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Remote sensing based change analysis of rice environments in Odisha, India

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ABSTRACT

The rainfed rice-growing environment is perhaps one of the most vulnerable to water stress such as drought and floods. It is important to determine the spatial extent of the stress-prone areas to effectively and efficiently promote proper technologies (e.g., stress-tolerant varieties) to tackle the problem of sustainable food production. This study was conducted in Odisha state located in eastern India. Odisha is predominantly a rainfed rice ecosystem (71% rainfed and 29% canal irrigated during kharif-monsoon season), where rice is the major crop and staple food of the people. However, rice productivity in Odisha is one of the lowest in India and a significant decline (9%) in rice cultivated area was observed in 2002 (a drought year). The present study analyzed the temporal rice cropping pattern in various ecosystems and identified the stress-prone areas due to submergence (flooding) and water shortage. The spatial distribution of rice areas was mapped using MODIS (MOD09Q1) 250-m 8-day time-series data (2000–2010) and spectral matching techniques. The mapped rice areas were strongly correlated ($R^2 = 90\%$) with district-level statistics. Also the class accuracy based on field-plot data was 84.8%. The area under the rainfed rice ecosystem continues to dominate, recording the largest share among rice classes across all the years. The use of remote-sensing techniques is rapid, cost-effective, and reliable to monitor changes in rice cultivated area over long periods of time and estimate the reduction in area cultivated due to abiotic stress such as water stress and submergence. Agricultural research institutes and line departments in the government can use these techniques for better planning, regular monitoring of land-use changes, and dissemination of appropriate technologies.

1. Introduction

Odisha is an agrarian state with agriculture and allied sectors contributing to nearly 22% of the state gross domestic product in 2009–10. Nearly 70% of the total workforce is directly or indirectly employed by this sector. Despite its importance in the state economy, agricultural production still depends on the mercy of the rain god. More than half of the 9 million hectares of total cropped area in 2008–09 depended on monsoon. Odisha, an eastern state with more than 9 million hectares of total cropped area, has been plagued by one or multiple stresses (drought, submergence and salinity) in most of the years during the last four decades. Rice is a major cereal grown in the state, with nearly 5 million hectares of area (884,282 ha of kharif-autumn rice, 3,401,572 ha kharif-winter rice, and 884,282 ha of rabi-summer rice) and 71% of the total rice crop is rainfed. More than 90% of the total rice is grown in the kharif season, accounting for two thirds of the total kharif cropped area. The plateau terrain of the state, with yellow laterite and lateritic soils, is low in organic matter and NPK, accounting for 60% of the state's rice area. The remaining 40% of rice is grown in the coastal belt with alluvial soil, which is generally fertile but low in nitrogen and phosphorus. The lower yield of paddy in the state could be explained to the lack of proper infrastructure, including irrigation facilities, input availability, output marketing, transportation, and storage; socioeconomic conditions of the farmers; and the size of landholdings.

In the last 50 years, Indian rice production has nearly tripled with the introduction of semi-dwarf modern varieties, as part of the Green Revolution package. During this period, production has been

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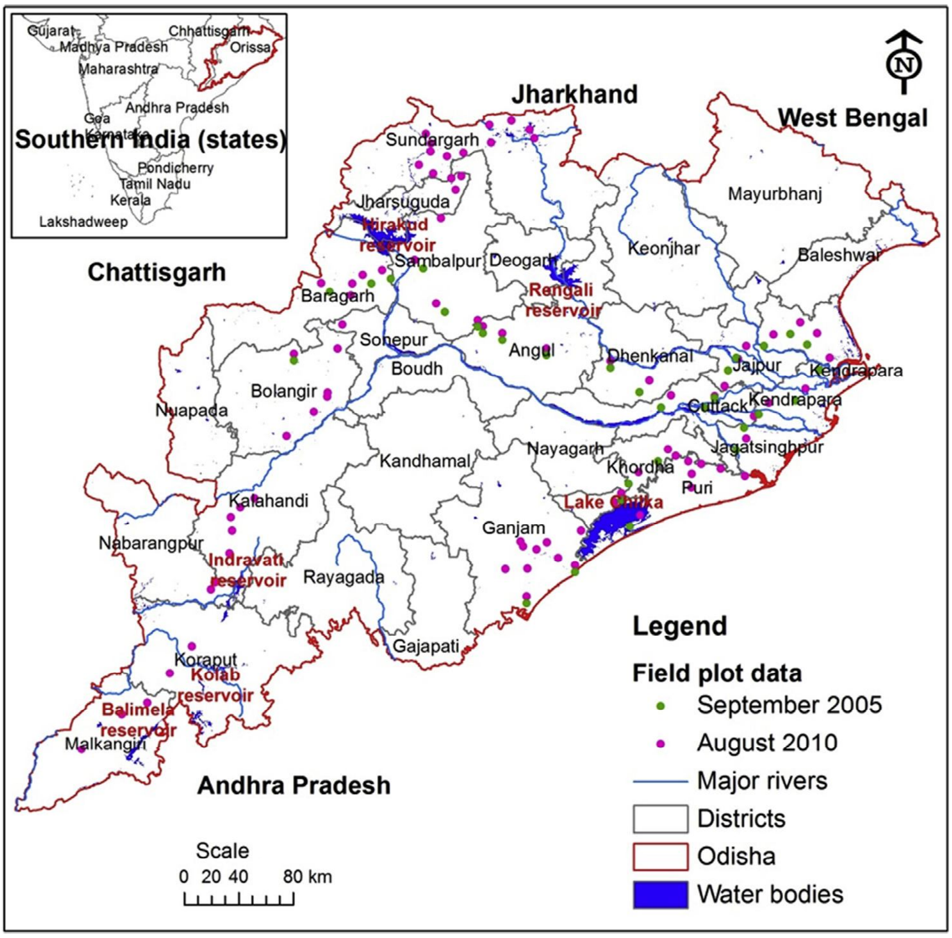

Fig. 1. The Odisha study area, showing major rivers and state and district boundaries. There are 114 field-plot locations where rice crop type, cropping intensity, water source (irrigated versus rainfed), and a number of other parameters (e.g., digital photos, land cover distribution) were also collected.

kept up with population growth, with a steady increase in per capita production in the 1970s and 1980s, before flattening out in the 1990s, and finally declining in the 21st century (Fujita, 2009). Historically, the eastern states of India had low productivity, especially Odisha, one of the lowest (1.5 t/ha). However with an increase to 2.5 tons/ha recently it is below the national average of 3 tons/ha. More than 90% of the rice area is rainfed. Poor infrastructure, inadequate credit, small landholdings, imbalanced fertilization have added to the difficulties to farmers including poor seed replacement rate. Erratic behavior of the monsoon has also led to variation in paddy yields over the years to make things worse. There is need to focus technology packages to improve yields in the rainfed systems taking into account the drought in the upland rice areas and submergence in the rainfed lowlands (Das and Bastia, 2013).

Several studies were conducted in different parts of the world using various remote-sensing techniques at different resolutions (Abderrahman and Bader, 1992; Ambast et al., 2002; Frolking et al., 2002; Sakamoto et al., 2006; Gumma et al., 2011a). Previous studies have reported the advantages of MODIS (moderate-resolution image spectroradiometer) satellite imagery in mapping agricultural changes between water-surplus and water-deficit years, including the dynamics of change in agriculture (Gaur et al., 2008; Biggs et al., 2010; Gumma et al., 2011c). Providing insights and methods for measuring short- to long-term changes in land use (Singh, 1989; Coppin et al., 2004; Lu et al., 2004), these studies have been done for a few years. Identifying crop land changes is very important for sustainable agriculture and livelihoods (Gautam et al., 2003; Semwal et al., 2004; Gumma et al., 2011a). However, it is seldom used to identify how rainfed rice areas change in response to variations in climate for improving food production and livelihood.

Since two-thirds of the total rice area is not irrigated, priority should be given to improving productivity in rainfed systems. The diverse ecosystems under which rice is grown within the rainfed region, blanket technology package for the entire region will not suffice and careful evaluation is needed to develop a customized technology package for each ecosystem. The main objective of this study is to map the rice areas in Odisha from 2000–01 to 2010–11 using MODIS 250-m 8-day time-series data using spectral matching techniques and identify stress-prone rice areas in the state. The information generated can potentially guide rice scientists and planners in developing technologies suited to rainfed conditions and other rice ecosystems as well as in targeting technologies adapted to local needs. Moreover, the information could be used to develop stress-adaptive measures and technologies focusing on the most vulnerable areas where drought is most severe and where rainfed rice production is the major livelihood of farmers.

2. Study areas

Odisha is located in the subtropical zone in the eastern region of India between 17°31′N and 20°31′N latitude and 81°31′E and 87°30′E longitudes (Fig. 1). It is bounded by Jharkhand to the north, Chhattisgarh to the west, Andhra Pradesh to the south, West Bengal to the northeast, and the Bay of Bengal to the southeast. The mountain ranges of the Eastern Ghats run from northeast to southwest in the middle of the state. These mountain ranges separate the eastern part of the state, which is a coastal belt with 482 km of coastline, and the western part, which is an extensive plateau. The state has a geographical area of 15.571 Mha. The state has been divided into four physiographic divisions: the Northern Plateau (25.5% of total geographical areas), Central Table Land (24.1%), Eastern Ghat Region (29.2%), and Coastal Region (21.2%).

Odisha, lying just south of the Tropic of Cancer, has a tropical climate. The climate is hot, moist, and sub-humid. The average rainfall is 1597 mm over 77 rainy days; 80% occurs in the monsoon season (during June to September) (Panigrahi et al., 2010). Odisha has five major irrigation projects, the Hirakud, Rangali, Indravati, Kolab, and Balimela reservoirs (Fig. 1), which can irrigate almost 3 million hectares, and within which rice is one of the most dominant crops. Rice is the major crop and staple food of the people in Odisha, mainly grown in the kharif season (predominantly rainfed rice), which contributes 94% of total rice and 92% of total rice production in Odisha (Samal and Pandey, 2005).

3. Data sets

3.1. Satellite data

The MODIS terra 8-day time-series data for Odisha were downloaded from calibrated global continuous time-series mega-data sets composed from individual files of NASA (www.modis.land.gsfc.nasa.gov). The MOD09Q1 2000 to 2010 (Table 1) Terra sensor data in two specific bands were processed for land applications as a MODIS surface reflectance product. The product is an estimate of the surface reflectance for each band as it would have been measured at ground level if there were no atmospheric scattering or absorption. Original MODIS data were acquired in 12-bits, and were stretched to 16-bits. Furthermore, the rate of observation coverage, the viewing angle, cloud or cloud shadow coverage, and aerosol loading were all assessed on a pixel-by-pixel basis to ensure that each pixel contained the best observation during that 8-day period. MODIS 8-day composites were used to calculate two indices: (a) normalized difference vegetation index (NDVI) and (b) NDVI monthly maximum value composites (NDVI MVC), using surface reflectance values from red (620–670 nm) and NIR1 (841–875 nm) bands with the following equations. In our study, monthly NDVI MVC were used for classification and an NDVI 8-day data set was used for identifying and labeling seasonal rice classes.

$$\mathrm{NDVI} = \frac{\lambda_{\mathrm{NIR}} - \lambda_{\mathrm{red}}}{\lambda_{\mathrm{NIR}} + \lambda_{\mathrm{red}}} \quad (1)$$

Table 1
MODIS Terra 2-band reflectance data and characteristics used in this study.[a]

MOD09A1 product[a]			
MODIS bands[b]	Band width (nm)[c]	Band center (nm)[c]	Potential application[d]
1	620–670	648	Absolute land cover transformation, vegetation chlorophyll
2	841–876	858	Cloud amount, vegetation land cover transformation

[a] Of the 36 MODIS bands, the 7 bands reported here are specially processed for land studies.
[b] MODIS bands are rearranged to follow the electromagnetic spectrum (e.g., blue band 3 followed by green band 4).
[c] Nanometers.
[d] Taken from MODIS Web site (http://modis.gsfc.nasa.gov/data/dataprod/index.php).

$$\mathrm{NDVI}_{\mathrm{MVC}_i} = \mathrm{Max}(\mathrm{NDVI}_{i1}, \mathrm{NDVI}_{i2}, \mathrm{NDVI}_{i3}, \mathrm{NDVI}_{i4}) \quad (2)$$

where MVC_i is the monthly maximum value composite of the ith month and i_1, i_2, i_3, and i_4 are every 8 days' data in a month.

3.2. Field-plot data

Field-level surveys were conducted during August 30–September 28, 2005, and August 16–August 25, 2010, across 146 locations covering the major rice-growing areas in Odisha (Fig. 1). Main purpose of field-plot data is to class identification and validation of resultant classified output. Location-specific data were collected from 500 m × 500 m plots consisting of GPS locations, land use categories, land cover percentages, cropping pattern during different seasons (through farmer interviews), crop types, and irrigation method (irrigated or rainfed). Field-plot samples were obtained within large contiguous areas of a particular land use/land cover (LULC). The locations were chosen based on the knowledge of local agricultural extension officers to ensure that the same crops were grown during previous years as were observed during the survey. The local experts also provided information on crop calendars, cropping intensity (single or double crop, including crop types), irrigation application, and percentage canopy cover for these locations from their recorded data for the previous years. Overall, 114 spatially well-distributed data points (Fig. 1) were collected. These field-plot data were used for identification and labeling class names (50 field-plot data) and also used for accuracy assessment (96 field-plot data).

3.3. District statistics for rice

Statistics on rice cultivated area, production, and price were obtained at the sub-national level (districts) from the Datanet India private limited (DIP, 2012). The information was also supplemented by the state agriculture department of Odisha. The amount of area cultivated for rice from the district statistics is mainly used to cross-check the amount of rice area obtained from remote-sensing techniques, while the rice varietal data are used for estimating rainfed/irrigated rice varieties, including hybrid/stress-tolerant varieties.

3.4. TRMM rainfall data

Daily rainfall data for Odisha were downloaded from the Tropical Rainfall Measuring Mission (TRMM) (TRMM, 2012) and processed as monthly rainfall to compare with 11 years (from 2000 to 2010) of monthly mean rainfall data. Also, monthly rainfall data were obtained from the Indian Institute of Tropical Meteorology (IITM, 2012).

4. Methods

An overview of the methods is shown in Fig. 2 and details are described below.

The process starts with mapping temporal rice areas using MODIS 8-day time-series data with spectral matching techniques and field-plot information. Accuracy assessment was performed with district-wise national statistics and field-plot data, then calculating sub-pixel areas with field-plot data. Finally, stress-prone areas with changes in rice-growing areas with monthly rainfall data were identified.

4.1. Mapping rice areas

MODIS 250-m spatial resolution 8-day time series of normalized difference vegetation index (NDVI) data (extracted from MOD09Q1

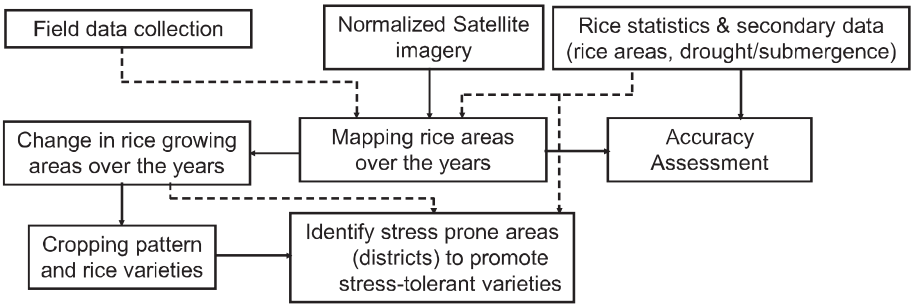

Fig. 2. Overview of the methodology for dissemination.

surface reflectance product) were used to map rice areas using spectral matching techniques, following the methodology adopted from Thenkabail et al. (2007). MODIS 8-day NDVI images were processed and stacked into a single composite for 2000–01 (46 NDVI images), 2001–02 (24 NDVI images), 2002–03 (24 NDVI images), 2003–04 (24 NDVI images), 2004–05 (24 NDVI images), 2005–06 (24 NDVI images), 2006–07 (24 NDVI images), 2007–08 (24 NDVI images), 2008–09 (24 NDVI images), 2009–10 (24 NDVI images), and 2010–11 (46 NDVI images). Thus, a total of eleven image composites were developed. The time series for each year was stacked for the kharif season, which runs from June to October/November, but we stacked June to December to consider late-sown crops as well.

Each year, MODIS NDVI time series composite was then classified using unsupervised ISOCLASS cluster K-means classification with a convergence value of 0.99 and 100 iterations, yielding 100 classes followed by successive generalization. Unsupervised classification was used instead of supervised classification in order to capture the range of variability in phenology over the image across the study area. The initial number of classes varied from 100 to 150 based on the area covered by the segment and the complexity of the area.

Land use/land cover class identification and labeling were based on MODIS NDVI time-series plots, ideal spectra, ground-truth data, and very high resolution images (Google Earth). Ideal spectra were generated using time series imagery with precise filed plot data of same type of land use at spatially distributed locations. The specific protocols included grouping class spectra based on class similarities and/or comparing them with ideal/target spectra, rigorous protocols for class identification, and labeling with the use of large volumes of ground-truth data and very high resolution imagery. After rigorous classification process most of the classes were identified except some mixed classes (Thenkabail et al., 2007; Gumma et al., 2011b,c). The processes were followed by resolving mixed classes through specifying GIS spatial analysis/modeling layers (DEM/rainfall). We established methods for area calculations and accuracy assessments. Once the classes were identified, we combined the similar classes by visual matching using spectral correlation coefficient within the classes using Equation (3). The spectral correlation coefficient is a combination of signature shape and magnitude (Thenkabail et al., 2007):

$$\mathrm{SCC} = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - x_{\mathrm{mean}}}{s_x}\right)\left(\frac{y_i - y_{\mathrm{mean}}}{s_y}\right) \tag{3}$$

where, "*SCC*" is spectral correlation coefficient, "*n*" is number of NDVI-MVC, "x_i" is NDVI of *i*th month in *x* class, "x_{mean}" is mean NDVI of *x* class, "s_x" is mean NDVI of *x* class, "y_i" is NDVI of *i*th month in *y* class, "y_{mean}" is mean NDVI of *y* class, and "s_y" is the mean NDVI of *y* class.

Spectral correlation coefficient is a combination of signature shape and magnitude. Class signatures with the closest correlation (coefficient 0.90–1.0, coefficients of irrigated rice classes varying from 0.95 to 1.0) were assigned the same class name for all the time periods. The classes generated from the unsupervised classification were aggregated into 15 classes and named on the basis of spectral similarity. Spectral matching was used to relate the classes for all years (Thenkabail et al., 2005, 2007, 2009; Gumma et al., 2011b). These processes are briefly explained in Thenkabail et al. (2007).

After rice areas were mapped, precise areas in each rice class for Odisha were calculated. However, in coarser resolution MODIS with 250 m on a side (pixel size), which was larger than many agricultural fields in the study area, the sub-pixel rice fractions were determined using intensive field-plot information (Gumma et al., 2011b).

4.2. Accuracy assessment

Accuracy assessment was performed based on two methods: First was to correlate between national statistics and MODIS-derived irrigated areas and the second was based on MODIS-derived irrigated areas evaluated with field-plot information through error matrix.

The final rice map was compared against the yearly district-wise rice area statistics of Odisha (Odisha Department of Agriculture and Statistics). The MODIS rice area fractions were aggregated to get the total mean rice areas from 2000 to 2009 and these were compared with the reported planted mean rice areas from 2000 to 2009 at the district level. Furthermore, the data sets generated from remote sensing were validated based on the intensive field-plot data.

Based on a theoretical description given by (Jensen, 2004), to generate an error matrix. The columns of an error matrix contain the field-plot data points and the rows represent the results of the classified rice maps (Congalton, 1991). The error matrix is a multi-dimensional table in which the cells contain changes from one class to another class (Congalton and Green, 1999).

$$\text{Accuracy of rice area classes} = A_{\mathrm{ra}} = 100 \times \frac{\mathrm{RFPCRA}}{\mathrm{TRFP}} \tag{4}$$

$$\text{Errors of commission for the rice area class} = E_c = 100 \times \frac{\mathrm{NRFPRA}}{\mathrm{TNRFP}} \tag{5}$$

$$\text{Errors of commission for the rice area class} = E_o = 100 \times \frac{\mathrm{RFPNRA}}{\mathrm{TRFP}} \tag{6}$$

4.3. Rice-growing areas

The MODIS-derived rice area maps for 2000–01 and 2010–2011 were used as the basis of the maximum possible extent of rice areas. As such, the 2000–01 map is the best available and most detailed map of the rice area in India (Gumma et al., 2011b). Based

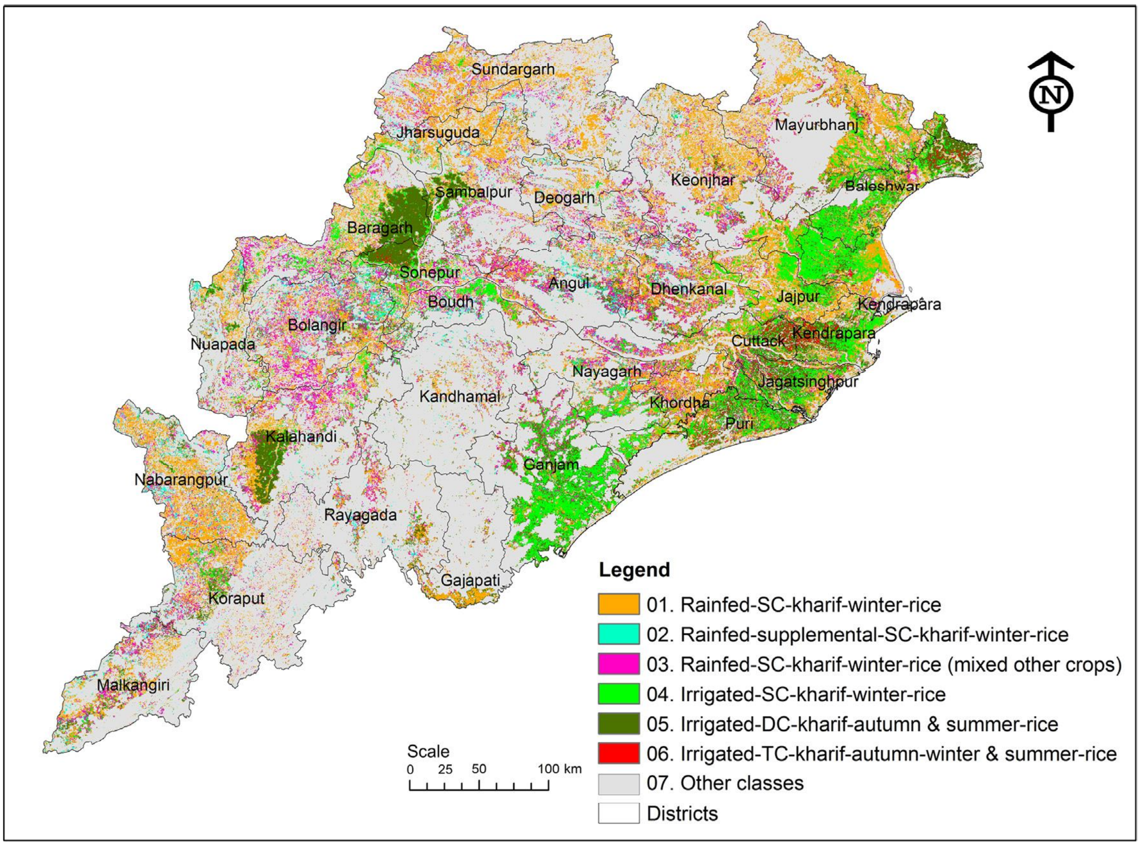

Fig. 3. Spatial distribution of rice (derived from 2000–01 to 2010–11 MODIS composite).

on our field knowledge and extension officer's knowledge of the area, we hypothesize that there was significant change in the potential area that could be planted to rice between 2000 and 2010. Almost all gains in productivity are due to increased yields rather than agricultural expansion.

4.4. Identifying changes using spectral matching techniques

A comparison between total rice area and yearly rice area was made (Section 4.4). If the rice class was identified as 'other class', then observed monthly rainfall was compared with normal monthly rainfall using spectral matching techniques. Spectral matching techniques (SMTs) match the rice class spectra extracted from a good year with rice with other class spectra extracted from a water-deficit or submergence year. We identified the duration, magnitude, and peak of NDVI. A higher value of NDVI was noticed during the kharif season (with the peak of NDVI observed during September) compared with the rabi season for land use change areas. For Odisha, the highest value of maximum mean NDVI was 0.8 during the kharif rice season, but the value of NDVI was never above 0.4 in any of the months during seasons of water deficit/submergence years.

5. Results & discussion

Results focus on a temporal analysis with changes in rice area mapping over the years, rice classification and accuracy assessment based on field-plot data with spectral matching techniques, and comparison between MODIS rice area estimates and national and sub-national statistics for Odisha. Comparative rainfall and NDVI trends for water deficit/submergence and normal years are used for identifying stress-prone districts for the dissemination of stress-tolerant varieties.

5.1. Rice maps and statistics

Rice classes identified based on field-plot data include GPS-referenced digital images and temporal NDVI signatures for each of the rice classes (Thenkabail et al., 2007; Gumma et al., 2011b). Six rice classes were identified and labeled in various eco-regions (Fig. 3), such as rainfed-single crop, groundwater-double crop, irrigated-single crop, Irrigated-surface water/groundwater-double crop irrigated-surface water and groundwater-double crop and irrigated triple crop. Area statistics are shown in Table 2. Rice areas were mapped for the last 11 years. But, 2010–11 will be the focus of the discussion (Fig. 3). Irrigated areas are mainly located under major irrigation projects that are spatially spread out in the districts of Baragarh, Cuttack, Jagatsinghpur, Khordha, Kalahandi, Puri, Baleswar, Sambalpur, and Sonpur (Fig. 1). Irrigated single crop rice is located in Bhadrak and Ganjam. Rainfed single crop rice area is distributed all over the study area, but the major areas are located in Bolongir, Nuapada, Nabrangpur, and Malkangiri districts.

The Ministry of Agriculture reported net rice areas of about 4.21 million hectares in various eco-systems. Fig. 3 (2010 rice map) shows almost the same rice-growing areas: net irrigated rice was 1.87 million hectares and rainfed rice areas (Table 2) (kharif season) were 2.4 million hectares.

5.2. Accuracy assessment based on field-plot data

A quantitative accuracy assessment was performed through error matrix whether a known rice area is classified as rice (without type of irrigation) or non-rice. This process was done using 96 independent field-plot observation points and they are summarized in Table 3. Each of the field-plot points refers to one of seven classes. The user accuracy varied from 76% to 100% across seven classes, with an overall accuracy of 77.08%. However, it must be noted that most rice classes are inter-mixed (rainfed rice mix with irrigated-surface water rice class). So, if we combine all six rice classes into one rice class, the accuracy of rice mapping will be very high (about 90%). So, the uncertainty of about 20% is due to the inter-mix among the various rice classes. Therefore, accuracy will be very high between rice and non-rice classes. The irrigated classes generally have higher classification accuracies than the rainfed or mixed irrigated/rainfed classes (Table 3).

5.3. Comparison with national statistics

District rice area statistics obtained through MODIS derived rice map were in good agreement across all classes with published rice statistics (Fig. 4). We performed a comparison at the district level (30 spatial units) across the study area, and we calculated the mean of the district rice areas for both MODIS derived rice areas and national statistics. The degree of agreement between the MODIS derived rice area estimates and the published statistics is very high (89.48%) at the district level, indicating the reliability and accuracy of the results obtained and of the conclusion drawn. Although some districts had rice area over- or under-estimated, we believe that these estimates are correct because remote-sensing techniques are a more scientifically valid measure.

5.4. Temporal changes in rice-growing area

Temporal variations in rice-growing areas in Odisha from 2000 to 2010 at the district level are shown in Fig. 5. During the period 2000–2010 the stress prone years were grouped into 5 types: 1. normal rice areas and 2. partial damaged area due to drought 3. complete damage due to due to drought 4. partial damage due to floods and 5. complete damage due to floods Table 3. In the last decade, 2002 had the lowest total rice area in Odisha, with an estimated rice area of 3,048,376 ha (149,348 ha of complete damage and 1,379,195 ha of partial damage; see Table 4), compared with the average of the 11 years. This reduction in rice area was brought about by a severe incidence of water stress as indicated by the data on low rainfall. The average rainfall for severe drought-affected areas in 2002 was only 840 mm compared with the normal rainfall of 1498 mm. Similarly, mean NDVI was 0.62 in normal years compared with only 0.42 for drought year 2002 (Gumma et al., 2011a). The data for a normal year is the average value for the last 50 years (1960–2009) for both mean monthly rainfall and NDVI generated from the remote-sensing database.

The western districts of Odisha (mainly Baragarh, Bolangir, and Nabarangpur) were severely affected by drought in 2002: there was an estimated more than 30% reduction in rice area planted due to the low and uneven rainfall distribution during rice planting and early crop growth (Table 4). Some districts were affected by flooding that occurred in the latter part of the rice-growing season during 2007–10 in coastal districts (mainly in Bhadrak, Kendrapara, and Puri).

5.5. Identification of stress-prone areas

In order to identify the frequency of drought and submergence years, the stress prone areas are grouped into 3 classes of frequency of drought and 3 classes of frequency of submergence (Fig. 6 and Table 5). It provides information on prioritizing areas that are often affected by stress.

It can be observed that 1,761,988 ha were affected by water deficiency 1–2 times (mainly in 2000, 2002, and 2009) in 11 years while 1,163,800 ha were affected 3–5 times. A relatively small area (188,856 ha) was affected by more than five occurrences of water deficiency. More than half (57%) of the total rice area of Bolangir (161,707 ha) was affected by one to two occurrences of water deficiency. Sundargarh, although ranking 9th in terms of rice area (171,225 ha), was greatly affected by water deficiency, with 52% affected rice area (3–5 times) and 16% affected rice area (more than 5 times).

Submergence (flooding) was also observed but it was not as spectacular as the extent and occurrence of water deficiency. Only 5% (not more than 215,000 ha) of the total Odisha rice area was affected, with Bhadrak having the highest percentage of submerged rice area of 35% (1–2 times), 29% (2–5 times), and 4% (more than 5 times).

5.6. Rice production planning and targeting

In Odisha, rice is grown under diverse ecosystems with a range of management practices suited to a wide range of edaphic and climatic conditions. Immense diversity in growth habits makes classification and characterization of the rice environments a challenging task. Classification of rice lands on the basis of some important traits that influence rice productivity is essential for varietal development and formulation of a package of practices for crop management.

The development of improved varieties fulfilling the varietal requirements of the three broad rice ecosystems dates back to the late 1930s. Breeding for short high-yielding varieties was

Table 2
Rice areas (ha) with various ecosystems generated by remote-sensing technique for 2010–11. (Note: SC: single crop; DC: double crop; TC: triple crop; SW: surface water; GW: groundwater).

Rice class#	Full pixel area	Rice area fraction	Sub-pixel rice area (ha)	%
01. Rainfed-SC-kharif-winter-rice	21,04,388	79%	16,65,042	39%
02. Rainfed-supplemental-SC-kharif-winter-rice	2,28,463	84%	1,91,165	4%
03. Rainfed-SC-kharif-winter-rice (mixed other crops)	8,83,969	62%	5,52,457	13%
04. Irrigated-SC-kharif-winter-rice	11,43,631	87%	9,92,908	23%
05. Irrigated-DC-kharif-autumn & summer-rice	9,27,328	89%	8,22,302	19%
06. Irrigated-TC-kharif-autumn-winter & summer-rice	69,908	89%	61,990	1%
Total kharif-autumn-Irrigated-rice (class 6,7)			8,84,292	
Kharif-winter-rainfed rice (classes 1,2 and 3)			24,08,664	70%
Kharif-winter-irrigated rice (classes 4 and 7)			10,54,899	30%
Total kharif-autumn-rice			34,63,562	
Rabi-summer-Irrigated rice (classes 6 and 7)			8,84,292	
Total rice area (kharif + rabi)			52,32,146	

Table 3
Fuzzy accuracy assessment from field-plot data. Values in the table indicate the % of field-plot windows in each class with a given correctness %.

Classified data	Reference data (field-plot data)							Row total	Number correct	Producers accuracy	Users accuracy	Kappa
	01. Rainfed-SC-kharif-winter-rice	02. Rainfed-supplemental-SC-kharif-winter-rice	03. Rainfed-SC-kharif-winter-rice (mixed other crops)	04. Irrigated-SC-kharif-winter-rice	05. Irrigated-DC-kharif-autumn & summer-rice	06. Irrigated-TC-kharif-autumn-winter & summer-rice	07. Other classes					
01. Rainfed-SC-kharif-winter-rice	19	1	0	3	2	0	0	25	19	86%	76%	69%
02. Rainfed-supplemental-SC-kharif-winter-rice	0	0	0	0	0	0	0	0	0	–	–	0%
03. Rainfed-SC-kharif-winter-rice (mixed other crops)	0	0	5	0	0	0	0	5	5	83%	100%	100%
04. Irrigated-SC-kharif-winter-rice	0	0	0	14	1	0	1	16	14	58%	88%	83%
05. Irrigated-DC-kharif-autumn & summer-rice	2	0	1	0	15	0	0	18	15	75%	83%	79%
06. Irrigated-TC-kharif-autumn-winter & summer-rice	0	0	0	0	1	6	0	7	6	100%	86%	85%
07. Other classes	1	1	0	7	1	0	15	25	15	–	–	52%
Column total	22	2	6	24	20	6	16	96	74			
Overall classification accuracy = 77.08%						Overall kappa statistics = 0.7165						

accelerated after the introduction of two short-height varieties, TN 1 from Taiwan and IR8 developed at IRRI, into India in 1965 and 1966, respectively. These two varieties of exotic origin ushered in a revolution in rice production and were extensively used in hybridization programs for the indigenous development of high-yielding rice varieties, primarily for irrigated lands and for rainfed uplands and medium lands. Varietal improvement for lowlands was intensified in the late seventies. Altogether, 55 rice varieties have been released during the last 40 years and these are shown in Table 6.

Of the 55 varieties, only a few have gained popularity among the farmers of Odisha and neighboring states and are cultivated in a sizable area. Part of the reason for the non-adoption of these high-yielding varieties by farmers could be the limited attention given to production planning and targeting to increase productivity in the different domains and stress regions. The identification of stress-prone areas, including those with water stress and floods, along with the appropriate management practices for each domain can help rice farmers adopt to various rice ecosystems as well as in disseminating technologies adapted to local needs. Moreover, this information could be used to develop stress-adaptive management techniques like SRI, to promote stress tolerant rice varieties and technologies focusing on the most vulnerable areas where drought is most severe and where rainfed rice production is the major livelihood of the farmers. These production domains are also niche areas for studying and developing adaptation strategies due to climate change and develop climate change ready varieties. C4 rice could be one such future product.

6. Conclusions

This study identified the changes in rice-growing areas in Odisha due to floods and water scarcity. First, a baseline rice map of Odisha was produced for 2000 to 2010 with an estimation of rice area under different classes. Accuracy was determined by correlating the MODIS-derived rice areas with field-plot data and sub-national statistics obtained from Odisha's Ministry of Agriculture. The R^2 values were 90% at the district level. In 2002, rice area was damaged by 5% compared with the 10-year mean due to a severe

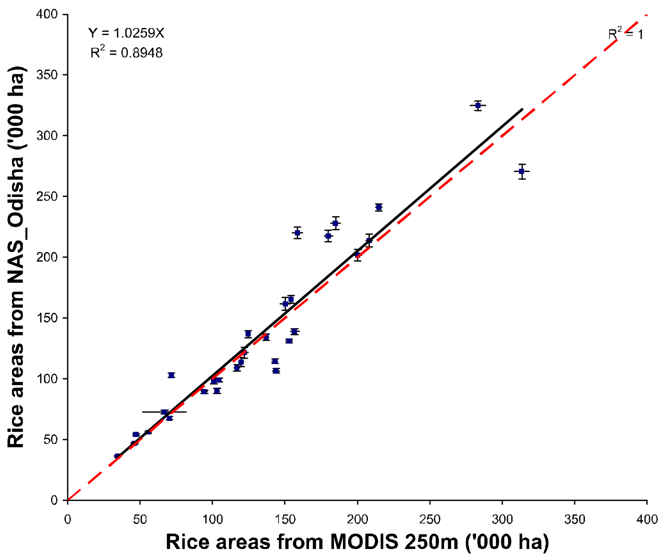

Fig. 4. The 10 years (years 2000–2009) of mean rice areas of Odisha derived using MODIS 250 m were compared with mean rice areas from agricultural census data. (Administrative boundaries are shown in Fig. 1.)

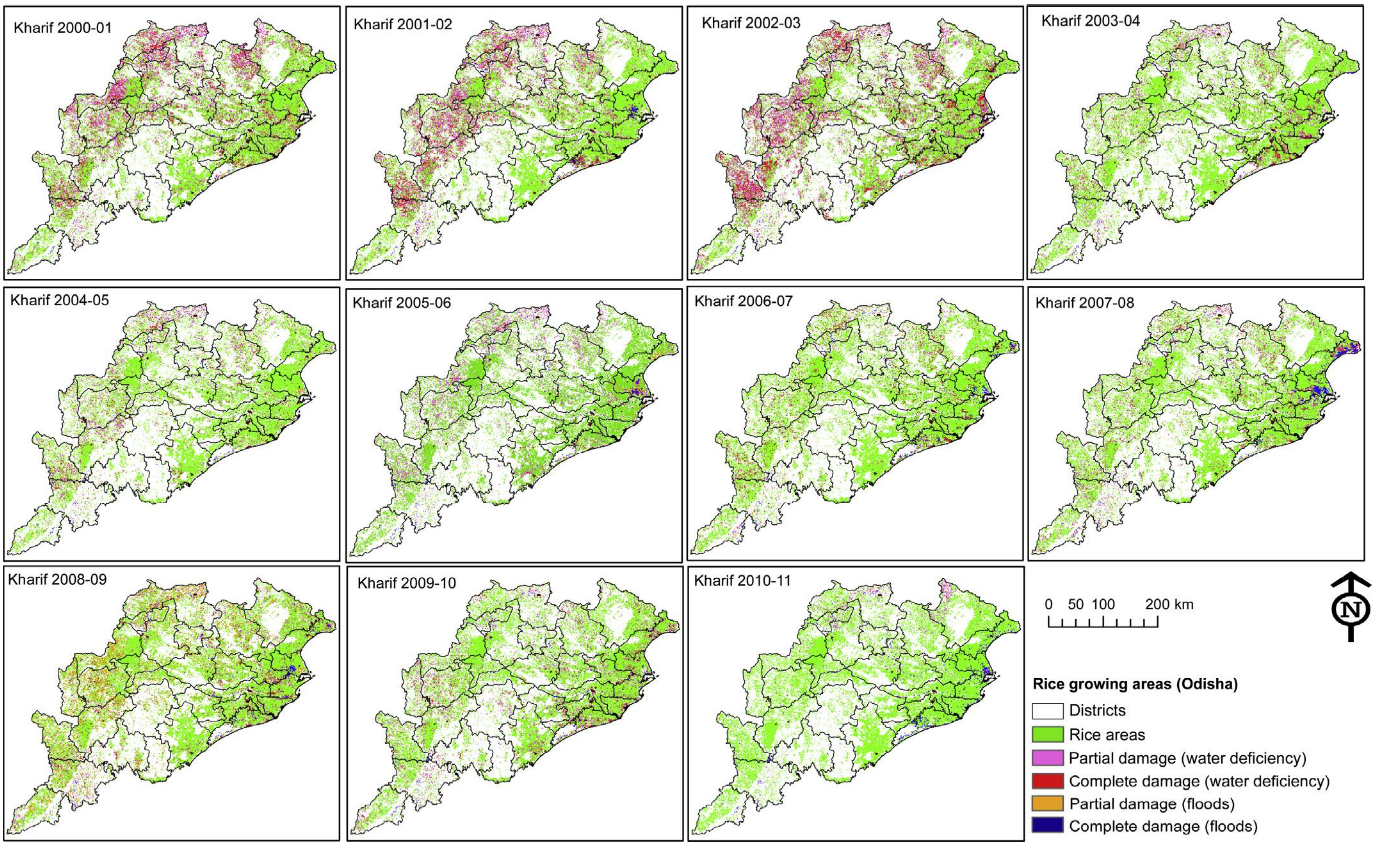

Fig. 5. Spatial distribution of rice areas and areas affected by various stresses.

incidence of drought as indicated by the low rainfall and low NDVI in drought-affected areas. During the last eleven years the rice growing area has increased by 791,715 ha. The overall accuracies (correctness) of the six rice classes varied from 76% to 100%. However, rice versus non-rice accuracies exceeded 90%. Almost all intermixing was only between rice classes. We recommend these methods and protocols for mapping stress-prone rice environments in other countries using time-series satellite sensor data at various resolutions.

Mapping stress prone areas is very important to understand rice researchers and planning departments for sustainable rice development and livelihoods. Precise up-to-date land use change maps are important inputs for promoting stress-tolerant varieties to increase rice production. A significant reduction in rice area and production in 2002 and 2006 (as indicated by the remote-sensing analysis and national statistics) reveals a need to further focus on the development and promotion of drought-tolerant rice varieties and the associated crop management practices for rainfed environments. This will help reduce production losses and yield variability over the years, thus minimizing the negative impacts of drought and other abiotic stresses. In technology development, differences in target domain characteristics and local technological needs should be considered. Remote sensing techniques were useful for assessing the impact of early-season drought by mapping

Table 4
Rice areas affected by various stresses across Odisha (water deficiency and floods).

Year	MODIS rice area (ha)	Partial damage (ha)		Complete damage (ha)		Partial damage %		Complete damage %		TRMM rainfall (mm) (affected areas)	
		Water deficiency	Submergence	Water deficiency	Submergence	Water deficiency	Submergence	Water deficiency	Submergence	Water deficiency	Submergence
2000	3,494,139	744,277	10,568	408,779	8160	21.3%	0.3%	11.7%	0.2%	−396	50
2001	3,667,406	601,868	17,042	339,437	15,163	16.4%	0.5%	9.3%	0.4%	−8	16
2002	3,291,008	840,582	3345	508,001	1126	25.5%	0.1%	15.4%	0.0%	−413	82
2003	4,160,843	321,368	8268	160,181	4246	7.7%	0.2%	3.8%	0.1%	264	497
2004	4,071,079	419,382	4692	178,849	1121	10.3%	0.1%	4.4%	0.0%	−171	269
2005	4,123,355	369,499	15,157	156,517	8494	9.0%	0.4%	3.8%	0.2%	−5	522
2006	3,782,380	586,205	15,383	267,238	7505	15.5%	0.4%	7.1%	0.2%	76	255
2007	4,108,566	351,556	27,964	155,451	21,349	8.6%	0.7%	3.8%	0.5%	0	481
2008	4,016,866	413,767	76,397	179,382	13,905	10.3%	1.9%	4.5%	0.3%	174	535
2009	3,992,179	472,484	41,868	191,743	30,261	11.8%	1.0%	4.8%	0.8%	−140	335
2010	4,285,854	287,620	21,332	106,700	8823	6.7%	0.5%	2.5%	0.2%	−96	50

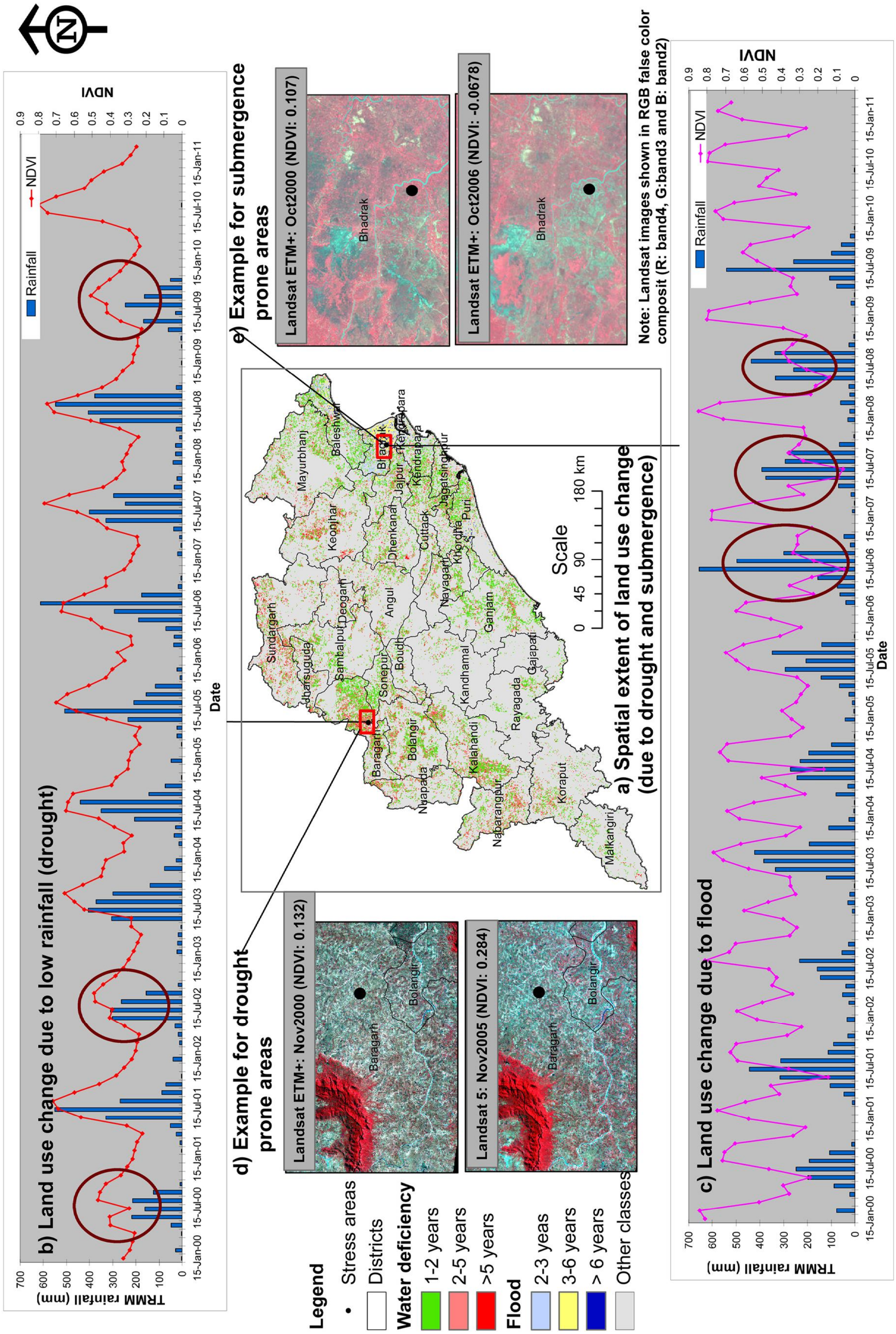

Fig. 6. Identification of stress-prone areas and the number of years in which stresses occurred during the last 10 years.

Table 5
Stress-prone areas at district level with number of times affected during the last 10 years and total rice areas derived from remote-sensing data (year 2010–11).

District	Total rice area (ha)	Water deficiency (area in ha)			Flood (area in ha)		
		1–2 years	2–5 years	>5 years	2–3 years	3–6 years	>6 years
Angul	126,508	42,750	31,013	6700	1706	1094	231
Baleshwar	237,143	113,213	36,006	4038	49,438	18,269	2338
Baragarh	220,275	122,313	103,013	13,075	419	294	81
Bhadrak	178,378	82,975	24,269	1250	61,981	52,263	7263
Bolangir	161,707	92,956	69,975	12,400	256	150	69
Boudh	63,644	23,469	15,744	2025	456	506	231
Cuttack	164,208	69,469	40,475	4538	4338	2563	556
Deogarh	45,578	17,050	15,088	4131	994	719	94
Dhenkanal	137,114	47,194	28,825	7681	925	806	131
Gajapati	36,157	10,381	3363	313	100	106	–
Ganjam	341,031	124,169	45,919	4944	594	156	–
Jagatsinghpur	103,409	34,313	18,331	2244	4169	750	25
Jajpur	162,248	62,056	39,463	4425	20,538	6206	513
Jharsuguda	64,677	24,475	24,600	3175	2663	1813	669
Kalahandi	186,920	104,625	88,200	13,375	744	506	44
Kandhamal	45,744	17,944	10,550	1844	13	–	–
Kendrapara	142,725	56,206	25,225	1988	24,294	8169	1669
Keonjhar	220,853	68,600	71,500	16,481	7300	1013	25
Khordha	125,814	46,406	26,431	2956	4563	1863	1106
Koraput	129,230	51,500	40,275	7456	1788	781	94
Malkangiri	99,617	33,244	12,131	2413	575	300	–
Mayurbhanj	303,301	118,619	72,294	10,931	1663	275	–
Nabarangpur	176,627	53,506	65,025	10,763	475	413	188
Nayagarh	103,648	40,025	22,888	3400	956	363	113
Nuapada	76,874	38,938	37,550	6281	144	94	–
Puri	148,028	61,625	31,231	3319	19,875	8606	2300
Rayagada	62,851	29,944	11,713	1169	25	25	–
Sambalpur	147,198	61,106	42,025	5825	1981	1188	394
Sonepur	103,120	46,175	21,381	2700	663	344	81
Sundargarh	171,225	66,744	89,300	27,019	938	331	44

reductions in rice area but not for estimating a reduction in crop yields caused by mid- and later-season drought. Future research should focus on designing suitable techniques to measure the impact of terminal drought (yield effect) in combination with other suitable methods not (Such as owing to its unique interaction with water/soil, RADAR remote sensing might have potential application in the mapping of irrigated rice areas) covered in the current study. Similarly, future studies that encompass effects of other non-climatic stresses may provide more insights.

Table 6
High-yielding varieties released during the last 40 years.

Year of release	No. of releases	Variety
1969	1	Jagannath
1971	3	Hema, Kumar, Rajeswari
1976	2	Parijat, Suphala
1980	3	Keshari, Subhadra, Jajati
1983	5	Shankar, Rudra, Sarathi, Daya, Pratap
1985	3	Pathara, Gouri, Rambha
1988	4	Shrabani, Lalat, Ananga, Bhuban
1992	12	Nilagiri, Khandagiri, Badami, Ghanteswari, Birupa, Bhanja, Samant, Meher, Manik, Urbasi, Mahalaxmi, Kanchan
1999	12	Lalitagiri, Udayagiri, Bhoi, Sebati, Konarka, Kharavela, Gajapati, Surendra, Prachi, Mahanadi, Indrabati, Ramachandi
2002	1	Jagabandhu
2005	4	Sidhanta, Jogesh, Pratikshya, Upahar
2008	1	Manaswini
2009	1	Ranidhan
2010	3	Mandakini, Tejaswini, Mrunalini

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