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWD14d / 90d / 80 / urea / manure	AWD, 2d drain, 14d flood	short (90d)	80 kgN/ha/crop	urea	manure
AWD14d / 90d / 80 / urea / no manure	AWD, 2d drain, 14d flood	short (90d)	80 kgN/ha/crop	urea	no manure
AWD50% / 120d / 100 / ammonium sulfate / manure	AWD, 50% flooded	long (120d)	100 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 120d / 100 / ammonium sulfate / no manure	AWD, 50% flooded	long (120d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 120d / 100 / urea / manure	AWD, 50% flooded	long (120d)	100 kgN/ha/crop	urea	manure
AWD50% / 120d / 100 / urea / no manure	AWD, 50% flooded	long (120d)	100 kgN/ha/crop	urea	no manure
AWD50% / 120d / 120 / ammonium sulfate / manure	AWD, 50% flooded	long (120d)	120 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 120d / 120 / ammonium sulfate / no manure	AWD, 50% flooded	long (120d)	120 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 120d / 120 / urea / manure	AWD, 50% flooded	long (120d)	120 kgN/ha/crop	urea	manure

AWD50% / 120d / 120 / urea / no manure	AWD, 50% flooded	long (120d)	120 kgN/ha/crop	urea	no manure
AWD50% / 120d / 170 / ammonium sulfate / manure	AWD, 50% flooded	long (120d)	170 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 120d / 170 / ammonium sulfate / no manure	AWD, 50% flooded	long (120d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 120d / 170 / urea / manure	AWD, 50% flooded	long (120d)	170 kgN/ha/crop	urea	manure
AWD50% / 120d / 170 / urea / no manure	AWD, 50% flooded	long (120d)	170 kgN/ha/crop	urea	no manure
AWD50% / 120d / 80 / ammonium sulfate / manure	AWD, 50% flooded	long (120d)	80 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 120d / 80 / ammonium sulfate / no manure	AWD, 50% flooded	long (120d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 120d / 80 / urea / manure	AWD, 50% flooded	long (120d)	80 kgN/ha/crop	urea	manure
AWD50% / 120d / 80 / urea / no manure	AWD, 50% flooded	long (120d)	80 kgN/ha/crop	urea	no manure
AWD50% / 90d / 100 / ammonium sulfate / manure	AWD, 50% flooded	short (90d)	100 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 90d / 100 / ammonium sulfate / no manure	AWD, 50% flooded	short (90d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 90d / 100 / urea / manure	AWD, 50% flooded	short (90d)	100 kgN/ha/crop	urea	manure
AWD50% / 90d / 100 / urea / no manure	AWD, 50% flooded	short (90d)	100 kgN/ha/crop	urea	no manure
AWD50% / 90d / 120 / ammonium sulfate / manure	AWD, 50% flooded	short (90d)	120 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 90d / 120 / ammonium sulfate / no manure	AWD, 50% flooded	short (90d)	120 kgN/ha/crop	ammonium sulfate	no manure

AWD50% / 90d / 120 / urea / manure	AWD, 50% flooded	short (90d)	120 kgN/ha/crop	urea	manure
AWD50% / 90d / 120 / urea / no manure	AWD, 50% flooded	short (90d)	120 kgN/ha/crop	urea	no manure
AWD50% / 90d / 170 / ammonium sulfate / manure	AWD, 50% flooded	short (90d)	170 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 90d / 170 / ammonium sulfate / no manure	AWD, 50% flooded	short (90d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 90d / 170 / urea / manure	AWD, 50% flooded	short (90d)	170 kgN/ha/crop	urea	manure
AWD50% / 90d / 170 / urea / no manure	AWD, 50% flooded	short (90d)	170 kgN/ha/crop	urea	no manure
AWD50% / 90d / 80 / ammonium sulfate / manure	AWD, 50% flooded	short (90d)	80 kgN/ha/crop	ammonium sulfate	manure
AWD50% / 90d / 80 / ammonium sulfate / no manure	AWD, 50% flooded	short (90d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWD50% / 90d / 80 / urea / manure	AWD, 50% flooded	short (90d)	80 kgN/ha/crop	urea	manure
AWD50% / 90d / 80 / urea / no manure	AWD, 50% flooded	short (90d)	80 kgN/ha/crop	urea	no manure
AWDWT / 120d / 100 / ammonium sulfate / manure	AWD, specified water table	long (120d)	100 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 120d / 100 / ammonium sulfate / no manure	AWD, specified water table	long (120d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 120d / 100 / urea / manure	AWD, specified water table	long (120d)	100 kgN/ha/crop	urea	manure
AWDWT / 120d / 100 / urea / no manure	AWD, specified water table	long (120d)	100 kgN/ha/crop	urea	no manure
AWDWT / 120d / 120 / ammonium sulfate / manure	AWD, specified water table	long (120d)	120 kgN/ha/crop	ammonium sulfate	manure

AWDWT / 120d / 120 / ammonium sulfate / no manure	AWD, specified water table	long (120d)	120 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 120d / 120 / urea / manure	AWD, specified water table	long (120d)	120 kgN/ha/crop	urea	manure
AWDWT / 120d / 120 / urea / no manure	AWD, specified water table	long (120d)	120 kgN/ha/crop	urea	no manure
AWDWT / 120d / 170 / ammonium sulfate / manure	AWD, specified water table	long (120d)	170 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 120d / 170 / ammonium sulfate / no manure	AWD, specified water table	long (120d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 120d / 170 / urea / manure	AWD, specified water table	long (120d)	170 kgN/ha/crop	urea	manure
AWDWT / 120d / 170 / urea / no manure	AWD, specified water table	long (120d)	170 kgN/ha/crop	urea	no manure
AWDWT / 120d / 80 / ammonium sulfate / manure	AWD, specified water table	long (120d)	80 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 120d / 80 / ammonium sulfate / no manure	AWD, specified water table	long (120d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 120d / 80 / urea / manure	AWD, specified water table	long (120d)	80 kgN/ha/crop	urea	manure
AWDWT / 120d / 80 / urea / no manure	AWD, specified water table	long (120d)	80 kgN/ha/crop	urea	no manure
AWDWT / 90d / 100 / ammonium sulfate / manure	AWD, specified water table	short (90d)	100 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 90d / 100 / ammonium sulfate / no manure	AWD, specified water table	short (90d)	100 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 90d / 100 / urea / manure	AWD, specified water table	short (90d)	100 kgN/ha/crop	urea	manure

AWDWT / 90d / 100 / urea / no manure	AWD, specified water table	short (90d)	100 kgN/ha/crop	urea	no manure
AWDWT / 90d / 120 / ammonium sulfate / manure	AWD, specified water table	short (90d)	120 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 90d / 120 / ammonium sulfate / no manure	AWD, specified water table	short (90d)	120 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 90d / 120 / urea / manure	AWD, specified water table	short (90d)	120 kgN/ha/crop	urea	manure
AWDWT / 90d / 120 / urea / no manure	AWD, specified water table	short (90d)	120 kgN/ha/crop	urea	no manure
AWDWT / 90d / 170 / ammonium sulfate / manure	AWD, specified water table	short (90d)	170 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 90d / 170 / ammonium sulfate / no manure	AWD, specified water table	short (90d)	170 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 90d / 170 / urea / manure	AWD, specified water table	short (90d)	170 kgN/ha/crop	urea	manure
AWDWT / 90d / 170 / urea / no manure	AWD, specified water table	short (90d)	170 kgN/ha/crop	urea	no manure
AWDWT / 90d / 80 / ammonium sulfate / manure	AWD, specified water table	short (90d)	80 kgN/ha/crop	ammonium sulfate	manure
AWDWT / 90d / 80 / ammonium sulfate / no manure	AWD, specified water table	short (90d)	80 kgN/ha/crop	ammonium sulfate	no manure
AWDWT / 90d / 80 / urea / manure	AWD, specified water table	short (90d)	80 kgN/ha/crop	urea	manure
AWDWT / 90d / 80 / urea / no manure	AWD, specified water table	short (90d)	80 kgN/ha/crop	urea	no manure
CF / 120d / 100 / ammonium sulfate / manure	continuous flooding	long (120d)	100 kgN/ha/crop	ammonium sulfate	manure

CF / 120d / 100 / ammonium sulfate / no manure	continuous flooding	long (120d)	100 kgN/ha/crop	ammonium sulfate	no manure
CF / 120d / 100 / urea / manure	continuous flooding	long (120d)	100 kgN/ha/crop	urea	manure
CF / 120d / 100 / urea / no manure	continuous flooding	long (120d)	100 kgN/ha/crop	urea	no manure
CF / 120d / 120 / ammonium sulfate / manure	continuous flooding	long (120d)	120 kgN/ha/crop	ammonium sulfate	manure
CF / 120d / 120 / ammonium sulfate / no manure	continuous flooding	long (120d)	120 kgN/ha/crop	ammonium sulfate	no manure
CF / 120d / 120 / urea / manure	continuous flooding	long (120d)	120 kgN/ha/crop	urea	manure
CF / 120d / 120 / urea / no manure	continuous flooding	long (120d)	120 kgN/ha/crop	urea	no manure
CF / 120d / 120 / urea / no manure	continuous flooding	long (120d)	120 kgN/ha/crop	urea	no manure
CF / 120d / 170 / ammonium sulfate / manure	continuous flooding	long (120d)	170 kgN/ha/crop	ammonium sulfate	manure
CF / 120d / 170 / ammonium sulfate / no manure	continuous flooding	long (120d)	170 kgN/ha/crop	ammonium sulfate	no manure
CF / 120d / 170 / urea / manure	continuous flooding	long (120d)	170 kgN/ha/crop	urea	manure
CF / 120d / 170 / urea / no manure	continuous flooding	long (120d)	170 kgN/ha/crop	urea	no manure
CF / 120d / 170 / urea / no manure	continuous flooding	long (120d)	170 kgN/ha/crop	urea	no manure
CF / 120d / 80 / ammonium sulfate / manure	continuous flooding	long (120d)	80 kgN/ha/crop	ammonium sulfate	manure
CF / 120d / 80 / ammonium sulfate / no manure	continuous flooding	long (120d)	80 kgN/ha/crop	ammonium sulfate	no manure
CF / 120d / 80 / urea / manure	continuous flooding	long (120d)	80 kgN/ha/crop	urea	manure
CF / 120d / 80 / urea / no manure	continuous flooding	long (120d)	80 kgN/ha/crop	urea	no manure
CF / 90d / 100 / ammonium sulfate / manure	continuous flooding	short (90d)	100 kgN/ha/crop	ammonium sulfate	manure

CF / 90d / 100 / ammonium sulfate / no manure	continuous flooding	short (90d)	100 kgN/ha/crop	ammonium sulfate	no manure
CF / 90d / 100 / urea / manure	continuous flooding	short (90d)	100 kgN/ha/crop	urea	manure
CF / 90d / 100 / urea / no manure	continuous flooding	short (90d)	100 kgN/ha/crop	urea	no manure
CF / 90d / 120 / ammonium sulfate / manure	continuous flooding	short (90d)	120 kgN/ha/crop	ammonium sulfate	manure
CF / 90d / 120 / ammonium sulfate / no manure	continuous flooding	short (90d)	120 kgN/ha/crop	ammonium sulfate	no manure
CF / 90d / 120 / urea / manure	continuous flooding	short (90d)	120 kgN/ha/crop	urea	manure
CF / 90d / 120 / urea / no manure	continuous flooding	short (90d)	120 kgN/ha/crop	urea	no manure
CF / 90d / 120 / urea / no manure	continuous flooding	short (90d)	120 kgN/ha/crop	urea	no manure
CF / 90d / 170 / ammonium sulfate / manure	continuous flooding	short (90d)	170 kgN/ha/crop	ammonium sulfate	manure
CF / 90d / 170 / ammonium sulfate / no manure	continuous flooding	short (90d)	170 kgN/ha/crop	ammonium sulfate	no manure
CF / 90d / 170 / urea / manure	continuous flooding	short (90d)	170 kgN/ha/crop	urea	manure
CF / 90d / 170 / urea / no manure	continuous flooding	short (90d)	170 kgN/ha/crop	urea	no manure
CF / 90d / 170 / urea / no manure	continuous flooding	short (90d)	170 kgN/ha/crop	urea	no manure
CF / 90d / 80 / ammonium sulfate / manure	continuous flooding	short (90d)	80 kgN/ha/crop	ammonium sulfate	manure
CF / 90d / 80 / ammonium sulfate / no manure	continuous flooding	short (90d)	80 kgN/ha/crop	ammonium sulfate	no manure
CF / 90d / 80 / urea / manure	continuous flooding	short (90d)	80 kgN/ha/crop	urea	manure
CF / 90d / 80 / urea / no manure	continuous flooding	short (90d)	80 kgN/ha/crop	urea	no manure
crop variey	Thai Binh, short	Thai Binh, long	An Giang, short	An Giang, long	