AN OPERATIONAL REMOTE SENSING BASED SERVICE FOR RICE PRODUCTION ESTIMATION AT NATIONAL SCALE

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Abstract **— One goal of the Remote Sensing based Information and Insurance for Crops in emerging Economies (RIICE) project is to estimate, on an operational basis, rice production at national scale *in primis* targeted to food security and crop insurance purposes. There are two unique elements to this proposed service:**

1. **Multi-year, annual, and seasonal SAR data are acquired from all existing operational spaceborne systems are used and complemented by MODIS 250/500 m 16-/8-days composite data. This solution:**
   - **overcomes the spatial-temporal problem, hence assuring an appropriate temporal repetition at an adequate scale (i.e. spatial resolution) even over large areas;**
   - **provides sensor independent operational monitoring with sufficient data redundancy to ensure information delivery.**
2. **A crop growth simulation model estimates yield and hence production using dedicated remote sensing products in addition to the usual meteorological, soil, and plant parameters. This remote sensing-crop model approach to yield estimation:**
   - **uses relevant remote sensing derived information on rice phenology to initialize the model on the correct date;**
   - **uses remote sensing parameters as measurements of the crop's response to the environment and management thus reducing the reliance on other input data to the model that would impossible to obtain over wide geographic areas;**
   - **considers the spatial distribution of rice fields;**
   - **improves the yield estimation figures by forcing the model towards actual rather than attainable yields.**

Initial results and experiences gained in the past two years in seven Asian countries are presented and discussed.

Index Terms **— Synthetic Aperture Radar (SAR), Aqua and Terra MODIS, rice, cultivated area and extent, phenology, Leaf Area Index (LAI), yield.**

1. INTRODUCTION

Rice from an agronomic perspective

1. Rice farming is one of the largest single uses of land for producing food, covering over 160m ha across 200m farms. Rice has been cultivated for over 10,000 years, mostly in Asia but with increasing importance in Africa and Latin America as well as pockets of production in Europe, Australia and the US. The development of short duration varieties for irrigated conditions means that rice can be grown continuously in the humid and sub humid tropics with up to three harvests a year —on the same plot of land. 75% of the world's rice is cultivated under irrigated conditions on some 93m ha. Rice is also cultivated in rainfed lowland, upland, mangrove, and deepwater environments albeit with lower productivity.
2. Rice systems are characterized by seasonally-dependent spatio-temporal variations. After field preparation (plowing, harrowing and leveling) the field will usually be irrigated, and later rice will be transplanted (as young seedlings from a nursery bed) or directed seeded in the paddy. The plant then develops through distinct stages, vegetative, reproductive and ripening until harvest. Water is present in the paddy at different depths through most of the season until draining prior to harvesting.
3. Rice may be grown in different cropping systems such as rice/fallow, rice/other crop, rice/rice, rice/rice/other crop and rice/rice/rice. Other crops in these systems would usually be planted in the dry season and can include wheat, maize or pulses for example. Rice varieties range from short duration (90 days) to medium (120 days) and long (150 days) with some traditional varieties taking up to 180 days to reach maturity. The seasonality also varies considerably with much of Asia's rice crop being planted in the monsoon season which can start (in the northern hemisphere) any time between from June and September depending on location with some areas able to cultivate two rice crops during the wet season. Dry season rice (in the northern hemisphere) may be planted anytime between November and February, but again this will vary by location. In short, there is no standard duration, season or cropping system.

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Rice from a remote sensing perspective

1. Due to the fact that most rice systems are generally not subject to seasonal rotations (upland rice is one exception but it accounts for a small portion of the total rice area), an accurate rice extent/area map derived from remote sensing data has high value, because it provides an estimation of variations of the total cultivated extent/area, of the different seasonality/crop practices and to assess shortages, due to drought or flood events.
2. Field soil changes and their evolution over time are not random whenever multi-temporal remote sensing data are analysed. With *a priori* knowledge of the crop calendar and land practices, multi-temporal remote sensing data offer valuable information to determine at the earliest stage of the crop season, when and where fields are prepared and irrigated, and later, the phenological crop status such as flowering, tillering, plant senescence and harvesting. In summary: assuming that data are/have been appropriately acquired, the key information is the temporal RS signature [1,2]. Systematic acquisitions are key; one image or randomly acquired scenes, even if very high resolution, are not suitable for monitoring purposes.

Reliable and seasonally updated information on rice area, phenology, status, and yield are important requirements for decision making related to food security, management of natural resources and agricultural productivity. Spaceborne remote sensing combined with crop modeling offers an effective alternative to conventional methods that are time consuming, expensive, and which result in production and area statistics that are often questioned. However, so far, existing remote sensing based crop (including rice) services are:

i. Often restricted to the use of a single sensor;
ii. Often restricted in terms of time (one crop season), space (province level) and detail;
iii. Usually empirical in that yield is often estimated using models derived from observed historical relationships between remote sensing parameters and area based yields, limiting the amount of spatial detail;
iv. Not maximizing the amount of available remote sensing information to explain spatial and temporal variability in yield.

In essence, the use of remote sensing products and their integration into a yield modeling is strongly limited.

In collaboration with national partners, the RIICE service is being tested in seven countries in South and South-East Asia, i.e. Philippines, Vietnam (Red and Mekong River Delta), Thailand, Cambodia, Bangladesh, Tamil Nadu (India), and Java (Indonesia). From a remote sensing perspective ENVISAT ASAR (Image Mode/Alternating Polarization and Wide Swath), ALOS PALSAR-1 (Fine Beam Single and Dual), Cosmo-SkyMed (StripMap and WideRegion) and TerraSAR-X (StripMap and ScanSAR), RISAT-1 (Fine and Medium Resolution) and Aqua and Terra MODIS 8/16-days composite data are supported. Due to the large amount of data – tens of thousands of scenes – within RIICE, a dedicated and automated processing chain (MAPscape-RICE) has been developed and operationally implemented including on a low cost local cluster solution. Rice products (area, start of season, peak of season, phenological stages, and flood/drought damages, leaf area index) generated from multi-temporal (multi-year, annual, seasonal) multi-sensor remote sensing data are subsequently incorporated into an upgraded version of the crop growth simulation model (CGSM) Oryza2000 [3], so that yield and production estimates can be derived and summarised at a given administrative level. Intermediate and final products are validated by national partners using standard monitoring protocols.

It is well known that SAR data availability is currently problematic, mainly due to the recent failure of the ENVISAT ASAR and ALOS PALSAR-1 systems. Hence, the current use of RIICE products is partially hampered, but the potential to expand the service is clear. Nevertheless, today, there are tens of thousands of archived unexploited images that could be leveraged for baseline mapping of rice areas and seasonality. Within RIICE, these data have been obtained in order to generate rice baseline maps at 1 hectare and 15 meter resolution representing the most updated rice extent/area information in the selected countries. These maps serve to guide the planning of new acquisitions (in terms of geographical area and crop season). These new acquisitions, based on very high resolution SAR data, enhance the level of detail and enable the provision of information at field level. Moreover, the launch of RISAT-1, Sentinel-1A (and subsequently 1B) and as ALOS PALSAR-2 for example will assure monitoring at continental scale in the near future.

It is well known that the use of high resolution optical data in the tropics is strongly limited for crop monitoring purposes. Persistent and widespread cloud contamination can only be partially dealt with by gap filling and smoothing, and while this can still capture the general phenology, it becomes problematic when those interpolated remotely sensing parameters are used as yield predictors. Thus, moderate resolution systems with daily revisiting cycles – such as MODIS, Proba V and the forthcoming Sentinel-3 – have the appropriate spectral bands and temporal resolution to be used for crop identification [4] and phenological monitoring [5] but yield estimation can still be challenging. Thus SAR is the most important data source for spatially detailed information on rice area/extent, start of season (SoS), peak of season (PoS), and Leaf Area Index (LAI) at key growth stages for the yield estimation process.

2. METHOD

Figure 1 gives an overview of the service. While rice area, emergence/transplanting, phenological monitoring, and LAI are determined/inferred by remote sensing time-series, yield is estimated using an upgraded version of Oryza2000.

Oryza2000 – developed by the International Rice Research Institute – is a crop growth model simulating rice growth based on sets of rice crop growth parameters describing rice development and growth, crop management, daily meteorological data and soil characteristics. The model can also exploit remote sensing derived information including rice crop location, LAI and SoS dates. Rice production (area multiplied by yield) is calculated at a given administrative level and supplied in form of tables, graphs and/or maps. Rice area is additionally provided at administrative level for each acquisition date, enabling crop monitoring through the season.

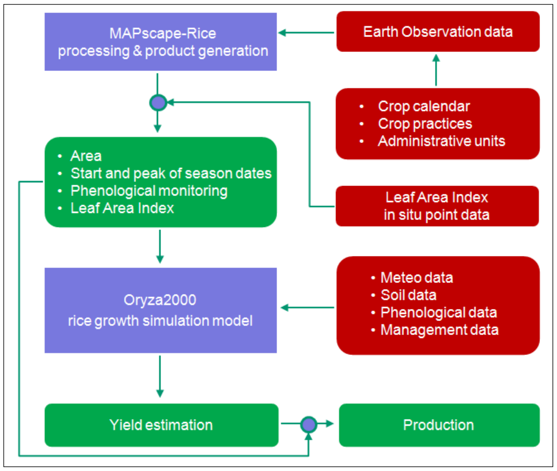

Figure 1 – Service overview.

2.1 Remote sensing based rice products

Figure 2 shows the multi-temporal multi-sensor approach in RIICE.

Multi-temporal (i.e. multi-year, annual, seasonal) SAR data acquired from past (ENVISAT ASAR *in primis*) and existing/forthcoming spaceborne SAR systems are/will be considered and complemented by daily existing (MODIS) / forthcoming medium resolution optical data. This solution:

– overcomes the spatial-temporal problem, hence assuring an appropriate temporal repetition at an adequate scale (i.e. spatial resolution) even over large areas;
– provides operational monitoring that is sensor independent and based on data redundancy.

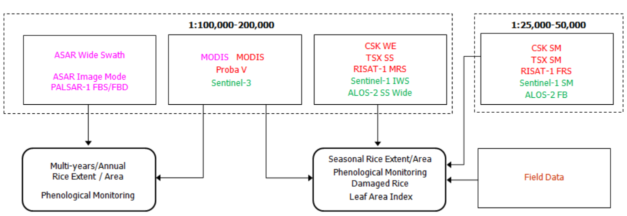

Figure 2: Products and supported sensors (past, current, near future) including acquisition modes.

It is essential that SAR time-series are appropriately acquired and rigorously processed. For this reason SAR data from the above sensors (Figure 2) are selected (if archive) / planned (if new acquisitions) according to the most suitable acquisition geometries, modes, and crop season periods. In a second step, Single Look Complex (SLC) data are transformed – in a fully automated way – into terrain geocoded backscattering coefficient ($\sigma°$) by means of:

– Strip mosaicing of single frames in slant range geometry and multi-looking;
– Grouping of the strip mosaics acquired with the same geometry;
– Digital Elevation Model (DEM) based orbital correction, if needed;
– Co-registration;
– De Grandi time series speckle filtering;
– Terrain geocoding, radiometric calibration and normalisation;
– Anisotropic Non-Linear Diffusion filtering;
– Removal of cloud related effects, particularly from X-band data in monsoon season where intense localised events can contaminate the image.

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 low cost, high performing cluster solution, where a *master* PC coordinates *processing* PCs and supervises the overall processing (MAPscape-RICE). Each *processing* PC is equipped with CPU with parallel processors or GPU. Note that i) all 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.

Multi-year and/or Annual Rice Extent/Area

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, not updated or of questionable quality – is generated using multi-year or annual ASAR WS archive data (100m) and/or – depending upon the availability of archive data – 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.

Phenological Monitoring

The *Multi-year or Annual Rice Extent/Area* product is extended i) to identify yearly rice extent changes and ii) to monitor seasonal rice crop cycles by a synergic use of 16-day 250 m vegetation indices products from MODIS Terra (MOD13Q1) and Aqua (MYD13Q1) and 500m 8-day composite reflectance (MOD09A1) archive data (1998 to 2013) within a PhenoRice algorithm.

The PhenoRice approach [5,6] has been developed to detect rice extent and to monitor rice seasonal phenology by means of spectral indices derived from 16-/8-days composite data. The algorithm identifies rice when a clear and unambiguous agronomic flood is detected and is shortly followed by a rapid increase in vegetation growth. Once rice is detected – or where *Multi-year or Annual Rice Extent/Area* maps are available – the seasonal phenological monitoring is performed by analyzing the temporal signature of various vegetation indices. The algorithm consists of:

a. Pre-processing of MODIS composite data involving i) the identification of noise data by analyzing blue band values and Science Data Set cloud quality flags; ii) the computation of spectral indices, able to highlight the vegetation growth (NDVI/EVI) and flood conditions (Land Water Surface Index) [4].
b. NDVI/EVI time series filtering using the Savitzky-Golay filter [7] and weighting of the indexes according to the noise and quality information.
c. Computation of the derivative of the filtered NDVI/EVI values and identification of all points of local (relative) minima and maxima. Rice crop minima (flood condition from LSWI) and maxima (heading) points are subsequently identified using a series of criteria. Finally, the occurrence of SoS and EoS of the rice growing season are identified for each rice pixel.

Seasonal Rice Area and Phenological Monitoring

When multi-temporal data are acquired during the most critical rice growth stages but on an irregular temporal basis – as is typical in the *Multi-year or Annual Rice Extent/Area* products that mostly rely on archive data – the most appropriate way to identify rice and, to some extent, other related information, is by means of temporal features.

However when 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 crop's 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 agro-practices/phenological inputs for accurate rice growth modelling. These products are generated based on the well known temporal relationship between the radar backscatter and rice phenology by considering the different wavelengths and polarizations but also crop practices and seasonal lengths. PhenoRice information from 16-/8-days composite MODIS data are used to complement the rice phenology.

Leaf Area Index

LAI is defined as the one sided green leaf area per unit ground area in broadleaf canopies 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 norm. A common and straightforward way to retrieve it from remote sensing data is to calculate an exponential function between the backscattering coefficient at season peak and the in situ field measurements through regression. The derived function is subsequently used to estimate LAI for the whole image. Alternatively, LAI may be inferred from the backscattering coefficient by means of a radiative transfer or semi-empirical model such as the vegetation water cloud model [8]. However, even in this case, model parameters have to be derived from in situ measurements.

Damaged Rice

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 the upgraded version of the Crop Growth Simulation Model (CGSM) of Oryza2000 [3]. In order to consider soil nitrogen dynamic processes, the CGSM has been updated by including soil data [12] extracted from the World Inventory of Soil Emission potential (WISE) dataset [13] and the Harmonized World Soil Database (HWSD) [14] where assumptions on the puddling effect on physical soil properties have been made. Weather data are obtained from the NASA POWER dataset [15]. These are subsequently corrected based on reported values from local weather stations [16] 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. Rainfall data are derived from the Tropical Rainfall Measurement Mission (TRMM) [17].

The simulations account for water and nitrogen dynamics based on climatic, soil conditions and management rice practices. Irrigation and nitrogen fertilizer inputs are assumed at recommended doses for achieving attainable yield. LAI values – 50 days after emergence (where emergence is provided by the SoS product) – are inferred from radar backscatter using cloud vegetation model [8] 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 250 meter resolution.

3. DATA SET

So far, in RIICE, the mapped (physical) rice area is around 24 million hectares, corresponding to 36 million hectares of harvested rice area. In terms of SAR data, around 15,000 scenes were necessary to map and monitor a total area of 1.5 million km^2. In particular:

1. 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*. ALOS PALSAR-1 FBD L-band data (70x70km, 15m) were also used for the Philippines. In general, South-East Asia has

been well covered during the ENVISAT ASAR mission, in particular in the WS mode. Unfortunately, this valuable data source has not yet been fully exploited for baseline mapping purposes.

2. For the generation of the *Seasonal Rice Area and Phenological Monitoring*, dedicated multi-temporal Cosmo-SkyMed and TerraSAR-X StripMap (40x40km, 3m; 30x50km, 3m) and ScanSAR (100x150km, 15m; 200x270km, 38m) X-band acquisitions are regularly carried out over selected areas according to the local rice crop calendars. RISAT-1 Fine (30x30km, 3m) and Medium Resolution (115x115km, 23m) C-band data are, at time of this writing, in testing phase in Tamil Nadu. So far, in most of the countries, two crop seasons have been covered using Cosmo-SkyMed data. In the same areas, national partners conduct field observations on or near acquisition dates to collect rice plant parameters for LAI estimation.
3. Archive and current MODIS Terra and Aqua 16-/8-days composites are downloaded and processed for the provision of the *Phenological Monitoring* at national/state level.

4. RESULTS AND DISCUSSION

Some representative results from the first season of monitoring are presented and discussed below.

4.1 Results

Philippines

The existing ASAR WS and IM data archive is, in general, irregular. This is partly because of the geographic location; being located in far East Asia (where ASAR acquisitions were often canceled in favor of high priority acquisitions in the western part of the globe) and due to the highly fragmented and North-South elongated shape of the country. For some geographical areas the coverage (in spatial and temporal terms) is still acceptable, while for other it is very poor. For this reason – even if L-band is not the most suitable frequency for the targeted application – ALOS PALSAR-1 FBD archive data have been used to detect the agricultural flooding date (due to the longer wavelength, the irrigated fields have a low radar backscatter significantly longer than at C-band) that is often undetectable in the imperfect multi-year ASAR C-band archive data.

Multi-year and Annual Rice Extent/Area products, as illustrated in Figure 3, have been generated country-wide. In general, it can be stated, based on several field visits, that the products have a good accuracy in areas where rice fields are homogeneous, while lower accuracies (expected, due to the limited ASAR data availability) have been reported in those areas where the fields are scattered, fragmented and heterogeneous.

Three geographical areas – Nueva Ecija in Luzon, Leyte in the Visayas and Agusan del Norte in Mindanao – characterized by different field dimensions and rice practices have been acquired using Cosmo-SkyMed SM and WideRegion during three crop seasons. Since the start of the last wet season TerraSAR-X ScanSAR data have been added. Some products examples are shown in Figure 4.

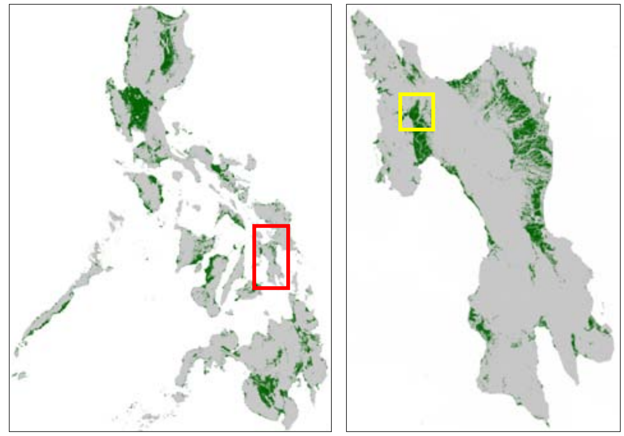

Figure 3: Left – Multi-year rice extent (1 ha) based on ASAR WS archive data acquired from 2003 to 2010. Right – Annual rice area (15m) of a sample area in Leyte (red box on the left) based on ASAR AP/IM and ALOS PALSAR-1 FBD archive data.

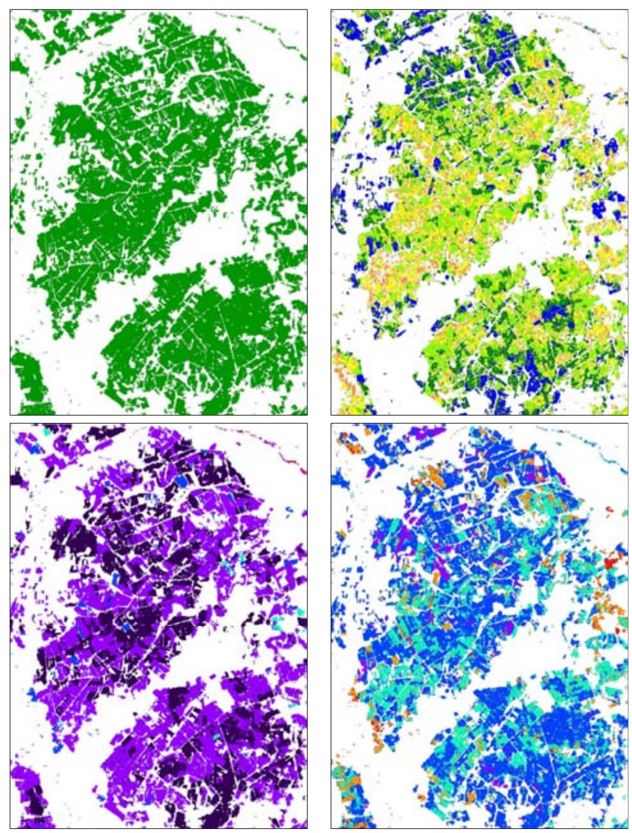

Figure 4: Top – Seasonal rice area (3m) of western part of Leyte (yellow box in Figure 3) based on Cosmo-SkyMed SM data acquired during the 2012 rice wet season (left) and LAI at PoS (right). Bottom – Phenological rice dates (represented by different colors) of SoS (left) and PoS (right).

The Philippines has been the first country where RIICE has tested and applied the procedure of inferring LAI from backscattering coefficients as an input to Oryza2000. Figure 5 shows the simulated yield including the same area (orange box) depicted in Figure 4.

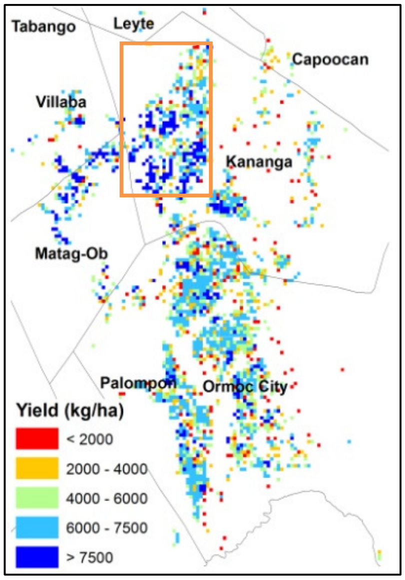

Figure 5: Estimated rice yield (250 m) in western part of Leyte (orange box refer to Figure 4) using Oryza2000 including rice area, SoS and LAI for 2012 wet season.

Table 1 provides a first validation at barangay or village level with respect to the estimated rice yield. On average, compared to the observed yield from crop cutting experiment (CCE), the accuracy is 85% with a Root Mean Square Error (RMSE) of 702 kg ha^{-1}. The accuracy increases to 95% (RMSE of 392 kg ha^{-1}) at municipal level, which is still more detailed than published statistics.

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) = 702
Accuracy (%) = 85

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

Table 1 – Validation of rice yield estimates.

Bangladesh

Most probably due to dedicated background missions, ASAR scenes acquired in WS mode provide an almost ideal data set for the generation of a *Multi-year Rice Extent* product in this country. In fact, apart some years, the data have been often regularly acquired from 2004 to 2010. Figure 6 illustrates on the top left the resulting product at 1 ha, where, in addition to the rice extent also single, double and deep water rice systems have been identified, while, top right shows an example of rice seasons detection for 2011 from PhenoRice based on 8-days composite MODIS data at 500m. The phenological stages occurrence – i.e. agronomic flooding and rice peaks – are illustrated for the three typical rice seasons in Bangladesh, on the bottom.

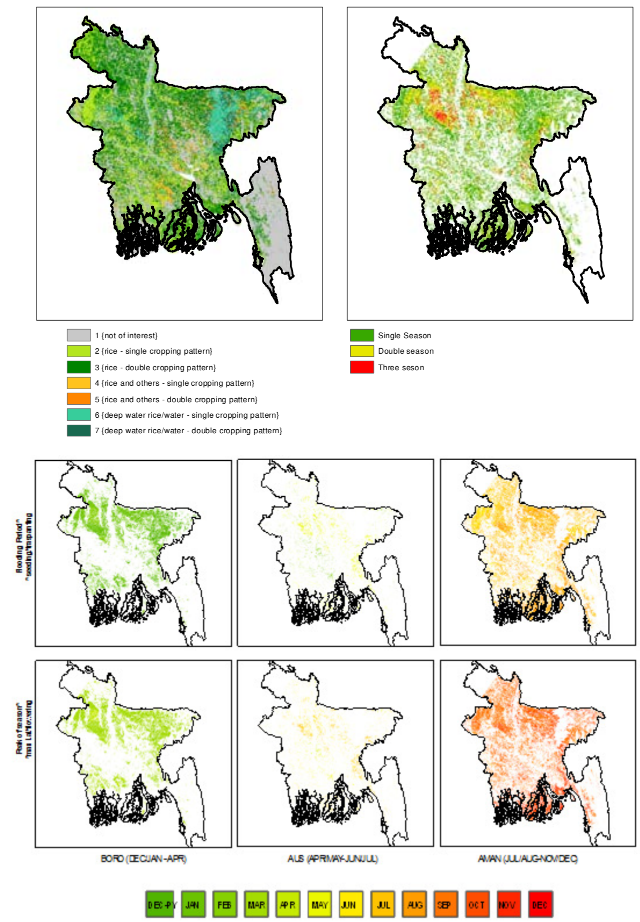

Figure 6: Top – Multi-year rice extent (1 ha) based on ASAR WS archive data acquired from 2004 to 2010 (left) and 2011 rice seasons based on 8-days composite MODIS 500m (right). Bottom – Phenological monitoring (MODIS 500m) for the 2011 rice season. On the top, the start of first (boro), second (aus) and third (aman) season is illustrated, on the bottom, the corresponding rice season peaks.

Vietnam – Red River Delta

The well populated ASAR WS and IM data archive in this geographical area 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 7 and 8 (top). Moreover, the use of very high resolution Cosmo-SkyMed SM data regularly acquired every 16 days resulted in a very detailed phenological monitoring at field level for each rice season, as shown in Figure 8 (center and bottom). Land cover category boundaries have been provided by the National Institute of Agricultural Planning and Projection (NIAPP).

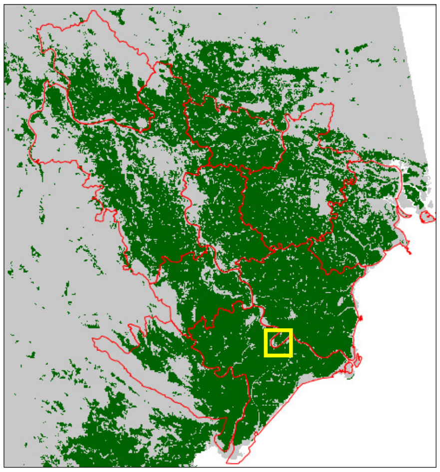

Figure 7: Multi-year rice extent (1 ha) based on ASAR WS archive data acquired from 2003 to 2010.

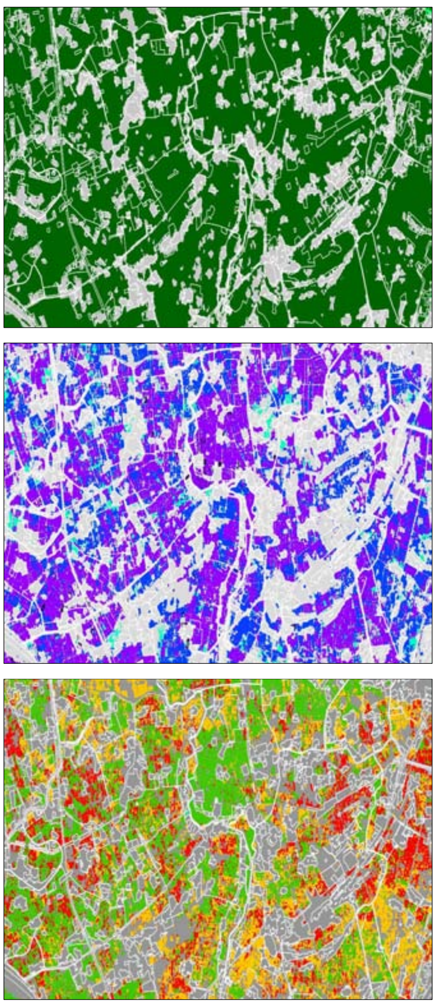

Figure 8: Annual rice area (15m) and seasonal rice area (3m) for a sample area (yellow box in Figure 7) based on ASAR IM archive data acquired during 2011 (top) and on Cosmo-Sykmed SM from January to May 2013 (center and bottom). The different colors correspond to the phenological rice dates of SoS (center) and PoS (bottom).

Vietnam – Mekong River Delta

This geographical area – probably the most known and published in the remote sensing rice literature – is characterized by complex rice cropping systems through almost the entire whole year. In fact, up to three or even four rice seasons (seven seasons across two years) can be observed in places. However, even though the ASAR WS spatial and temporal coverage from 2004 to 2010 is acceptable, the ASAR IM one is scarce. Figure 9 shows the resulting *Multi-year Rice Extent* product: it is worth mentioning that due to the 35 days repeat cycle of the ASAR system and the frequent and short rice cycles, it is impossible to provide additional information to the rice extent. On the other hand, seasonal rice area and phenological monitoring at field level is provided by Cosmo-SkyMed SM time-series data regularly acquired every 16 days, corresponding to 5-6 images per crop season. An example of the various crop grow stages existent in a typical Cosmo-SkyMed SM coverage is shown in Figure 9 bottom.

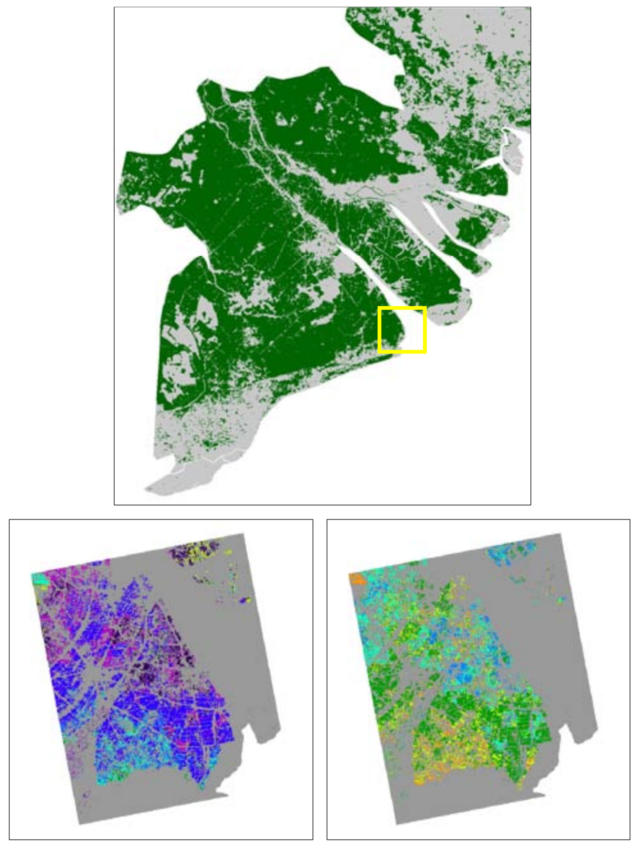

Figure 9: Top – Multi-year rice extent (1ha) based on WS archive data acquired from 2005 to 2010. Bottom – Seasonal rice area (3m) and corresponding phenological rice dates of SoS (bottom left) and PoS (bottom right) based on Cosmo-Sykmed SM data acquired from September to December 2012 (yellow box).

Cambodia

The ASAR WS data archive 2005 to 2010, in spatial and temporal terms, is quite complete, hence enabling the generation of an accurate *Multi-year Rice Extent* product.

Unfortunately, the existing ASAR IM mode acquisitions are insufficient for generating reliable *Multi-year Rice Area* or *Annual Rice Area* products. Due to the rice type characteristics in this country – i.e. short and medium-long duration – Cosmo-SkyMed SM time-series during 7 months at 16 days interval have been acquired. As an example, Figure 10 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.

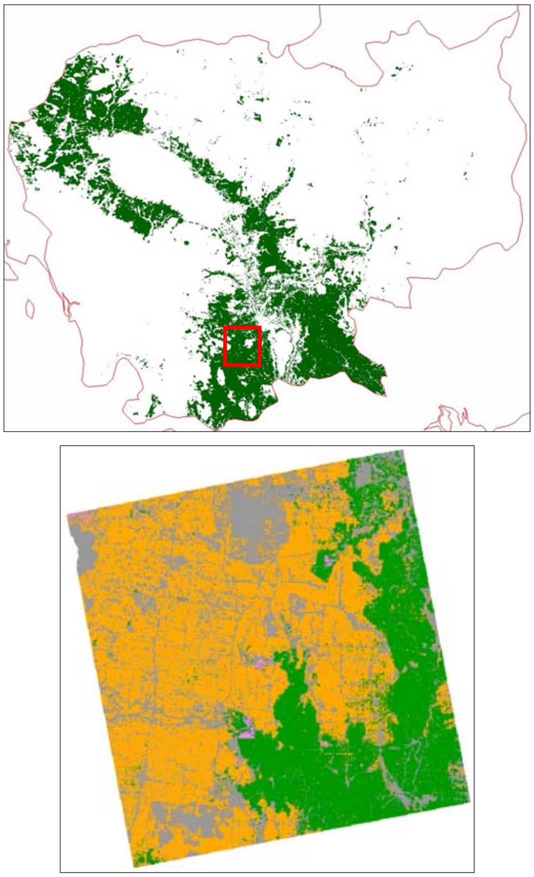

Figure 10: Top – Multi-year rice extent (1 ha) based on ASAR WS archive data acquired from 2005 to 2010. Bottom – Seasonal rice area (red box) for short duration (green) and medium-long (yellow) duration (3m) based on Cosmo-SkyMed SM acquired from September 2012 to March 2013.

Thailand

Between the start of September and mid November 2011, severe flooding occurred along the Chao Phraya River. On request, during this period, the European Space Agency regularly acquired ASAR data in WS mode in order to completely cover the damaged area. Due to the large swath of the system, the ASAR scenes are strongly overlapping in East-West direction, resulting in a revisit time of approximately ten days. Figure 11 on the right shows the resulting flood map indicating in the different red tonalities the duration (in days) of the flooding. The figure on the right illustrates the *Annual Rice Area* product (15m) for 2011 based on ASAR IM acquisitions.

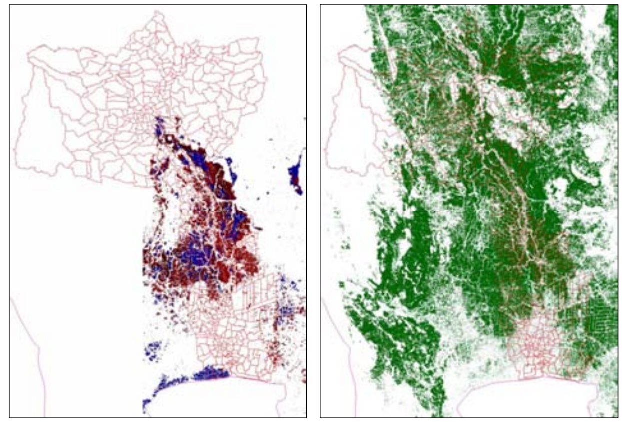

Figure 11: Right – Chao Phraya River flood map (red) based on ASAR WS data acquired from September to November 2011. Left – Annual rice area (15m) based on ASAR IM data during 2011.

Indonesia – Java

The East-West elongated island of Java is in general well covered by ASAR data mainly due to the interest in tropical rainforest monitoring. However, in terms of temporal coverage, the acquisitions do not always correspond to the known rice crop calendars which vary across the island. Nevertheless, in both ASAR acquisition modes – WS and IM – quite accurate rice products could be generated. An example is illustrated in Figure 12, where for some limited areas, existing rice field boundaries could be overlaid to the *Multi-year Rice Extent* product.

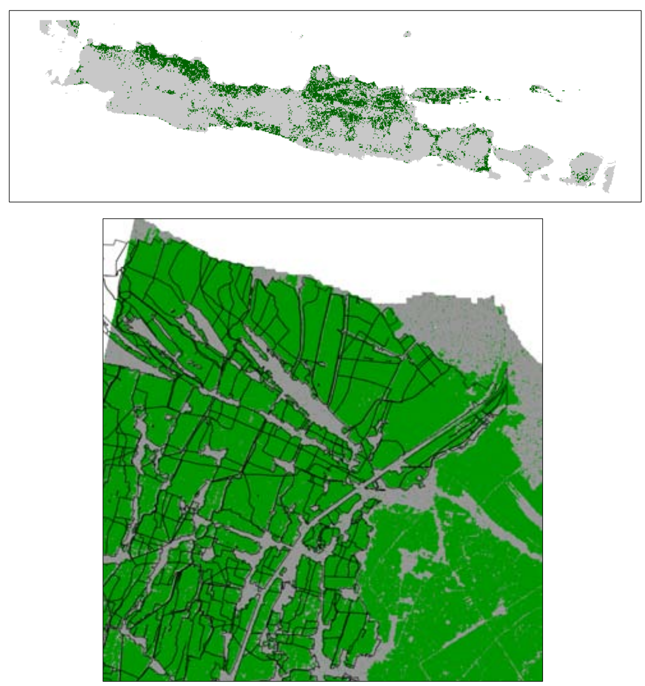

Figure 12: Multi-year rice extent (1ha) based on ASAR WS archive data acquired from 2004 to 2010 and, bottom, rice field boundaries (provided by ICALRD) overlaid to a multi-year rice extent sample.

As in other countries, Cosmo-SkyMed SM data have been regularly acquired every 16 days. Even in this case, the detected detailed information of the different rice grow stages at field level have been confirmed by a field visit. Figure 13 shows an example. The main challenge in this tropical area is the effect of the clouds at X-band: almost all SAR acquisitions were spot-wise strongly affected. For this reason, a multi-temporal automated cloud removal filter has been developed, making the X-band data useful for the purpose of this application.

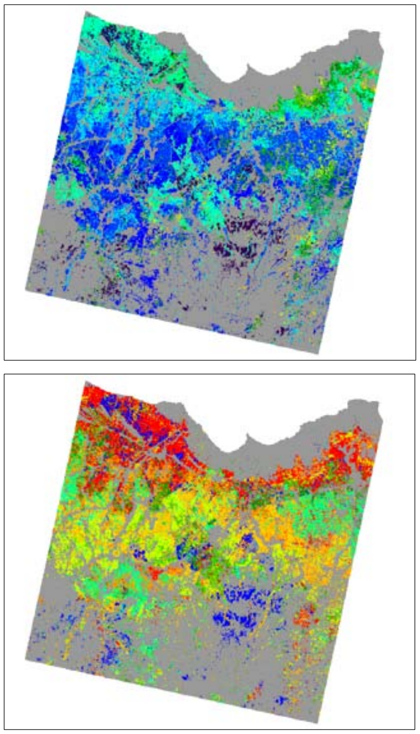

Figure 13: Seasonal rice area (3m) and corresponding phenological rice dates (in color) of SoS (top) and PoS (bottom) based on Cosmo-Sykmed SM data acquired from October 2012 to March 2013.

India – Tamil Nadu

Unfortunately, the available ASAR WS data archive from 2005 to 2010 is not sufficient for the generation of a *Multi-year Rice Extent* product, because only sporadic SAR acquisitions are available. For this reason, in 2011 a dedicated ASAR IM planning was made and even though not all planned data were delivered, it was possible to develop an *Annual Rice Area* product as shown in Figure 14.

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 imperative, that multi-temporal SAR data are acquired according to known locally varying rice calendars. This strategy was adopted over three sites by using Cosmo-SkyMed SM time-series during 4 months at 16 days interval. Some results are illustrated in Figure 15.

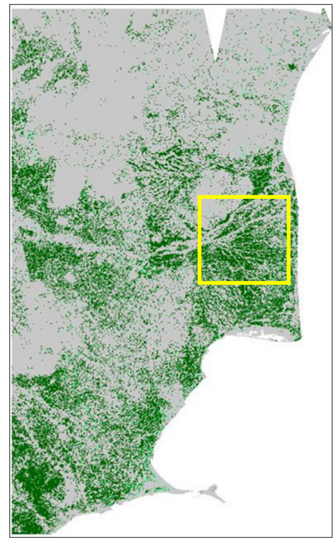

Figure 14: Annual rice area (15m) based on ASAR IM data acquired during 2011.

Finally, if is worth mentioning that for the forthcoming rice crop season RISAT-1 acquisitions are planned, in order to test and compare the performance of this Indian SAR system with Cosmo-SkyMed SM and TerraSAR-X SM data.

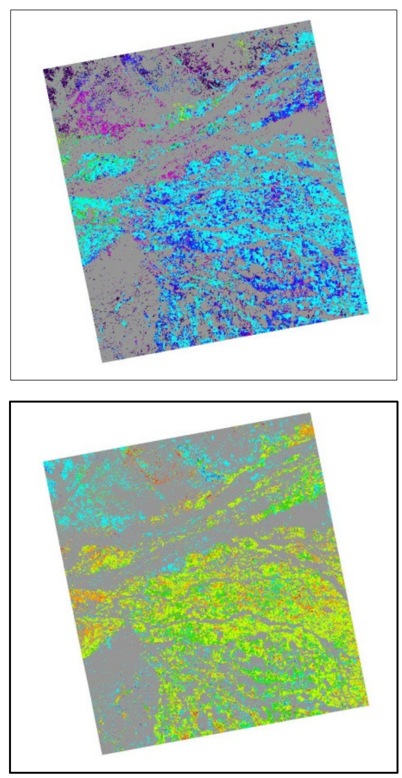

Figure 15: Seasonal rice area (3m) and corresponding phenological rice dates (in color) of SoS (top) and PoS (bottom) based on Cosmo-Skymed SM data acquired from September 2012 to December 2012 (yellow box in Figure 14).

4.2 Validation of remote sensing products

Product validation is always led by the national partner since they have the required local knowledge and easy access to the monitored areas. A well accepted methodology is to use a regular sampling grid and randomly select locations to ground truth from that sample: this guarantees the selection of a representative and spatially well distributed sample [9]. The disadvantage of this rigorous procedure is that its execution is very time consuming and too expensive. For this reason, a rapid land cover appraisal method has been adopted whereby partners travel through the site and collect geo-referenced digital pictures (and when necessary farmer interviews) with a good spatial coverage with the aim to collect data points that are approximately distributed 50%-50% across rice and non-rice land cover. In order to facilitate the terrestrial data collection the teams have been introduced in the use of Android tablets on which the various digital products are stored and visualized through Quantum GIS: the location is provided by the GPS embedded in the Android tablet. These terrestrial observations are subsequently used to compute commission/omission errors and overall accuracy for each product. It is planned that the validation will be completed by the end of this year. Nevertheless, based on preliminary qualitative and quantitative assessments (for instance by overlaying – where possible – rice field boundaries or by visiting some reference areas and early quantitative assessments [10] on a pilot area mainly characterized by fragmented rice fields) of *Multi-year and/or Annual Rice Extent/Area* generated without any ground reference data, any knowledge of local rice practices, and standard setting parameters accuracy has ranged between 75% and 85%. In general, lower accuracies are observed where rice fields are fragmented (in terms of dimensions and/or fields heterogeneity) and where rice is rainfed or dry seeded. Products will be regenerated tuning the data processing parameters by local expert in cases where accuracy is unacceptably low.

Finally, national partner involvement is crucial, not only for the terrestrial data collection and validation, but also for the product generation, where the knowledge on the rice types and the local rice practices is *conditio sine qua non* for the generation of reliable information. For this reason, technology transfer and capacity building has been ongoing with national partners since early 2012 and the current service and methods are undergoing validation by all parties.

5. 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 modelling 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 has been demonstrated in seven Asian countries and it is under validation and evaluation by national partners.

We can make the following observations from the results and experience so far across multiple sites, countries and partners:

- 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 that space agencies with mandates for future SAR missions should incorporate systematic background missions according to the geographical areas and applications instead of building data archives according to sporadic user requests.
- Multi-temporal (multi-year, annual, seasonal) data are 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, 100m, and 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, ALOS-2 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 [2] and the corresponding phenological monitoring. However, a wise application-oriented fusion of information at semantic level is needed to obtain the best possible product.
- So far, in land cover area estimation, remote sensing is often considered just as a mapping tool. In fact in [11], a *simple pixel counting from a classified* [remote sensing] *image* is described as a *naïve estimator and risky in most cases*. 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. The proposed solution is attractive, less time consuming and less expensive compared to area regression estimators based on field survey. Furthermore, the remote sensing solution provides a monitoring component (note, agricultural area can significantly vary during a crop season): 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:
  - a reduction in the amount of non-remote sensing parameters, since the remote sensing derived parameters such as LAI capture the plants response to unmeasured (and we argue unmeasureable) environmental conditions over large areas;
  - the inclusion of relevant information on rice phenology and to initialise the model on the correct date;

- the spatial distribution of rice fields to be consider so that yield estimates are only made where rice is cultivated that season;
- an overall improvement in the yield estimation figures by forcing or calibrating the model to actual yields rather than 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.

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REFERENCES

[1] Kam S.P., F. Holecz, E. van Valkengoed, M. Barbieri, C.B. Casiwan, S.L. Asilo, L. A. Santos, R.G. Manalili, W.B. Collado, S.A. Adriano, and A. Maunahan, The makings of an internet-based rice information system: Piloting in the Philippines, First Symposium on Geoinformatics, Philippines, 2004.

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

[3] Bouman B.A.M. et al., Oryza2000: modeling lowland rice, IRRI and Wageningen University, 2001.

[4] Xiao, X., Boles, S., Frolking, S., Li, C., Babu, J.Y., Salas, W., Moore III, B., Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images, Remote Sensing of Environment 100, 2006.

[5] Boschetti M., D. Stroppiana, P.A. Brivio, and S. Bocchi, Multi-year monitoring of rice crop phenology through time series analysis of MODIS images, International Journal of Remote Sensing, 30:18, 2009.

[6] Manfron G., A. Crema, M. Boschetti, and R. Confalonieri, Testing automatic procedures to map rice area and detect phenological crop information exploiting time series analysis of remote sensed MODIS data, Proc. SPIE 8531, Remote Sensing for Agriculture, Ecosystems, and Hydrology XIV, 2012.

[7] Chen J., P. Jönsson, M. Tamura, Z. Gu, B. Matsushita, and L. Eklundh, A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter, Remote Sensing of Environment 91, 2004.

[8] Attema E.P.W. and F.T. Ulaby, Vegetation modeled as a water cloud, Radio Science, Vol. 13, 1978.

[9] Global Monitoring for Food Security, Validation protocol, ESA GMFS C05 report, 2011.

[10] Skorzus R., Mapping and characterizing rice fields using multi-temporal SAR imagery - a case study in Leyte, Philippines, Master Thesis, Friedrich-Schiller University, 2013.

[11] Gallego F.J., Remote sensing and land cover area estimation: a review, International Journal of Remote Sensing, Vol. 25, No. 15, 2004.

[12] https://sites.google.com/a/irri.org/oryza2000/

[13] http://www.icasa.net/toolkit/wise.htm

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

[15] http://power.larc.nasa.gov

[16] http://www.ncdc.noaa.gov

[17] http://trmm.gsfc.nasa.gov