Monitoring changes on mangroves coasts using high resolution satellite images. A case study in the Perancak estuary, Bali

[1]Christophe Proisy*, [1,2]Rinny Rahmania, [3]Gaëlle Viennois, [2]Ariani Andayani, [4]Sophie Baudel, [2]Riza Fahran, [2,5,6]Niken Gusmawati, [4]Olivier Germain, [5]Hugues Lemonnier, [2]Nurman Mbay, [2]Bambang Nugraha, [7]Juliana Prosperi, [8]Frida Sidik, [2]Berni Subki, [9]Suhardjono, [8]Nuryani Widagti, [4]Philippe Gaspar

[1]IRD-UMR AMAP, Montpellier, France
[2]Research Center for Marine Technology, Agency for Marine and Fisheries Research, Ministry of Marine Affairs and Fisheries, Jakarta, Indonesia
[3]CNRS-UMR AMAP, Montpellier France
[4]Collecte Localisation Satellites, Ramonville, France
[5]IFREMER, LEAD/NC, Nouméa, New Caledonia
[6]Université de la Nouvelle-Calédonie (UNC), PPME EA- 3325, Nouméa, New Caledonia
[7]CIRAD-UMR AMAP, Montpellier, France
[8]Institute for Marine Research and Observation (IMRO), Jembrana, Bali, Indonesia
[9]Herbarium Bogoriense (LIPI), Bogor, Indonesia

**christophe.proisy@ird.fr*

ABSTRACT

Very high resolution (VHR) satellite images provide crucial information on fast changing coastal regions of the world. Within the framework of the INDESO project, we designed a specific application dedicated to the monitoring of mangroves in Indonesia. In this work, we focused on the case study of the Perancak river estuary, Jembrana, Bali. The estuarine area was subject to aquaculture development during the 80's and most of the mangrove forest was cleared. Since the 90's, mangroves are progressively reintroduced thanks to plantation practices. Now, many shrimp ponds are abandoned. We based our analysis on a temporal series of VHR satellite images acquired since 2001 in the aim of following-up 9 years of changes occurring in mangrove vegetation. We map and quantify the trends of evolution in mangroves surface extents, forest types and structure (young, adult, mature) after ground trothing surveys. Overall, the Perancak estuary is currently greening, i.e. increasing extent and continuous growing of mangroves are observed. However, the estuarine hydrology is still constrained by ponds dykes and plantations are monocultures of *Rhizophora* species which are probably not the initial dominant species. The sustainability of the Perancak estuary must be questioned confronted to this greening evidence.

Keywords: Mangroves, high resolution images, change detection, coastal sustainability, Bali

1. INTRODUCTION

Monitoring and assessing coastal changes in the Tropics provide crucial milestones for keeping local livelihoods, economy and ecosystems healthy. However, coasts are fast changing environments due to human activities, coastal dynamics or extreme oceanic events. They are also complex landscapes where human activities juxtapose, damage or even converse natural areas. This is particularly the case of mangrove coasts where the emblematic forest of the sea-land interface must cope with increasing anthropogenic pressures (e.g. Duke et al. 2007).

Measuring fast changing patterns in mangrove coasts may benefit from the increasing availability of very high resolution satellite (VHRS) images with pixel size ranging from 50 cm to 2 meters. Individual trees crowns, including those of small size (e.g. Zhou et al. 2013) can be detected at such spatial resolutions. In addition, textural measures of contrasted sunlit-shadowed canopy patterns in VHRS images showed correlations with above ground biomass in mangroves (Proisy et al. 2007) and rainforests (Ploton et al., 2013).

Multispectral imaging for species discrimination and repetitiveness for monitoring purposes also combine to make the use of VHRS images very attractive for insight into changes of coastal zones.

However, ordering series of VHRS multispectral images requires a budget ranging from about 10€/km² for Ikonos imagery (standard product, archive>90 days, minimum order of 25 km²) to about 60€/km² for Worldview-2 tasking or fresh archive with a minimum order of 100 km² (e.g. e-GEOS, 2014). Besides, there is much left to do in the physical interpretation of the combined potential of high spatial resolution data and (broadband) spectral information acquired in the visible and near infrared domains (e.g. Asner and Warner, 2003; Gastellu-Etchegorry et al. 2004). ‘Pretty images are not enough’ as outlined by Adams & Gillespie (2006). To our knowledge, few works have investigated the potential of temporal series of VHRS images for monitoring mangrove coasts.

Here, we reported a preliminary and visual analysis of 6 VHRS images acquired over the Perancak estuary, Bali within the frame of the Infrastructure Development for Space Oceanography (INDESO) project. This mangrove bay was submitted to mangrove natural processes, man-made mangrove plantations and aquaculture practices. We highlighted the changes in surface extents of the main land cover types. We also discussed on the potential and limits of series of VHRS images for mapping such perturbed coastal environment and how our findings could be used for building sustainable integrated coastal zone management

2. STUDY AREA AND DATA COLLECTION

The experimental site is located located 8.395°S and 114.630°W, 80km northwest of Denpasar in Bali, Indonesia (Fig. 1).

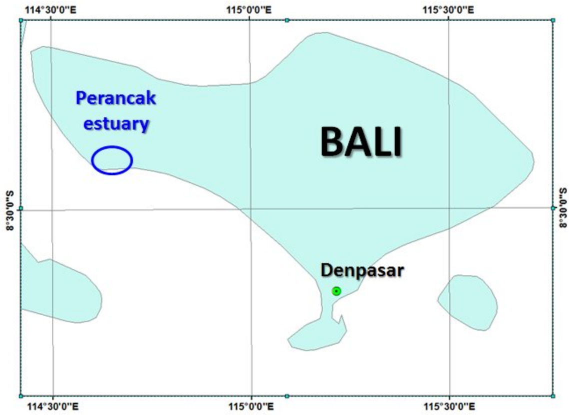

Figure 1: location of the Perancak estuary, southwest coast of Bali province, Indonesia.

2.1 History of land conversion

The study area is a typical example of land cover changes in coastal zone of Indonesia since the 80’s. At that time, the Perancak bay was subject to aquaculture development and most of the mangrove forest was cleared. Since the 90’s, mangroves are reintroduced through plantations. Now, many shrimp ponds are abandoned but most of the pond dykes are kept operational by local government and local owners. The earliest ones were probably managed by the Japan International Cooperation Agency. After 2000, local owners and offices also plant mangroves and seem to continue planting. We have to investigate more on the origins and objectives of such plantation practices in this region. Are they done for forest harvesting and/or with the objective of coastal zone rehabilitation or mangrove restoration?

2.2 Ground truth

We conducted a field survey in May 2014. It consisted first of all in traveling the entire estuary to correlate with a priori visual interpretation of images. We observed that not all but most of the shrimp ponds were abandoned. As observed in the images, pond dykes remain in good conditions almost everywhere. We also measured salinity of the surface water layer. It varied from 0‰ upstream to 30‰ downstream at the Perancak river mouth. In the central part where mangrove has now the largest extension, we measured values of about 27‰.

We selected 6 different areas corresponding to 1) mangrove plantations at different growth stages, 2) well-developed natural mangroves and 3) ponds with natural regeneration inside. Dimensions of plot areas were adjusted in function of the forest homogeneity and/or growth stage (Table 1). Inside each plot, we identified mangrove species and recorded diameters at breast height (DBH) for each tree with DBH>1cm and tree heights for a subset of trees. The largest DBH measured (around 20cm) were collected on *Avicennia* or *Sonneratia* individuals. We also computed basal area for each species as the sum of trunk sections measured at breast height. This computation allowed pointing out the species dominance in a given plot. A total of 16 mangrove species was recorded and we highlighted the contrast in terms of both species composition and diversity between plantations and natural areas (table 1). Plantations are monocultures of *Rhizophora* species with almost no regeneration capability whereas *Avicennia* and *Sonneratia* species seem to be the native species that dominate in natural areas with numerous occurrences of the other species in the lower canopy layers. Additional forest inventories are necessary to capture the whole variability in terms of mangrove forest species composition and structure. The first ground truth was crucial to ensure robustness of visual interpretation and associated conclusions.

Table 1: Synthesis on the forest data. N_{sp}, $\widehat{SP}$, $\overline{DBH}, \widehat{H}$ correspond to the number of species inside the forest plot, the dominant species (in terms of basal area), mean diameter at breast height with deviation and dominant height, respectively. The acronyms taken for the species are: *Rm: Rhizophora mucronata, Ra: R. apiculata, Sa: Sonneratia alba, Aa: Avicennia alba, Am: Avicennia marina.*

Plot ID	**Area (m^2)**	N_{sp}	$\widehat{SP}$	$\overline{DBH}$ (cm)	$\widehat{H}$ (m)
PL1	100	1	Rm	3.6 ±0.85	2.5
PL2	400	6	Ra, Rm	7.6 ±2.3	13-13
PL3	400	4	Ra	8.8 ±3.2	16-20
PL4	625	4	Rm	6.9 ±1.6	12 - 14
NT1	2500	15	Sa, Aa	15.1 ±5.4	>20m
NR1	900	4	Am	NA	2

2.3 Remote sensing data

We acquired 4 Ikonos-2 and 3 Geoeye satellite images over the Perancak estuary with a time interval between 2001 and 2010 (Table 2). These optical images are provided with pixel resolution of 1 m and 0.5m in the panchromatic mode and 4 and 2 m in the multispectral modes, for Ikonos-2 and Geoeye, respectively.

Even if the images were already geo-registered on the local UTM grid, it was necessary to refine the registration of Ikonos images. For that, we used the image of the 1st October 2010 as a reference to which all other images were superimposed with an accuracy of 2 or 3 pixels (i.e. 1 to 1.5m).

Table 2: Image parameters including satellite name, date of image acquisition and angular configurations. θ_s, θ_v and $\phi_{s\text{-}v}$ are, respectively, the sun and viewing elevation angles and the sun-viewing azimuth.

Satellite	*Date*	θ_s (°)	θ_v (°)	$\phi_{s\text{-}v}$ (°)
IKONOS-2	02-Aug-01	37	40	-166
IKONOS-2	12-Oct-01	75	89	-114
IKONOS-2	09-Mar-02	67	84	-38
IKONOS-2	27-Jun-03	75	36	-47
GEOEYE	01-Oct-10	65	79	-80
GEOEYE	18-Oct-10	62	94	-225
GEOEYE	23-Oct-10	65	99	-89

Unfortunately, at the date of writing this paper, we did not receive a second dataset of 11 VHRS images ordered several months ago and that included Quickbird and Worldview-2 with acquisition dates ranging from September 2007 to March 2014.

3. IMAGE ANALYSIS

Visual interpretation of the above listed series of images was conducted in order to delineate various land cover types. First, we delineated the estuary zone i.e. the region of salinity influence where mangrove could develop. It was easily done since flooded forest on the river banks, rice fields and human infrastructures exhibit contrasted spectral and textural signature compared with mangroves and shrimp ponds responses. We then adjusted the area of study to the highest common part of the whole dataset of images, since some images did not cover the whole estuary zone. The extent of the whole estuary was about 7.5 km² and the extent of the area of study monitored through years was 7.1 km². We also visually delineated the river main, secondary and artificial channels. They accounted for nearly less than 1 km² with slight variations among images due to building of new water channels or appearance of new mangrove islands. Finally, the region of interest (ROI) was of about 6.1 km² (Figure 2).

Figure 2: Color composite pan-sharpened of a Geoye image acquired over the Perancak estuary the 1st October 2010. The shrimp pond layer is displayed. ROI is shown by masking outer region and river channels in black.

The second step was to delineate shrimp ponds for each date of acquisition. We started with the 1st October 2010 image (the reference) and delineated almost 1350 shrimp ponds. We replicated the work in other images after duplicating the reference GIS layer. For example, at a given data, we had to remove or add segments or polygons to take into account appearances or disappearances of pond dykes and mangrove. Even if it was a fastidious work, it was realized without too much ambiguity. Ponds dykes exhibit a bright signature compared with pond soils or mangroves. The area covered by shrimp ponds did not vary significantly between dates and stayed around 4.2 km² (~69% of the ROI). The average size of the shrimp ponds over the Perancak estuary was 0.3 ±0.2 ha. We also delineated areas of natural mangroves i.e. areas where mangrove can grow, are growing or are already developed. They correspond to areas where pond dykes remain absent or unobservable. Some of them consist of *Nypa* palm trees (planted or natural) formations which will be removed from the analysis in further work as we considered them not as mangroves but rather as associated vegetation. We found about 1.3 km² potentially available for mangrove extension (21 % of the ROI) and growth over all the images. The cumulated sum of all areas allocated to shrimp ponds and natural mangrove reached 5.5 km². The difference of about 0.6 km² between the ROI area and this latter land cover extent mainly corresponded to elongated areas along the river banks difficult to delineate. We will reduce this error margin after joining the polygons vertices.

The last step consisted in undertaking a recognition analysis of the different types of mangrove formations found inside ponds (Figure 3). The combined used of high spatial resolution for detection of individual trees and multispectral information especially in the infrared domain allowed discriminating areas 1) without vegetation, 2) with presence of individual trees or group of trees (discontinuous canopy) or 3) completely covered by vegetation (closed canopy). Moreover, we could detect row organization typical of plantations from random distribution of trees suggesting natural colonization. However, we did not try to apply this typology in natural mangrove areas since it was particularly difficult to state on the class in heterogeneous areas where dispersed trees can juxtapose closed canopy forest. This point will be discussed hereafter.

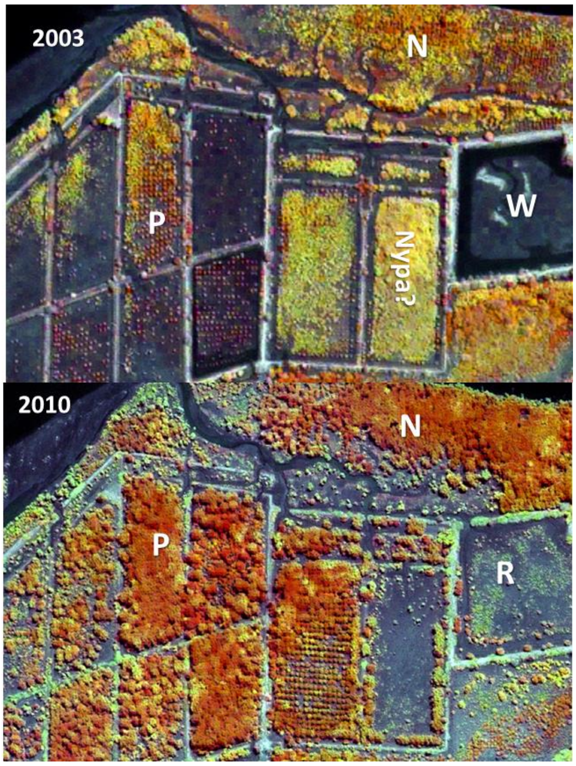

Figure 3: Illustration of the VHRS images potential for visual identification of mangrove types in 2003 (top) and 2010 (bottom). The letters P, N, W, R correspond to plantation, natural mangrove, bare soil and (natural) regeneration, respectively. Mangrove extent increases as number and size of mangrove trees do.

4. RESULTS

4.1 Changes in mangrove extent

Between 2001 and 2003, the area of shrimp ponds with mangrove was nearly constant and of about 0.5 km² i.e. 12% of the total area submitted to aquaculture. In 2010, it has doubled with about 1.1 km² of shrimp ponds occupied with mangroves (Figure 4).

From visual observation of natural areas through times, we also stated on the fact that mangrove was also extending outside shrimp ponds. Signs of extension were clearly visible not only around the central part of the estuary but also along river banks. Three mangrove islands appeared for an extent of about 150 hectares (Figure 4).

4.2 Evidences of mangrove growth

Over the 0.5 km² of shrimp ponds areas covered by mangroves between 2001 and 2003, we classified around 70% as natural regeneration or juvenile plant stages. The remaining 30% corresponded to well-developed mangrove with closed canopy. In 2010, the percentage of newly growing mangroves slightly increased to about 73%. We pointed out that about 29 hectares (28%) were planted between 2003 and 2010. In essence, all the plantations continue to grow and natural colonization and growth can be observed inside shrimp ponds even if the ponds are maintained (Figure 4).

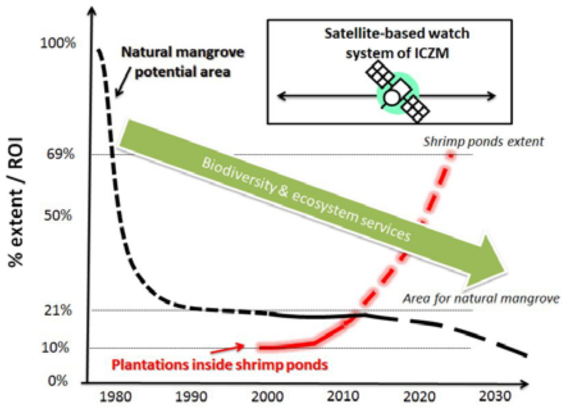

Figure 4: Challenges for Integrated Coastal Zone Management as revealed by the case of study of the Perancak estuary.

5. DISCUSSION

We need to go back on the field to control the realism of our distinction between plantation and natural areas especially at juvenile stages. The reception of the 2007-2009 images will also be crucial to understand and quantify past changes.

Visual interpretation of VHRS images is a fastidious but essential work to understand the changes occurring during last decade on mangrove coasts. It is the basis for ongoing works dedicated to the development of new remote sensing (and automatic) methods based for example on the analysis of changes in reflectance signatures to map changes in biodiversity or in texture properties to monitor mangrove growth.

Anyway, these preliminary results suggest a deep and extensive transformation of the Perancak estuary into a system where hydrology remains constrained by ponds dykes (even if shrimp farming is no more rentable) and where planted monocultures of *Rhizophora* species do not correspond to the native and dominant mangroves species.

6. CONCLUSIONS

For sure, the Perancak estuary has probably a history common to many coastal regions in Indonesia. What is original is the relative small and workable size of the estuary compared to other vast regions submitted to aquaculture like the Mahakam delta (Dutrieux et al. 2014).

However, we wish to draw attention that the greening of the estuary has probably nothing to do with the sustainability of ecosystem services since hydrology and expansion of biodiversity remain constrained by pond dykes.

The region appears thus very challenging for giving recommendations for sustainable integrated coastal zone management. And it cannot be done without the help of VHRS images and robust remote sensing methods. We are probably now at the beginnings of a satellite-based watch system of coastal management practices.

7. ACKNOWLEDGMENTS

This work is part of and funded by the INDESO project (2013-2017) led by Balitbang KP (Ministry of Marine Affairs and Fisheries, Indonesia). We thank Adewole Olagoke for his careful reading and correction on the English.

8. REFERENCES

Adams, J.B., & Gillespie, A.R. (2006). *Remote sensing of landscapes with spectral images. A physical modeling approach*: Cambridge University Press.

Asner, G.P., & Warner, A.S. (2003). Canopy shadow in IKONOS satellite observations of tropical forests and savannas. *Remote Sensing of Environment*, *87*, 521-533.

Dutrieux, E., Proisy, C., Fromard, F., Walcker, R., Ilman, M., Pawlowski, F., Ferdiansyah, H., & Ponthieux, O. (2014). Mangrove restoration in the vicinity of oil and gas facilities: lessons learnt from a large scale project. In, *2014 SPE Conference on Health, Safety, and Environment*. Long Beach, California, USA.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I., & Dahdouh-Guebas, F. (2007). A World Without Mangroves? *Science*, *317*, 41 – 42.

e-GEOS, 2014, Price list', http://www.e-geos.it/products/pdf/prices.pdf

Gastellu-Etchegorry, J.P., Martin, E., & Gascon, F. (2004). DART: a 3D model for simulating satellite images and studying surface radiation budget. *International Journal of Remote Sensing*, *25*, 73-96.

Ploton, P., Pelissier, R., Proisy, C., Flavenot, T., Barbier, N., Rai, S.N., & Couteron, P. (2012a). Assessing aboveground tropical forest biomass using Google Earth canopy images. *Ecological Applications*, *22*, 993-1003.

Proisy, C., Couteron, P., & Fromard, F. (2007). Predicting and mapping mangrove biomass from canopy grain analysis using Fourier-based textural ordination of IKONOS images. *Remote Sensing of Environment*, *109*, 379-392.

Zhou, J., Proisy, C., Descombes, X., le Maire, G., Nouvellon, Y., Stape, J.-L., Viennois, G., Zerubia, J., & Couteron, P. (2013). Mapping local density of young Eucalyptus plantations by individual tree detection in high spatial resolution satellite images. *Forest Ecology and Management, 301*, 129-141.