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Monitoring mangrove forests after aquaculture abandonment using time series of very high spatial resolution satellite images: A case study from the Perancak estuary, Bali, Indonesia

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A R T I C L E I N F O

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A B S T R A C T

Revegetation of abandoned aquaculture regions should be a priority for any integrated coastal zone management (ICZM). This paper examines the potential of a matchless time series of 20 very high spatial resolution (VHSR) optical satellite images acquired for mapping trends in the evolution of mangrove forests from 2001 to 2015 in an estuary fragmented into aquaculture ponds. Evolution of mangrove extent was quantified through robust multitemporal analysis based on supervised image classification. Results indicated that mangroves are expanding inside and outside ponds and over pond dykes. However, the yearly expansion rate of vegetation cover greatly varied between replanted ponds. Ground truthing showed that only *Rhizophora* species had been planted, whereas natural mangroves consist of *Avicennia* and *Sonneratia* species. In addition, the dense *Rhizophora* plantations present very low regeneration capabilities compared with natural mangroves. Time series of VHSR images provide comprehensive and intuitive level of information for the support of ICZM.

1. Introduction

The ever-growing appetite of the aquaculture industry for new land areas takes a heavy toll on mangrove ecosystems (Alongi, 2002; Giri et al., 2015; Richards and Friess, 2016; Valiela et al., 2001), to the extent that their future is not guaranteed (Duke et al., 2007; Friess et al., 2016). Stevenson et al. (1999) warned that “even if the shrimp industry were to achieve sustainability today, disused shrimp ponds would still remain, as would the poverty and the environmental problems they create”. Revegetation of disused ponds, over thousands of square kilometers, may partially offset mangrove losses resulting from the unsustainable legacy of aquaculture practices. This should be a priority of any ongoing integrated coastal zone management (ICZM) plan (Bosma et al., 2012; Carter et al., 2015).

In Indonesia, in the period between 1980 and 2003, characterized by weak governance of the aquaculture sector (Ilman et al., 2016), thousands of hectares of coastal zone were transformed into a mosaic of aquaculture ponds, of which about 250,000 ha have remained disused ever since (Gusmawati et al., 2017-in this issue). The scale of the conversion is particularly visible in large areas like the Mahakam delta covering about 75,000 km^2 in East Kalimantan, Borneo Island (Dutrieux et al., 2014). Anyone using Google Earth, with its high-resolution

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satellite images, can see and understand the scale of the impact of aquaculture on such coastal areas. In Indonesia alone, a further 600,000 ha of mangrove are projected for conversion into aquaculture ponds in the next 20 years (Ilman et al., 2016) because the life-span of intensive shrimp farming does not exceed 10 years (Boyd et al., 1998; Sathirathai, 1998). It is therefore quite frightening to consider the further enormous waste that will result. We know that mangroves provide a diversity of ecosystem services (Barbier et al., 2011) that are estimated to total about US$194,000 ha/year (Costanza et al., 2014) and their value is further increasing due to recognized roles in, for example, coastal protection (Barbier, 2016) and wastewater management (Bouchez et al. (2013). It is apparent that the cost–benefit equation of aquaculture development is biased and uncalibrated.

In areas converted by aquaculture, monitoring programs are necessary to document mangrove coast degradation (Ilman et al., 2016) as a prerequisite for any mangrove rehabilitation plan (Lewis, 2005) and toward restoration of good environmental conditions. The viability of existing replanting programs and evaluation of the potential for natural recolonization also require monitoring (Check, 2005; Primavera et al., 2016; Primavera and Esteban, 2008). Mangrove replanting programs need detailed justification (Duncan et al., 2016; Lewis, 2005, 2009; Samson and Rollon, 2008) and the "revival" of each disused pond should be carefully and individually implemented based on the testing of different mangrove management regimes for different ecosystem services (van Oudenhoven et al., 2015b). Different silvo-fishery models, all including mangroves on pond floors and/or pond walls, could be experimented with in the context of the local environment and then monitored (van Oudenhoven et al., 2015a).

Lewis et al. (2016) note that observational programs have to be established by "embedding plot and remote sensing monitoring." However, the extent, spatial complexity, and temporal variability of areas fragmented by brackish-water aquaculture (Fig. 1) cannot be fully explored by ground observation even when combined with remote sensing images of medium spatial resolution (MSR), i.e., with a pixel size > 5 m. Mapping of large-scale conversion of mangroves can be roughly approximated using methods based on MSR images (Rahman et al., 2013). Identification and accurate delineation of aquaculture ponds and mangrove areas cannot be achieved using MSR images, as illustrated in Fig. 1.

Spatial observations at fine scale delivered by aerial photographs or very high spatial resolution (VHSR) satellite images provide more interpretable information on ecosystems (Benfield et al., 2005; Kuenzer et al., 2011; Oliver et al., 2012; Rapinel et al., 2014). Such satellite imagery, with pixel sizes ranging from 30 cm to 4 m, is increasingly available at affordable prices since the launch of the Ikonos satellite in 2001. Pixel intensities are the result of light scattering mechanisms within areas of a few square meters and provide an intuitive perception of the forest structure organization (Proisy et al., 2007) and canopy gaps (Amir, 2012). Tree crowns can be identified and planting density estimated at early developmental stages as demonstrated by Zhou et al. (2013) for *Eucalyptus* plantations.

This study examines the combined potential of ground truth and a unique time series of VHSR satellite images in the development of a monitoring system that could improve mangrove management after aquaculture abandonment in Bali, Indonesia. We started the analysis of the Perancak estuary, Bali, Indonesia with little background knowledge on the present status of the estuarine processes and management, apart from studies of Sidik and Lovelock (2013) on CO_2 emission from shrimp ponds, Lovelock et al. (2015) on vulnerability of mangrove forests to sea level rise, and (Gusmawati et al., 2017-in this issue) on the monitoring of aquaculture pond activity. The study aims to assess mangrove status and evolutionary trends in terms of extent, type (planted vs. natural), forest structure, and species composition in an estuary extensively fragmented by conversion to aquaculture ponds. Visual expertise and supervised classification methods were employed in parallel to provide meaningful information for monitoring mangrove changes. A situation diagnosis for the study site is followed by discussion of the overall potential of temporal series of VHSR imagery for improving ICZM plans on mangrove coasts.

2. Material and methods

2.1. Site description

The study area is the Perancak estuary, located in west Bali (8°23′S, 114°37′E), Indonesia, which extends over 7.55 km^2 (Fig. 2). The average annual air temperature is 26.6 °C with the dry season lasting from May to September. Additional information on the Perancak estuary climatic environment is given in (Gusmawati et al., 2017-in this issue). The Perancak estuary receives runoff from two mountain

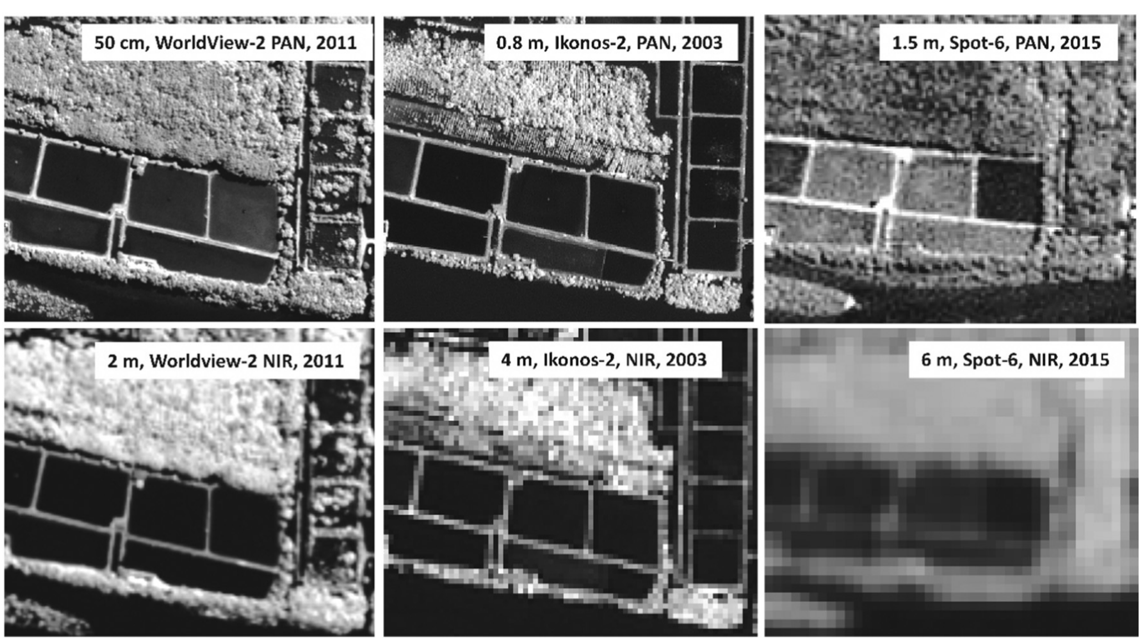

Fig. 1. Gray-scale image excerpts of 350 m × 250 m over disused and mangrove-vegetated ponds, Perancak estuary, Bali, Indonesia. Image pixel size, satellite platform, channel (PAN: panchromatic; NIR: near-infrared), and date of acquisition are indicated in the top right corner.