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Full Length Research Paper

Mapping Indonesian paddy fields using multiple-temporal satellite imagery

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There is a growing demand for rice with increase in population. As rice is still the major staple food in Indonesia, the task of increasing rice production continues to engage the attention of national planners. Various methods used in estimating rice areas can provide information periodically through different information satellite data, which have a wide coverage area, and can be used as a source of information on the condition of rice areas. This study has an objective of using multi-temporal satellite imagery from the Moderate Resolution Imaging Spectrometer (MODIS) to map the Indonesian rice paddies area. The algorithm was based on temporal profiles of vegetation strength and water content, using electromagnetic surface reflectance in visible to near infrared range. The results obtained from the analysis were compared to national statistics. Estimated Indonesian regional rice area was 8.27 million ha, which agrees with published values. The model performance was dependent on rice ecosystems. Good linear relationships between the model results and the national statistics were observed for all types of rice fields.

Key words: Geographic information system (GIS), satellite data, moderate resolution imaging spectrometer (MODIS), rice, paddy field, remote sensing.

INTRODUCTION

Indonesia is one of the world's leading rice producers, with paddy production in 2003 of more than 50 million tonnes and a cultivated area of more than 11.5 million ha. Since 1980, Indonesia's national rice yield has been the highest in tropical Asia. Indonesians are also big consumers of rice, averaging more than 200 kg per head each year (Blum, 1993).

Rice is grown at varying altitudes, with about 75% of plantings in irrigated areas and less than 10% on rainfed lowlands. Most rice production takes place on the island of Java under irrigation. Lowland varieties belong mainly to the indica sub-species and about 85% of them are high-yielding (Blum, 1993). This research aims at mapping Indonesian rice paddies with different rice ecosystems.

The area planted to rice increased by 33% between 1969 and 1990. Since then, however, the conversion of many ricelands in Java to non-agricultural uses has contributed to a fall in total output. Sustainable rice production requires the development and deployment of new rice varieties and crop management technologies and approaches. Indonesia achieved rice sufficiency in 1984. From being a chronic rice importer in the 1970s, Indonesia is today, the third biggest rice producer in the world, and has been consistently so in the past decades. Between 1970 and 2006, Indonesia's average rice yield rose by 90% from 2.35 t/ha to 4.62 t/ha. Today, Indonesia is the 4th most populous country in the world. A population increase of 1.5% per year requires a corresponding increase in food supply (Blum, 1993).

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It is in this context that Indonesia's agricultural development program now has three main aims: a) increased national food security through higher food production and lower food imports, b) increased added value and competitiveness of agricultural products, and c) improved quality of life and less poverty for farming households through high productivity. Spatial information of Indonesian rice paddies is required for regional rice cropping/water managements and estimates of rice yield. Necessary information for informed management includes rice cropping frequency, rice ecosystem type (irrigated, rainfed lowland, upland, and flood-prone), and areal distribution. This research applies the multi-temporal satellite imagery for mapping rice paddies with different rice ecosystems over Indonesia.

Indonesia has very wide coverage area that consists of thousands of islands with various geographic conditions. It causes difficulties to carry out field data collection activities. The cost for inventory, monitoring and updating of land use in the conventional field survey is very high, so the method can not be implemented in a relatively short time. Remote sensing technology that periodically records earth surface can be used as an alternative to support field research mainly to changes in land use, including the planting period in the paddy field. Moderate resolution imaging spectroradiometer (MODIS) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS view the entire earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths (Canny, 1986).

MODIS has visible, near infrared and shortwave infrared bands; and therefore, a number of vegetation indices can be calculated, including normalized difference vegetation index (NDVI), enhanced vegetation index (EVI) and land surface water index (LSWI) that is sensitive to leaf water and soil moisture. In this research, we developed a paddy rice mapping algorithm that uses time series of the vegetation indices derived from MODIS images to identify that initial period of flooding and transplanting in paddy rice fields, based on the sensitivity of LSWI, increased surface moisture during the period of flooding and rice transplanting (Chang et al., 1998).

This research aims at mapping Indonesian rice paddies with different rice ecosystems. It is a simple method that can be applied at the regional scale. In addition, the results also include spatial information on rice cropping frequency. This information can further be used to quantitatively estimate air pollution emissions from Indonesian rice paddies and evaluate climate change effects attributed to the emissions.

MATERIALS AND METHODS

MODIS imagery data

The MODIS surface reflectance of 8-day L3 Global 500 m SIN Grid V005, or MOD09A1, data set from 2006 to 2007 was acquired for this research. Each grid value gives the percentage of the radiant energy in the specific bandwidth to the total energy integrated over the entire spectrum. In this research, the MODIS surface reflectance in four spectral bands, in the visible and near-infrared, was considered. These bands are 1: 620 to 670 nm (visible-red: VISR), band 2: 841 to 876 nm (near-infrared: NIR), band 3: 459 to 479 nm (visible-blue: VISB), and band 6: 1628 to 1652 nm (shortwave-infrared: SWIR). The products were downloaded from the USGS Land Processes Distributed Active Archive Center (Deriche, 1987) (Figure 1).

These reflectance products are reported at a 500 m resolution in a level 3, grid projection. Each pixel contains the best possible L2G (daily) observation during an 8-day period. These version 5 reflectance products are validated stage 1, meaning that accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program efforts. The products are in HDF-EOS format. Prior to the analysis, these data were converted to GeoTIFF format and reprojected to UTM zone 48 projected coordinate system with the WGS1984 (the World Geodetic Survey System of 1984) datum by using MODIS Reprojection Tool (MRT) from USGS/LPDAAC. These reprojected data sets were used in the land classification analyses running on the Model animation in ArcGIS 9.9 software with integrated Gozilla scripts (Gonzalez and Woods, 1992).

Climate

The climate of Indonesia is almost entirely tropical. The uniformly warm waters that make up 81% of Indonesia's area ensure that temperatures on land remain fairly constant, with the coastal plains averaging 28°C, the inland and mountain areas averaging 26°C, and the higher mountain regions, 23°C. Temperature varies slightly from season to season, and Indonesia experiences relatively slight change in the length of daylight hours from one season to the next; the difference between the longest day and the shortest day of the year is only forty eight minutes. This allows crops to be grown all year round.

The main variable of Indonesia's climate is not temperature or air pressure, but rainfall. The area's relative humidity ranges between 70 and 90%. Winds are moderate and generally predictable, with monsoons usually blowing in from the south and east in June through September and from the northwest in December through March.

Data processing

The normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI), the normalized build-up index (NDBI), and the land surface water index (LSWI: negative NDBI) are calculated from the surface reflectance, ρ, in visible-red (VISR; MODIS-band 1), near-infrared (NIR; MODIS-band 2), visible-blue (VISB; MODIS-band 3), and shortwave-infrared (SWIR; MODIS-band 6) using the following equations:

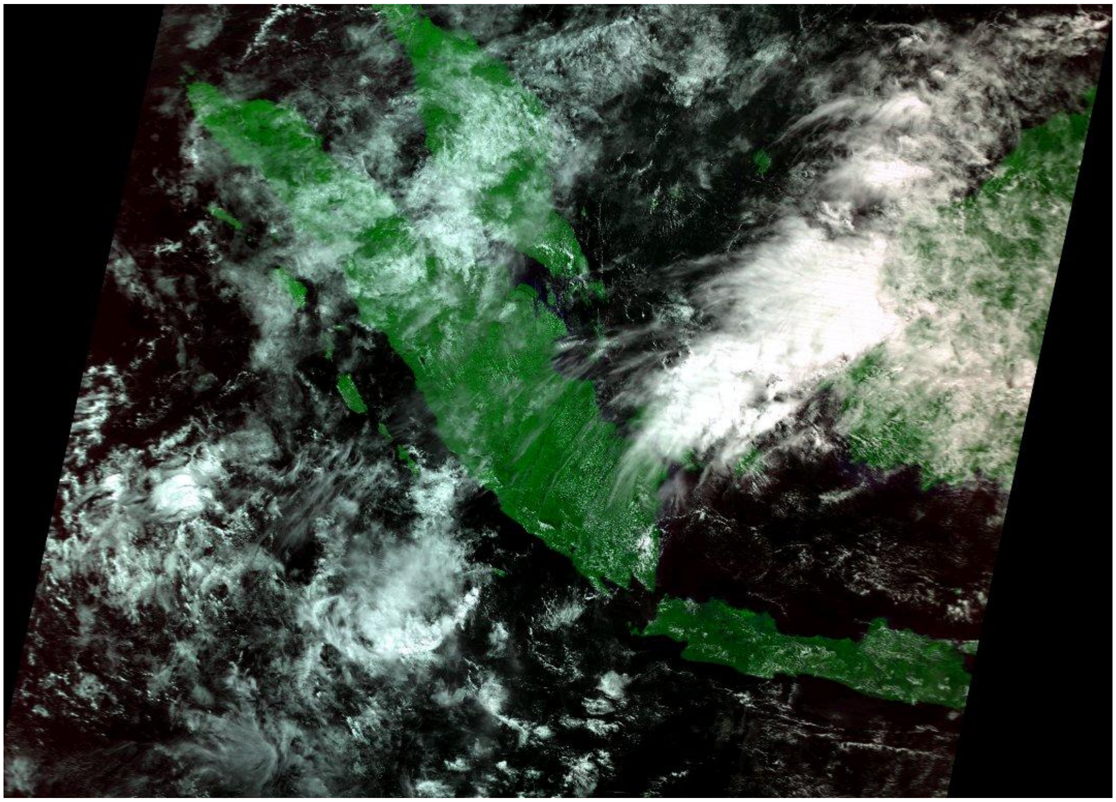

Figure 1. An example of MODIS imagery over Sumatra Island.

$$NDVI = (\rho NIR - \rho VISR)/ (\rho NIR + \rho VISR)$$

$$EVI = 10.5 (\rho NIR - \rho VISR)/ (\rho NIR + 10\, \rho VISR - 12.05\, \rho VISB + 0.75)$$

$$NDBI = (\rho SWIR - \rho NIR)/ (\rho SWIR + \rho NIR) \quad (3)$$

NDVI and EVI were used in this research to enhance the vegetation detection sensitivity of the MODIS surface reflectance. Both indices are estimated by normalizing the difference between the radiances in the near-infrared spectra and in the red-visible spectra. In addition, EVI incorporates the additional blue band to correct for aerosol influences in the red band and the canopy background adjustment.

In this research, the time-series NDVIs were used to identify forests, which include perennial and seasonal plantations. The time-series EVIs were used to identify rice paddies with different ecosystems because of its higher sensitivity to canopy structural variation.

Different rice ecosystems and the annual cropping frequency are identified from rice canopy development patterns. The four major rice ecosystems as categorized by International Rice Research Institute (IRRI) are: irrigated, rainfed lowland, upland, and flood-prone. All four ecosystems can be found in Indonesia. Their characteristics are detailed thus.

Irrigated rice is grown in fields with assured irrigation for one or more crops a year. It is planted in leveled, diked fields with water control. Rice can either be transplanted from nursery mats or directly seeded in puddled soil. Intermediate fallow periods range from a few days to three months.

Rainfed lowland rice is grown only once a year during the wet season when there is sufficient water from rain. It is planted in leveled to slightly sloping, diked fields with non-continuous flooding. The water level does not exceed 50 cm for more than ten consecutive days. Rice can either be transplanted in puddled soil or directly seeded on puddled or plowed dry soil.

Deepwater rice or flood-prone rice has only one crop per year during the wet season when natural flooding occurs. It is planted in leveled to slightly sloping or depressed fields. Water levels range from 50 to more than 300 cm for more than 10 consecutive days in growth stage. Rice can either be transplanted in puddled soil or directly seeded on plowed dry soil.

Upland rice can grow in both flat and sloping fields, which rarely flood and are not diked. This rice is prepared and directly seeded on plowed dry soil or dibbled in wet soil that depends on rainfall for moisture (Katsuaki et al., 1995).

A rice-cropping cycle takes three to six months depending on the rice ecosystems. Rice canopy development is generally divided into three phases:

1) Vegetative phase occurs around 60 days after sowing. Generally, germination and early seeding stages are prepared in nursery mats and then transplanted into puddled, leveled fields. The water signature dominates during transplanting.
2) Productive phase starts around 60 days after sowing or 30 days

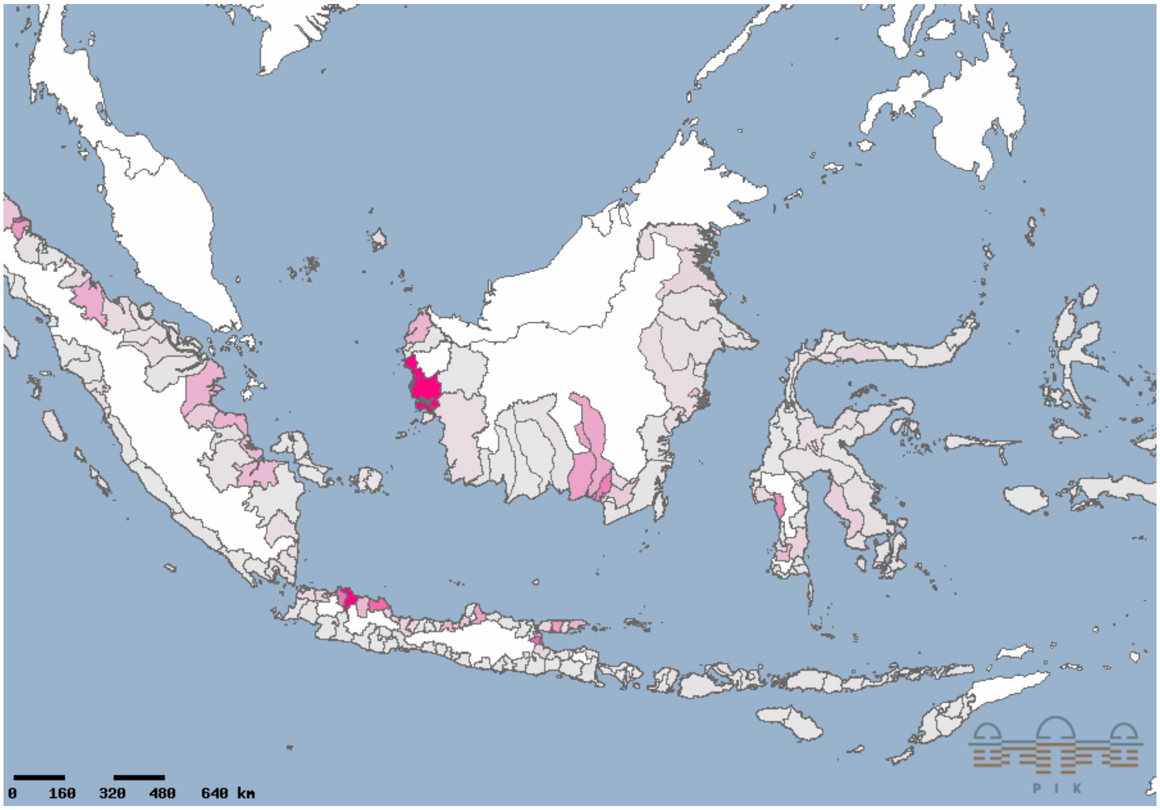

Figure 2. Spatial rice paddy distribution map over Indonesia generated from time-series MODIS imagery analysis.

after transplanting and lasts until the 90th day. Plants rapidly grow and reach fully developed height. The plant canopies cover most of the water surface, intensifying the vegetation signature.

3) Ripening phase is from the 90th day to about the 120th day. Golden grains start developing. The vegetation signature is still dominant but lessens due to drying leaves. This period could be extended to six months in the case of deepwater rice.

Accuracy assessment

The national statistics of forest, perennial plantation, and rice paddy areas were acquired to compare with the results obtained from the MODIS time-series models. These comparisons were done on a provincial /state level (Leech et al., 2003).

RESULTS

Figure 2 shows the spatial distributions of paddy rice in Indonesia. Rice cultivation covered a total of around 10 million ha throughout the archipelago, primarily on sawah. The supply and control of water is crucial to the productivity of rice land, especially when planted with high-yield seed varieties. In 1987, irrigated sawah covered 58% of the total cultivated area, rainfed sawah accounted for 20%, and ladang, or dryland cultivation, together with swamp or tidal cultivation covered the remaining 22% of rice cropland. Swampland in Indonesia is the most important remaining land resource for the development of new rice fields. However, the development and maintenance costs for the infra structure are high. The environmental impact of a new development could be considerable.

Large variations in rice yield levels in Indonesia are due to many factors. Those factors have different scales of magnitude within regions, provinces, and districts up to farmers' field level. Those factors are also classified as manageable and unmanageable. Yield gaps, therefore, should be divided into different scales and management. Yield gaps at different levels in various areas are indicated by the lowest and the highest yields of rice in such areas as compared to their average. The priorities of reducing yield gaps (bridging) are possibly either to increase the lowest yield to the average or to increase yields that give the highest impact to rice production of those areas (Pearlman et al., 2003). The data on rice

Table 1. Harvest areas, production and yield of lowland rice in each province in Indonesia.

Province	Harvest area (ha)	Production (tonnes)	Actual yield (t/ha)	Range of actual yield (t/ha)
1. D.I. Aceh	339785	1400425	4.12	3.75-4.81
2. North Sumatra	716182	2966681	4.14	3.57-4.66
3. West Sumatra	411716	1929622	4.69	3.89-5.29
4. Riau	116766	389776	3.34	3.12-3.47
5. Jambi	152383	530186	3.48	3.14-3.97
6. South Sumatra	395253	1456587	3.69	3.26-4.22
7. Bengkulu	91259	337835	3.7	3.51-3.84
8. Lumping	370942	1620487	4.37	4.16-4.65
Sumatra	2594286	10631599	4.1	3.12-5.29
9. DKI Jakarta	3576	17347	4.85	
10. West Java	1957743	10342690	5.28	4.34-5.59
11. Central Java	1534936	8170309	5.32	4.49-6.09
12. Yogyakarta	100125	562025	5.61	4.74-5.85
13. East Java	1529309	8377019	5.48	4.48-5.85
Java	5125689	27469390	5.36	4.34-6.09
14. Bali	155964	836047	5.36	5.22-5.65
15. Western-S.E. Nusa	268327	1232870	4.59	3.84-4.80
16. Eastern-S.E. Nusa	101657	323246	3.18	2.50-3.39
17. East Timor	17418	48835	2.8	
Bali and S.E. Nusa	543366	2440998	4.49	2.50-5.65
18. West Kalimantan	242030	674537	2.79	2.29-2.94
19. Central Kalimantan	102530	269530	2.63	2.01-2.82
20. South Kalimantan	355378	1103402	3.1	2.69-3.95
21. East Kalimantan	82436	248596	3.02	2.89-3.10
Kalimantan	782374	2296065	2.93	2.01-3.95
22. North Sulawesi	103130	446693	4.33	3.88-4.52
23. Central Sulawesi	163500	561383	3.43	3.10-3.57
24. South Sulawesi	841066	4008277	4.77	3.46-5.60
25. S.E. Sulawesi	77887	276556	3.55	3.10-3.70
Sulawesi	1185583	5292909	4.46	3.10-5.60
26. Maluku	6626	19619	2.96	2.94-3.01
27. Irian Jaya	13469	37675	2.8	
Maluku and Irian Jaya	20095	57294	2.85	2.94-3.01
Indonesia	10251393	48188255	4.7	2.01-6.09

yields at provincial level are presented in Table 1.

The result from the model showed that the rice paddy area accounted for 8.7% of total Indonesian land area. The estimated total regional rice paddy area is 8.27 million ha, which is consistent with the areas reported in Pour et al. (2011), 8.01 million ha, and by Blum (1993), 10 million ha. Linear regression plots of the MODIS rice paddy areas and the rice paddy areas were acquired from the national rice database by province (or state) for Indonesia (Figure 3).

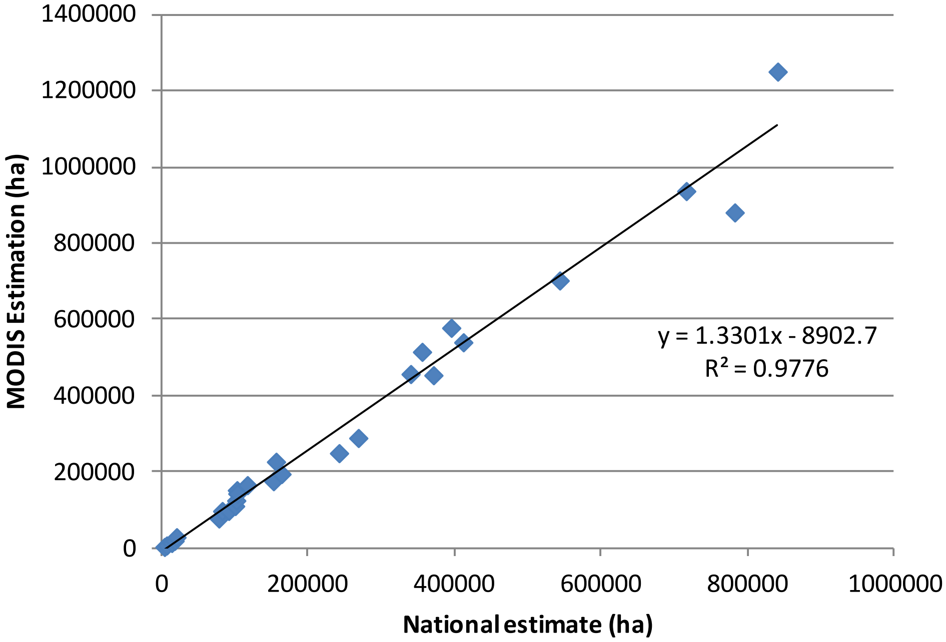

Figure 3. Linear regression plots of the MODIS rice paddy areas and the rice paddy areas acquired from the national rice database by province.

DISCUSSION

The combination of NDVI and EVI has been carried out to recognize various cropping pattern based on available knowledge on growing period of paddy and other seasonal crops. The analysis, integrated with logical inference based on knowledge of paddy growing stage, produces the map of paddy field distribution. By considering some influencing factors, agricultural condition can be prospective to develop the map of paddy field type. The paddy field level is derived from some parameters based on their level of influencing agricultural land condition.

There was poor correlation between the estimated rice areas and the national rice statistics. One of the outlier estimates was observed in the Papua region. The model reports 3 million ha rice paddies over this region, while the national rice statistics are only 0.02 million ha. The cause of this discrepancy is not understood. This model predicts that deepwater and irrigated rice are dominant in southern Papua. In actuality, the major crops are root and tuber crops, such as yam, taro, sweet potato, vegetables, and fruits.

Based on the results, strategies for bridging rice yield gaps in Indonesia are as follows:

a) To improve the infrastructure and methodology (technical improvement, socio-economic improvements, better policy environment) such as construction and improvement of irrigation systems including groundwater exploitation, improved drainage systems, and soil amelioration;
b) To set priorities on increasing rice yields of the districts having lower average yield compared to the average yield level of their province;
c) Site specific improvements: prescription farming, using adaptable rice varieties etc.

Major improvements should be carried out in Sumatra, Nusa Tenggara and Sulawesi to overcome major constraints, such as water shortages, poor drainage, Fe toxicities and acid soils, low prices of the product, and marketing. The examples of major improvements are construction and improvement of irrigation systems, drainage systems, soil amelioration, transport systems, market systems, and price policies. In this case, Java and Bali will not be considered as important, because the facilities in those regions are already considered sufficient, having good natural resources (high soil fertility and sufficient water resources).

Prioritized districts in each province to increase rice yield or to reduce yield gaps are using the afore-mentioned method. In Java, there is no special district to prioritize to increase rice yields. In this area, bridging rice yield gaps should be done in line with increasing the efficiency of production inputs such as adopting prescription farming, and using high-value rice varieties (of high grain quality with high price). Using the prescription farming procedure, in which the needs for fertilizers on rice are calculated based on soil tests, targeted yield levels and climate, the efficiency of fertilizer usage could be reduced or even, the rice yield could be increased (Waterman and Hamilton, 1975).

Conclusions

There is a growing demand for rice with increase in population. As rice is still the major staple food in Indonesia, the task of increasing rice production continues to engage the attention of national planners. There are five identified avenues to increase rice production, namely: a) by increasing the area under rice production through either increasing the cropping intensity or expansion into new lands; b) by increasing rice productivity; c) by stabilizing rice yields; d) by narrowing the rice yield gap; and e) by reducing yield losses during harvest and post-harvest.

In this context, increasing cropping intensity is related to the improvement/building irrigation systems to enable planting of two or three rice crops per year. Productivity is related to finding new high yielding rice varieties that potentially increase the yield per ha; stabilizing rice yields by better pest management to prevent or to control pest attacks and disease incidence; and post-harvest activities related to development of harvest and post-harvest technologies. The efficacy and efficiency of those methods for increasing rice production differ from one region to another, which are dependent on natural and socio-economic conditions.

Indonesian rice paddies with different rice ecosystems were mapped using time-series satellite imagery analysis. This imagery was generated from the 500 m resolution MODIS/terra spectral surface reflectance (MOD09A1) data acquired from 2006 to 2007. The algorithm for mapping rice paddy area was developed based on the observed temporal Indonesian rice canopy developments. This algorithm distinguishes different rice ecosystems and provides rice-cropping frequency.

The total estimated rice area for Indonesia was 8.27 million ha, which is consistent with published values. Comparison of the estimated rice paddy area (y) and the national rice statistics (x) on the provincial or state level show high linear correlations over the areas dominated by rainfed.

This model can be used to identify Indonesian areas that are influenced by activities attributed to rainfed, irrigated, and upland rice cultivation. Model users could be state officers or inter-country partners working on regional water management for agriculture and on agricultural yield estimation. Atmospheric scientists can also employ the model's results to estimate regional budget and spatial loading of pollutants attributed to biomass burning and rice cultivation.

Ground data should be collected in each paddy field class for validating the results. It is highly suggestive to have analysis using newly completed series data images with at least two years data series which represent each phase of paddy. Estimation of water demand by using remote sensing data and considering some water resources, such as amount of precipitation, available water surface, etc., could be expanded for the next research.

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