Remote Sensing based Crop Yield Monitoring and Forecasting

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ABSTRACT

Accurate and timely information on rice crop growth and yield helps governments and other stakeholders adapting their economic policies, enables relief organizations to better anticipate and coordinate relief efforts in the wake of a natural catastrophe, and provides technical backbone of an insurance solution where risks of yield losses from the rice smallholders are transferred to the insurance market. Such delivery of rice growth and yield information is made possible by regular earth observation using space-born Synthetic Aperture Radar (SAR) technology combined with crop modeling approach to estimate and forecast yield. Radar-based remote sensing is capable of observing rice vegetation growth irrespective of cloud coverage, an important feature given that in incidences of flooding the sky is often cloud-covered. Rice yield forecast is based on a crop growth simulation model using a combination of real-time and historical weather data and SAR-derived key information such as start of growing season and leaf growth rate. Results from pilot study sites in South and South East Asian countries suggest that incorporation of remote sensing data (SAR) into process-based crop model improves yield estimation for actual yields and thus offering potential application of such system in a crop insurance program. Remote-sensing data assimilation into crop model effectively capture responses of rice crops to environmental conditions over large spatial coverage, otherwise practically impossible to achieve with crop modeling approach alone. This study demonstrates the two angles of uncertainties reduction in forecasting crop yield: (1) minimizing model uncertainties, in this case by assimilation of remote-sensing data into crop model to recalibrate model parameters based on remotely sensed crop status on the ground, and (2) minimizing uncertainties in seasonal weather conditions by incorporating real-time throughout the forecasting dates.

Key Terminology: Crop Yield Monitoring, Crop Yield Forecast, Remote Sensing, Synthetic Aperture Radar (SAR), Crop Growth Modeling, ORYZA2000

1. Background

Climatic events such as flood and drought are major threats to food security, especially in developing countries and countries with emerging economies. About 20 million hectares of rice ─ the staple food of most of the world's poor ─ are vulnerable to such climatic events. Innovative tools are needed to mitigate such risks encountered by rice smallholder farmers. Crop insurance can cover farmers' shortfall in production due to natural catastrophes. However, agricultural production is hard to insure because assessment of production loss, among others, is difficult and costly. Many crop insurance schemes implemented in the past have not been sustainable and crop insurance markets in developing countries and emerging economies continue to be under developed. A timely rice information system linked to a crop insurance model is essential.

Remote Sensing-based Information and Insurance for Crops in Emerging Economies (RIICE, riice.org) is a public-private partnership project aiming to reduce vulnerability of rice smallholder farmers in low-income Asian countries using synthetic aperture radar (SAR) technology. SAR data is used to map and observe rice growth, and together with a crop growth model, the technology allows prediction of rice yield in selected rice-growing regions in Cambodia, India, Indonesia, Thailand, the Philippines and Vietnam. The use of SAR technology is crucial given cloud obstruction views from space is common phenomena for region where rice is grown in the tropics due to cloud insensitive feature of radar-based earth observation. National partners in the countries covered by RIICE provide expert knowledge and baseline data, and conduct fieldwork and monitoring of sites. This paper describes progress of RIICE project specifically in the technical aspects of remote sensing and crop yield estimation.

2. Methodology

Remote-sensing based rice yield estimation system involves two key modules: (1) MAPscape-Rice and (2) ORYZA2000 (Fig. 1). MAPscape-Rice is the interface from satellite-based observation data into SAR products such as rice area estimates, start of season (SoS), phenological field status, and leaf area index (LAI). The system assimilates SAR products, namely LAI and SoS into ORYZA2000 in order to generate yield estimates. Combined with rice area product, the estimated yield then can be converted into production estimates for the selected geographical area.

2.1. Remote sensing based rice products

The rice extent/area (extent, 1ha / area, 15m) based on archive ENVISAT ASAR data represents the location and the total multi-annual and/or annual extent/area. This product – which is essential when historical rice maps are either not available is generated using multi-year or annual ASAR WS archive data (100m) and/or high resolution SAR data such as ASAR AP/IM and PALSAR FBS/FBD data (15m). Omitting temporal outliers, the SAR time-series data, for a given time frame (for instance weekly), are temporally averaged, and, after the derivation of selected temporal features (such as minimum, maximum, range, minimum and maximum increase/decrease), mapped as rice using a knowledge-based classifier.

Multi-year ENVISAT ASAR WS (400x400km, 100m) and multi-year/annual IM/AP archive C-band data (100x100km, 15m) have been processed for the generation of Multi-year and Annual Rice Extent/Area. Moreover, exclusively for the Philippines, archive ALOS PALSAR-1 FBD L-band data (70x70km, 15m) have been used. Concerning archive SAR data, it is worth mentioning that, in general, South-East Asia has been well covered during the ENVISAT ASAR mission, in particular in the WS mode.

Dedicated multi-temporal Cosmo-SkyMed (40x40km, 3m) X-band acquisitions are regularly carried out (approximately every 16 days) over selected areas according to the local rice crop calendars. So far, in most of the countries, two crop seasons have been covered using Cosmo-SkyMed. In those areas, contemporaneously to the SAR acquisitions, national partners are conducting ground observations for correlating SAR products with actual ground conditions this include monitoring or rice phenology, measurement of LAI, and validation of rice area product.

SAR data processing is initiated by acquisition planning to select the most suitable geometries, modes, and proper crop season period. In the next step, Single Look Complex (SLC) data are transformed– in a fully automated way – into terrain geocoded backscattering coefficient by means of: (1) Generation of strip mosaics of single frames in slant range geometry and multi-looking; (2) Grouping of the strip mosaics acquired with the same geometry; (3) Digital Elevation Model (DEM) based orbital correction; (4) Co-registration; (5) De Grandi time series speckle filtering; (6) Terrain geocoding, radiometric calibration and normalisation; (7) Anisotropic Non-Linear Diffusion (ANLD) filtering; (8) Removal of cloud related effects. Subsequently, dedicated remote sensing products are generated which, in turn, are used within the crop growth simulation model to estimate yield.

Due to the large amount of the remote sensing data and the time consuming processing, the SAR processing is performed using a high performing cluster solution, where a master PC coordinates processing PCs and supervises the overall processing. Each processing PC is equipped with CPU with parallel processors or GPU. Note that i) all MAPscape-RICE algorithms have been implemented to fully exploit the processor characteristics; ii) the cluster can be extended according to the amount of data and/or requested product generation time.

When SAR data time-series are acquired on a regular basis and tuned according to the rice season period and crop practices then information on not only the rice area, but also when and where fields are prepared and irrigated, the phenological rice field status – such as flowering, tillering, plant senescence and harvesting – and related dates of irrigation, peak of rice season, and harvesting can all be detected. These are crucial spatial-phenological inputs for an accurate rice growth modeling. These products are generated based on the well known temporal relationship between the radar backscatter and the rice phenology, by considering the different wavelengths and polarizations but also crop practices and seasonal lengths.

LAI is defined as the one sided green leaf area per unit ground area and for rice it ranges between values close to zero for seedlings to a maximum of 10-12 at flowering, although maximum values closer to 6 or 7 are the typical. In this rice yield estimation system, LAI is inferred from the backscattering coefficient by means of the vegetation water cloud model (Attema and Ulaby, 1978).

Flood or drought affected areas can be identified if appropriate time-series data at the time of the event are available. In both cases, in general, a significant decrease of the backscattering coefficient is observed. However, the cause and nature of the decrease are different: in case of flooding, a sharp decrease is observed and is due to the dominant water surface scattering, while for plant moisture loss –or drought – is observed through a continuous radar backscatter decrease.

2.2 Rice Yield Estimation by Modeling

Rice yield estimation is based on Crop Growth Simulation Model (CGSM) of Oryza2000 (Boumman et al., 2001). In order to consider soil nitrogen dynamic processes, the CGSM uses soil data (https://sites.google.com/a/irri.org/oryza2000/) extracted from the World Inventory of Soil Emission potential (WISE) dataset (http://www.icasa.net/toolkit/wise.htm) and Harmonized World Soil Database (HWSD) (http://webarchive.iiasa.ac.at). Some assumptions on puddling effect on physical soil properties have been made. Weather data are obtained from NASA Power dataset (http://power.larc.nasa.gov). These are subsequently corrected based on reported values from local weather stations (http://www.ncdc.noaa.gov) and down-scaled to 15 arc-minutes resolution (Sparks et al., unpublished) for daily solar radiation, daily minimum and maximum temperature, vapor pressure at minimum temperature, and daily average wind speed, and from Tropical Rainfall Measurement Mission (http://trmm.gsfc.nasa.gov) for daily rainfall data.

The simulations account for water and nitrogen dynamics based on climatic, soil conditions and management rice practices. Irrigation and nitrogen fertilizer inputs are assumed as recommended for achieving attainable yield. LAI values – 50 days after emergence and provided by the SoS product – are inferred from radar backscatter using cloud vegetation model (Attema and Ulaby, 1978) with parameters calibrated with in situ LAI measurements. Inferred LAI are finally used to calibrate the relative leaf growth rates parameters in ORYZA2000. For processing efficiency, the spatial units for yield simulation are aggregated to 180 meter resolution.

Yield forecast is based on series of simulation using weather data set combining real-time weather and historical weather data and conducted on weekly basis. The assimilation of SAR products begin after at least 4 cycles of SAR data have been acquired since the onset of rice season period in the area (land-preparation). Beginning from 35 days after crop establishment, SAR product assimilation into the crop forecasting system is implemented. During this early part of the rice growing cycle leaf expansion parameters can be effectively calibrated against real ground condition inferred from satellite observation using radar technology.

3. Results

Multi-year rice area products, as illustrated in Figure 2a and 2b, have been generated. In general based on several field visits, that the products have a good accuracy in areas where rice fields are homogeneous, while lower (expected due to the ASAR data availability) accuracies have been observed in those areas where the fields are scattered, fragmented, and heterogeneous.

Three geographical areas – Nueva Ecija in Central Luzon, Leyte in the Visayas and Agusan del Norte in Mindanao, Philippines – characterized by different field dimensions and rice practices have been acquired using Cosmo-SkyMed SM and ScanSAR during three crop seasons. Some products examples are shown in Figure 2b and 3.

The well populated ASAR WS and IM data archive in the geographical area in Red River Delta, Vietnam combined with the large and homogeneous rice fields in both seasons means that very accurate Multi-year Rice Extent and Annual Rice Area products, could be generated as illustrated in Figure 4 (left panel). Moreover, the use of very high resolution Cosmo-SkyMed SM data acquired every 16 days resulted in a detailed the phenological monitoring at field level for each rice season, as shown in Figure 4 (right panel). Land cover category boundaries have been provided by NIAPP.

Due to the rice maturity type characteristics in Cambodia– i.e. short and medium-long duration – we opted to acquire Cosmo-SkyMed SM time-series during 7 months at 16 days interval. As an example, Figure 5 illustrates short duration rice in green and medium duration rice in yellow. Differentiation between the two was confirmed though a field visit carried out in the middle of the season.

In Cauvary Delta region in Tamil Nadu, India, a dedicated ASAR IM planning was carried out in 2011. Even though not all planned data were delivered, it was possible to develop an Annual Rice Area product, as shown in Figure 6 (left panel). The main challenge in this area is that rice is cultivated with several other crop types, which, at C-band, at some growth stages have a similar signature to rice. It is therefore important for supplementing the area estimates with multi-temporal SAR data according to known locally varying rice calendars. This strategy was adopted over three sites by using Cosmo-SkyMed SM time-series during 5 months at 16 days interval with results shown in Figure 6 (right panel).

In the Philippines, more extensive assessments have been made for the integration of LAI from SAR intensity data and ORYZA2000 crop growth model. Table 1 provides validation at 2nd administrative level (below the provincial level) with respect to the estimated rice yield against observed rice field from crop cutting experiments (CCE) in Leyte, Philippines. On average, compared to the observed yield, the accuracy is 85% with a Root Mean Square Error (RMSE) of 702 kg ha^{-1}. In Agusan Del Norte, ex-ante yield estimation (forecast) has also been tested as shown in Figure 7. Yield forecast was improved with the incorporation of SAR products since 35 days after crop establishment.

4. Conclusions

Lowland rice cultivation is the land use type showing the largest spatial and temporal dynamic in both vegetation and water during a short period (3 to 6 months). Reliable remote sensing-based rice area and rice crop status information requires a combination of good spatial and temporal resolution in a way that both dynamics are fully captured. Moreover, spatial and temporal seasonality and status information from remote sensing are key inputs for crop modeling to capture the spatial variability in yield and production across broad geographic extents that cannot be easily captured in any other way. The RIICE service is being applied in seven Asian countries and it is under validation and evaluation by the national partners.

5. Success achieved and issues for further research

The use of the existing ASAR WS and IM/AP archive data, even if not optimal for the targeted application, provides a valuable data source, enabling the generation of a consistent rice extent / area product over 1.5 million km^2. It is therefore strongly recommended to the space agencies that future SAR missions such as Sentinel-1A/B should incorporate systematic background missions according to the geographical areas and applications instead of building data archives according to sporadic user requests.

Multi-temporal data is fundamental from a data processing and analysis perspective. Few or sporadically acquired images are of little use for operational mapping and monitoring. -Systematic acquisitions of remote sensing data at different spatial resolutions – from 3-5m, 10-20m, and 100-250m at different wavelengths is essential for agricultural applications. In particular, the near future availability of Sentinel-1A/B, -2 and -3 combined with MODIS and very high resolution SAR data (Cosmo-SkyMed and TerraSAR-X StripMap mode) will enable country-wide provision of reliable cultivated area that would capture even small plot agriculture (Holecz et al., 2013) and the corresponding phenological monitoring.

As demonstrated in this paper, the spatial resolution of existing spaceborne remote sensing systems and the wise integration of different remote sensing sources enable to achieve a high level of detail and accuracy, whenever the data are understood, processed and used in the right way. Doubtless, the proposed solution is attractive, less time consuming and less expensive compared to area regression estimators exclusively based on field survey. Furthermore, the remote sensing solution provides a monitoring component; this is often not taken into account in the area regression estimator approach, simply because it is too time consuming to frequently repeat the field survey.

It has been demonstrated that the incorporation of dedicated remote sensing products into the yield crop model is essential. This enables the system to (1) capture the plants response to otherwise inestimable environmental conditions over large areas, (2) include relevant information on rice phenology to initialise the crop model on the correct date, (3) consider the spatial distribution of rice fields so that yield estimates are only made where rice is cultivated that season, (4) improve overall yield estimation figures by calibrating the model to actual yields rather than theoretical attainable or potential yields.

National partner involvement is crucial as the only way to sustain, promote and validate the need for in-country, operational crop monitoring. In RIICE, national partners lead the terrestrial data collection and validation, but also contribute to product generation, where the knowledge on the rice types and practices is essential. For this reason RIICE incorporates an intensive technology transfer to the national partners and applications of remote sensing based information for food security and crop insurance applications at national/government level.

6. References

Attema E.P.W. and F.T. Ulaby. 1978. Vegetation modeled as a water cloud. Radio Science. 13 (2): 357-364.

Bouman B.A.M. et al. 2001. ORYZA2000: modeling lowland rice, IRRI and Wageningen University.

Holecz F., F. Collivignarelli, and M. Barbieri. 2013. Estimation of cultivated area in small plot agriculture in Africa for food security purposes. ESA Living Planet Symposium. Edinburgh.

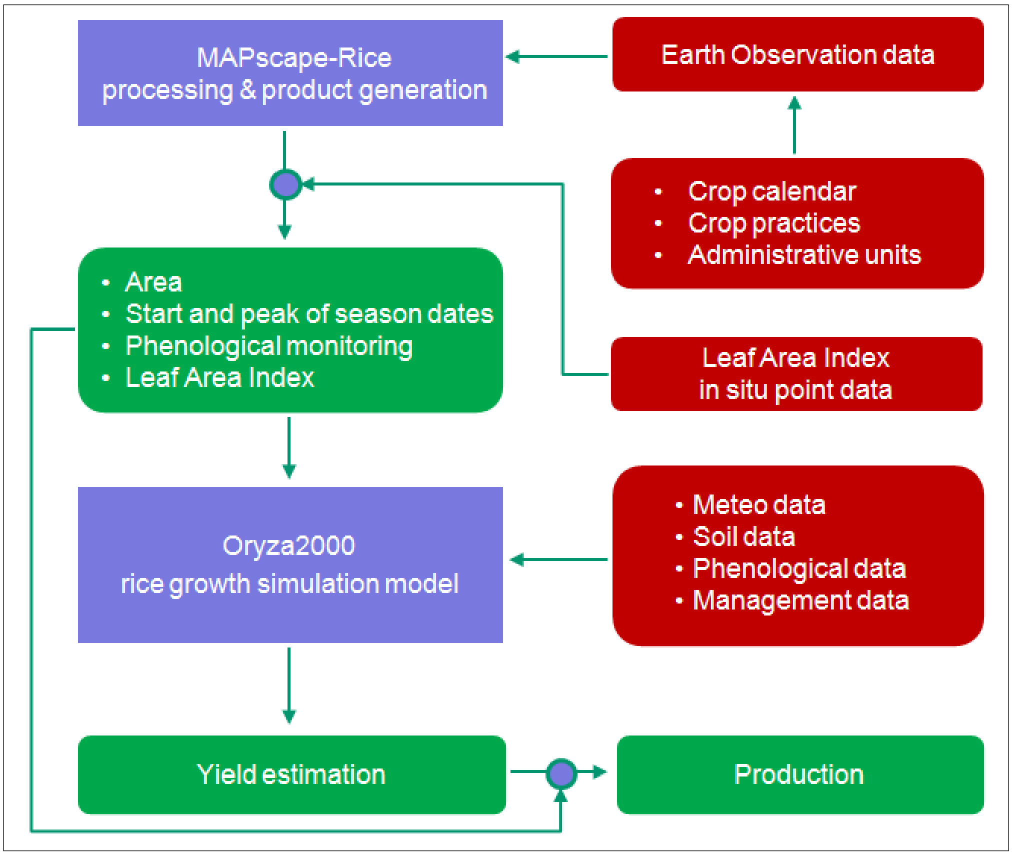

Figure 1: *RIICE yield and production estimation system involving MAPScape-Rice for SAR products generation and ORYZA2000 version configured to interface with remote sensing products. Title of the figure (under the Figure, 12 pt italics, left-justified)*

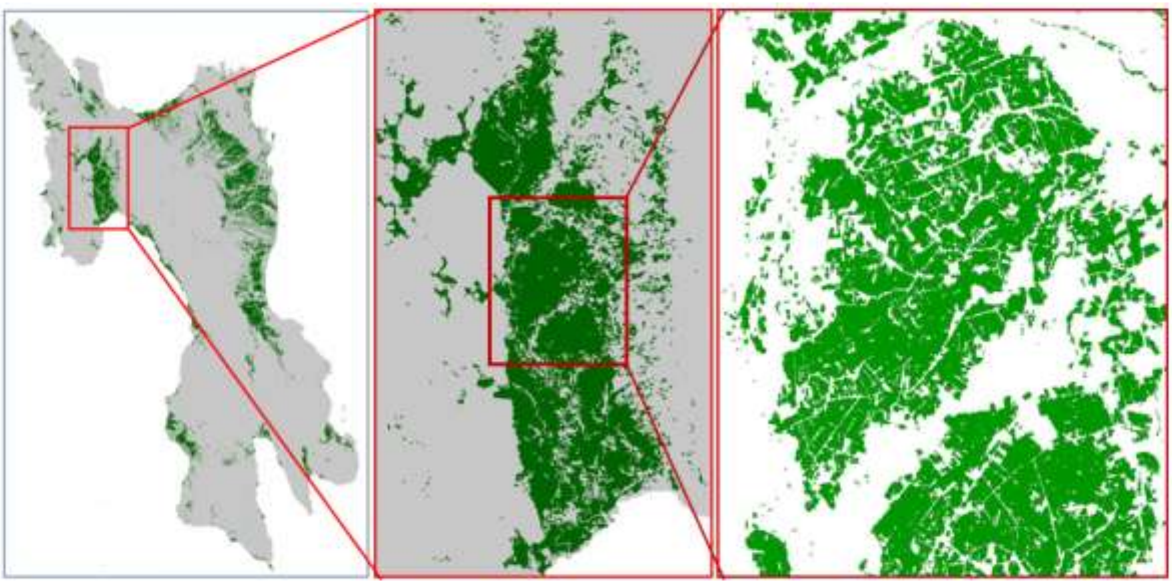

Figure 2: *(a & b) The rice extent map of Leyte at 1-ha resolution derived from ASAR wide swath images acquired from 2004 to 2012; (c) single season rice area product generated from 3m CSK data acquired from June to September 2012.© Cosmo-SkyMed data ASI distributed by e-GEOS, processed using MAPscape-Rice.*

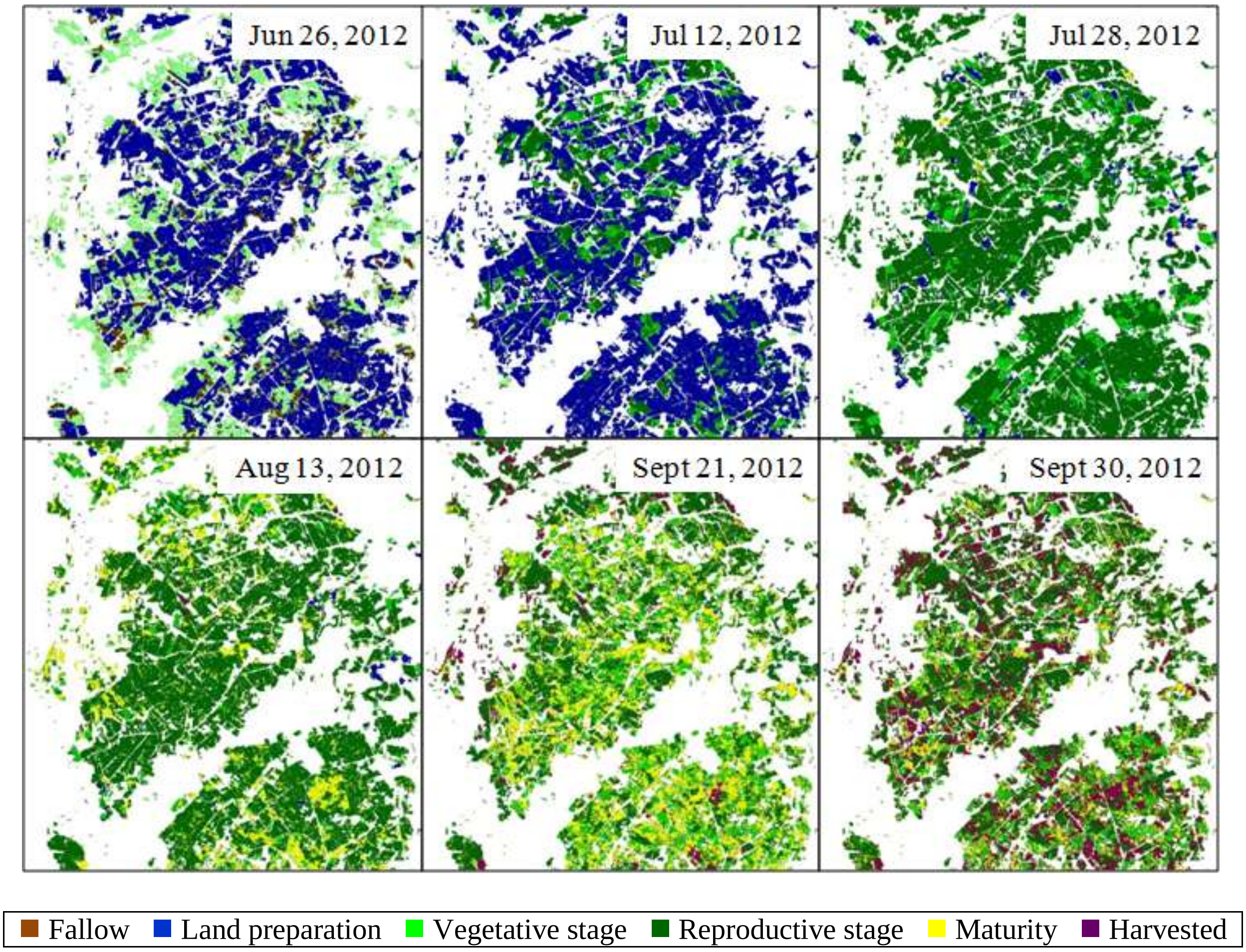

Figure 3*: The phenology of rice field during the wet season of 2012 in Leyte, Philippines as inferred from SAR product. © Cosmo-SkyMed data ASI distributed by e-GEOS, processed using MAPscape-Rice.*

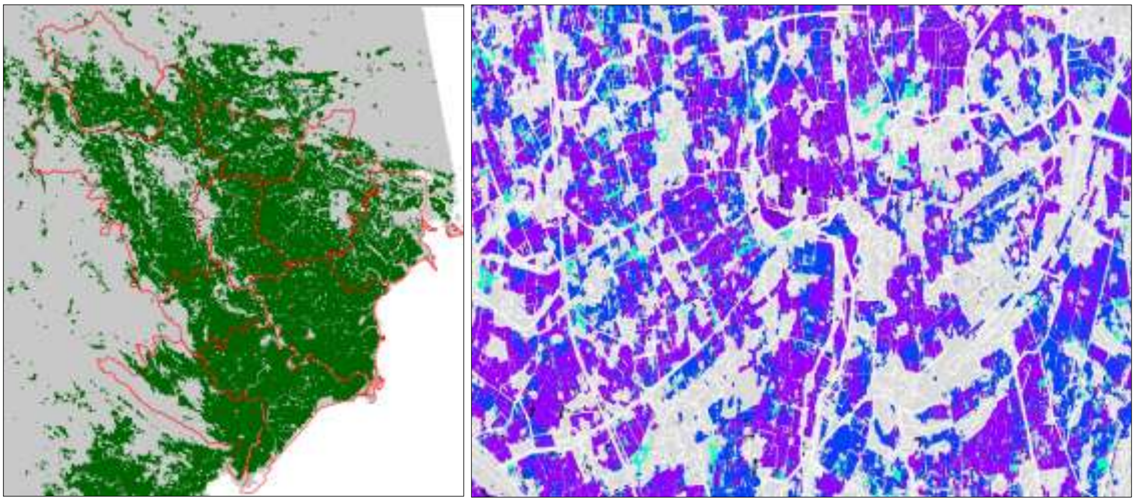

Figure 4*: Rice extent (1 ha) based on ASAR WS archive data acquired from 2003 to 2010 (left panel) and seasonal rice area at 3m for a sample area based on Cosmo-Sykmed Strip Map mode (SM) in Red River Delta, Vietnam from January to May 2013 (right panel). The different colors correspond to the different dates of start of season (SoS). © Cosmo-SkyMed data ASI distributed by e-GEOS, processed using MAPscape-Rice.*

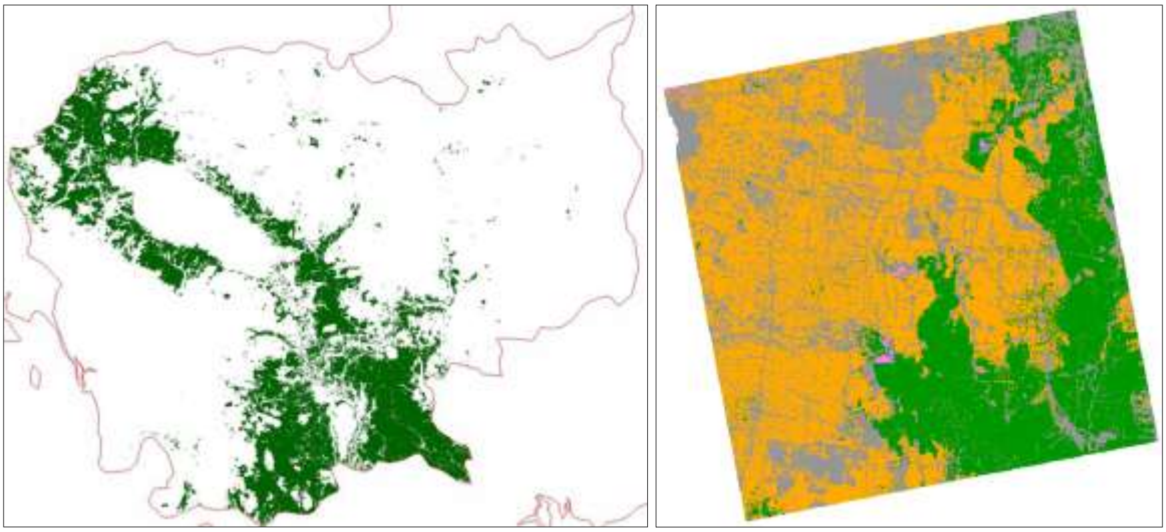

Figure 5*: Rice extent (1 ha) in Cambodia based on ASAR WS archive data acquired from 2005 to 2010 (left panel). Seasonal rice area (3m) for short duration (green) and medium-long duration (green)in sample area near Takeo, Cambodia based on Cosmo-SkyMed SM acquired from September 2012 to March 2013.. The different colors correspond to the different dates of start of season (SoS). © Cosmo-SkyMed data ASI distributed by e-GEOS, processed using MAPscape-Rice.*

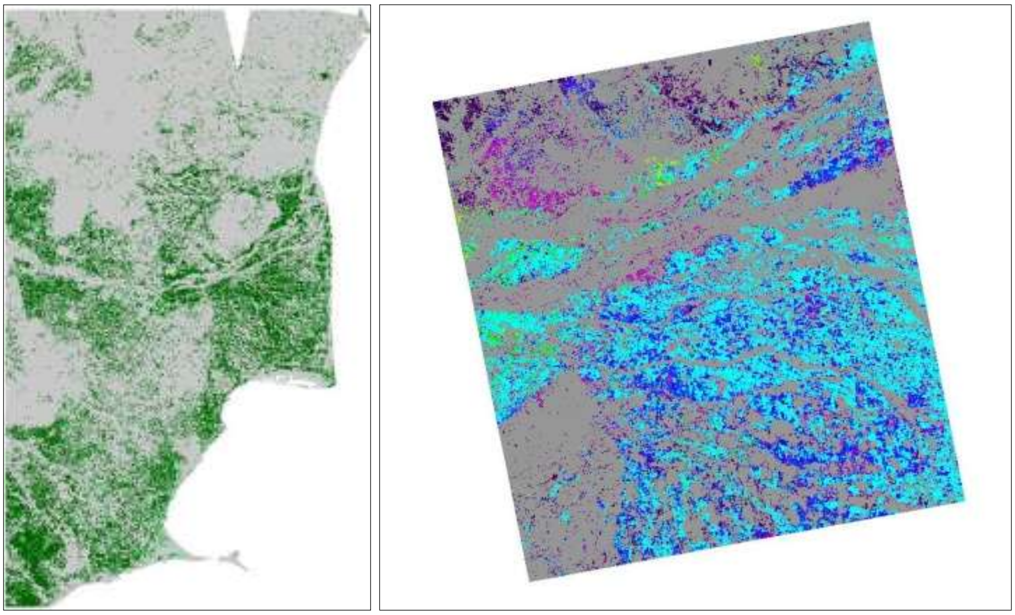

Figure 6*: Rice area (15m) based on ASAR IM data acquired during 2011in Cauvary Delta and surrounding area in Tamil Nadu, India (left panel) and seasonal rice area at 3m for a sample area near Thanjavur, Tamil Nadu, India based on Cosmo-Sykmed (SM) data acquired from September 2012 to February 2013. The different colors correspond to the different dates of start of season (SoS). © Cosmo-SkyMed data ASI distributed by e-GEOS, processed using MAPscape-Rice.*

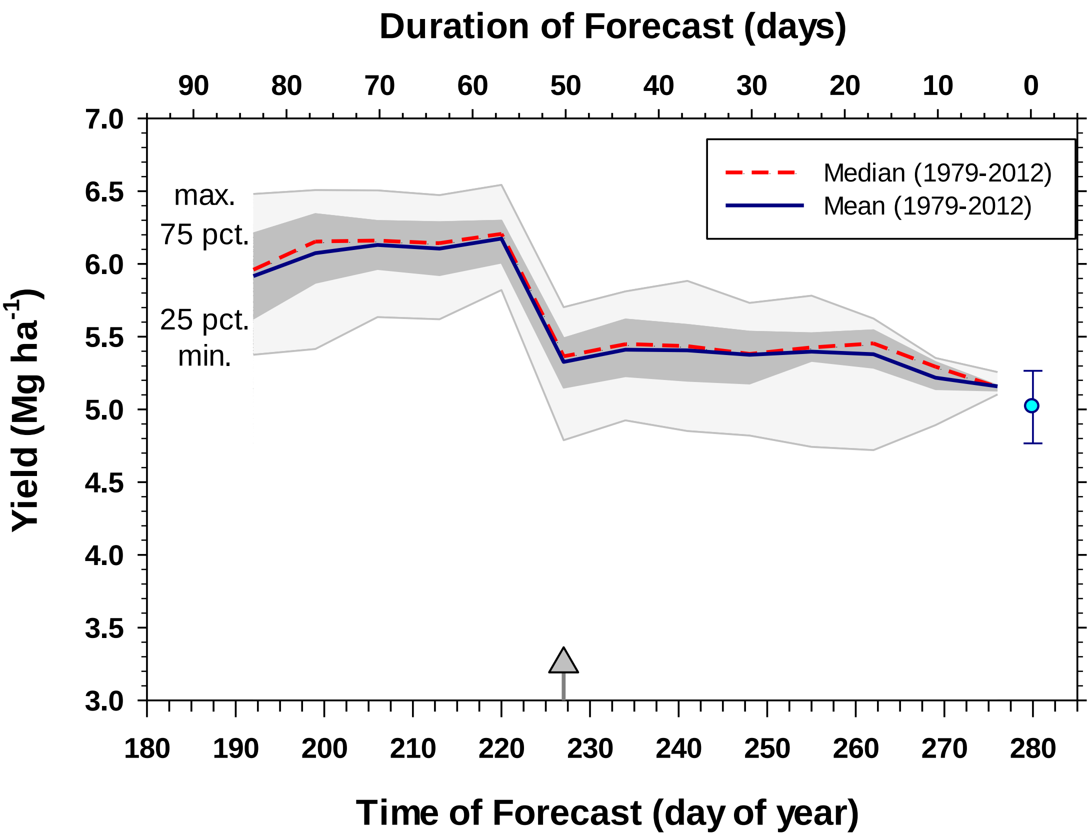

Figure 7*: Weekly yield forecast for one of the RIICE pilot field site in Agusan del Norte, Philippines in wet season 2012. Arrow on day 227 marks the start of SAR data assimilation with the yield estimation system. Symbol and error bar on day 280 indicates actual yield and standard error obtained from crop cut experiment in farmer's field involving 4 replications. The forecast started from the day of transplanting (day 192).*

Table 1: *Validation of RS-based rice yield estimates for RIICE study site in Leyte, Philippines in Wet Season 2012.*

Administrative unit	Yield (Mg ha^{-1})	
	Observed Yield[1]	Estimated Yield[2]
Amahit	2.96	1.94
Cuta	3.79	4.32
Liloan	5.96	5.04
Maticaa	5.14	5.69
Sabang Bao	4.99	4.94

RMSE (kg ha^{-1}) = 702
Accuracy (%) = 85

[1] crop cutting experiment
[2] SAR products-ORYZA2000