AMBIO (2010) 39:181–189
DOI 10.1007/s13280-010-0025-4

REPORT

Recent Change in the Extent of Mangroves in the Northern Gulf of Papua, Papua New Guinea

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Received: 7 March 2009 / Revised: 26 October 2009 / Accepted: 2 November 2009 / Published online: 28 April 2010

Abstract Existing at the interface of land and sea, in regions of low topographic relief, mangroves are likely to be some of the first ecosystems that undergo spatial modification due to sea-level rise. The mangrove ecosystems of the Gulf of Papua New Guinea are some of the largest and most pristine in the Asia–Pacific region; they have not been subject to clearance for crustacean farming nor suffered from land reclamation projects. This article establishes through analysis of a time series of aerial photography and satellite imagery from the period 1973–2007, that there have been substantial changes in the distribution of mangroves in this region. These changes include the seaward progradation of the Purari Delta and the regression of the Kikori Delta by an average of 43 m year^{-1} at its most seaward point. While these findings are likely to be continuations of long-term trends, it is probable that they can be explained by a variety of interacting factors including climate change, sea-level rise, subsistence in the northern Gulf of Papua and changes in sediment dynamics.

Keywords Mangroves · Sea-level change · Subsidence · Gulf of Papua · Kikori River · Purari River · Papua New Guinea

INTRODUCTION

Mangrove Distribution and Sea-Level Rise

Mangroves grow in the low-energy, sedimentary shorelines and intertidal zones of tropical and sub-tropical regions. Mangroves have physiological and morphological adaptations to the stresses of their intertidal habitat, of high salinity, low oxygen, low nutrient availability and substrate mobility. Estuarine shorelines are largely derived from the interaction between sediment supply and sea-level change (Ellison 2000). Mangrove systems accumulate peat and/or mud and this gives them the opportunity to adjust to a rising sea level. If sediment accretion rate equals the rate of relative sea-level rise, the inundation preferences of the species can be maintained; if it is lower, then mangrove systems are expected to migrate landward and/or be reduced in extent.

A significant sea-level rise is one of the major anticipated consequences of climate change. Estimates of global average sea-level rise are around 1–1.5 mm year^{-1} during the twentieth century. It is estimated that there has been an increase in this rate in more recent times—the average rate for the past 25 years being $\sim$2.1 mm year^{-1} (Church et al. 2001; Pugh et al. 2002, Church and White 2006). Global mean sea level is expected to rise by 18–76 cm by 2100 (IPCC 2007).

One likely local effect associated with rising sea level is likely to be accelerated coastal erosion (Stewart et al. 1990). Increased efficiency of wave erosion with a higher sea level causes the removal of sediment from the upper part of the tidal spectrum and deposition in the lower part (Bruun 1962). As the distribution of mangrove extent is closely controlled by sea-level at its seaward margin (Ellison 2000), its retreat may be an early indication of the effects of climate change. While mean sea level will probably be the most important factor influencing future distributions of mangroves, the result will vary dramatically depending on the local rate of sea-level rise and the availability of sediment to support the establishment of new mangroves (Field 1995). The greatest impact of

Electronic supplementary material The online version of this article (doi:10.1007/s13280-010-0025-4) contains supplementary material, which is available to authorized users.

sea-level rise on mangrove stands is likely to occur on coastlines of low relief with low sediment availability (Ellison 2000; Gilman et al. 2006). It is feasible, however, for sediment accumulation rates to occur at rates that exceed local sea-level rise as has been documented near the Amazon River mouth (Allison et al. 1995) and in regions of the Gulf of Papua (Walsh and Nittrouer 2004).

Areas of mangroves growing in deltaic and tidal coastal plains are likely, under conditions of rising sea level, to undergo erosion and loss from their seaward edges. Simultaneously, as saline conditions penetrate further inland, migration of inner margin mangroves will replace freshwater swamp and terrestrial communities. The limitations of such inland migration will be reached when the inland slope exceeds that of the seaward edge (Pernetta 1993). Simplistically, at this point, erosion of the seaward edge will outpace inland colonisation which will eventually cease and the mangrove system will be compressed becoming ultimately converted to a mangrove community typical of a drowned bedrock coast.

Mangroves in the Gulf of Papua New Guinea

The most recent land-cover study of Papua New Guinea estimated that the country possesses 592,900 ha of mangroves that are distributed along all of the coastal provinces (Shearman et al. 2009). In contrast to many parts of South-East Asia, there has not been any large scale clearance of mangroves in PNG for the creation of prawn farms or for land reclamation. The majority of the mangrove estate is only utilised by local people for subsistence use, firewood gathering and fishing, both of which are unlikely to have had any significant impact on mangrove area. The largest contiguous area of mangroves is the Purari and Kikori mangrove systems of the Gulf of Papua and covers an area of ~260,822 ha (Fig. 1). These mangroves exist within a river-dominated (Woodroffe 1992), deltaic environment consisting of ~110 depositional lobes greater than 500 ha, possessing the low slopes and wide inlets that are characteristic of low wave and high tidal energy environments.

Southern New Guinea (including West Papua and Papua New Guinea) possesses the highest mangrove diversity in the world (Ellison 1997b; Duke et al. 1998). Papua New Guinea has 33 species of mangrove, of which 31 have been recorded along the south coast (Ellison 1997b). Within the Kikori and Purari deltas, there is considerable zonation in mangrove species distribution (Floyd 1977; Cragg 1983; Paijmans 1976). At the seaward edge, mudbanks are predominantly colonised by *Avicennia* and *Sonneratia* species. Further inland, these give way to stands dominated by *Rhizophora* as well as mixed *Rhizophora* and *Bruguiera* forests. In tidal creeks to the north of this region where fresh and saline waters meet, forests are dominated by Nipa woodland (*Nypa fruiticans*). With better drainage, these forests then are replaced by lowland evergreen rainforest, dominated by an association of *Pometia* and *Octomeles*.

The Gulf of Papua receives 3.84 × 10^8 tons of sediment annually from three principal sediment suppliers, the Fly, Kikori and Purari Rivers (Milliman 1995; Walsh et al. 2004). The Kikori has a mean discharge of 1,500 m^3 s^{-1}, while the Purari has a mean discharge of 2,360 m^3 s^{-1} (Pickup 1983). Tides are semi-diurnal with a mesotidal

Fig. 1 The Gulf of Papua. The approximate landward extent of mangroves in the Gulf of Papua is demarcated in *red*

range of 2–2.5 m, up to 4 m in the mouth of the Fly (Alongi et al. 1992). This range is amplified to 5.1 m at the delta apex due to the funnel shape of the distributary channels (Wolanski and Eagle 1991). The majority of the Fly discharge is carried by prevailing currents to the north-east and along the shoreline of the Gulf Province (Robertson and Alongi 1995).

The Purari catchment covers an area of 3.46 million ha which reaches its highest point on Mt Wilhelm (4,509 m) in Chimbu Province. The catchment is 62% forested and has 1.3 million people living within it—of which ~97% are located in the highland valleys (National Statistical Office of PNG 2000; Shearman et al. 2009). The Kikori catchment covers ~1.93 million ha. The highest point within the catchment is 3,498 m on the border between Southern Highlands and Enga, to the south-west of Mt Kaijende. The catchment is 85% covered in primary forest. Of the 185,000 people in the Kikori catchment, the majority (94%) live above 1,000 m.

Rainfall at the district station of Kikori has an annual average of 5,773 mm, peaking in May (750 mm) and is driest in December (301 mm) (McAlpine et al. 1983). Rainfall at Ihu to the east of the delta and at Baimuru to the west is fairly evenly distributed throughout the year, with an annual average of 3,098 mm at Ihu and 3,455 mm at Baimuru (Cragg 1983; McAlpine et al. 1983). At Kerema, the mean annual maximum temperature during the 1970s was 29.6°C and the mean annual minimum was 22.7°C; the respective figures for Kikori were 29.9 and 21.8°C (McAlpine et al. 1983). The area experiences a monsoonal wind with south-easterlies predominating between May and October and north-westerlies between December and March. Strong afternoon sea breezes tend to occur in the delta.

The mangroves of the Gulf of Papua are considered to be important nursery areas for fish and prawns (Birkeland 1985; Robertson and Duke 1987; Robertson et al. 1991, 1998). They support a characteristic fish fauna in addition to forming a marginal habitat for both marine and riverine species. Haines (1979) found that 63 estuarine, 59 marine and 15 riverine fish species are found as adults in the Purari and Kikori mangrove areas. The prawn fishery in the Gulf was estimated to be worth US$1.8 million in 2004, and it is likely that much of its productivity is reliant upon the maintenance of the area and health of the mangrove systems (Kompas and Kuk 2008).

Changes in Mangrove Distribution in the Northern Gulf of Papua

An estimate of the potential for sea-level change to affect mangroves in the region was first made by Pernetta and Osborne (1990) who concluded that in the case of the 'actively prograding' Purari Delta, significant compression of mangrove zonation was unlikely to occur even under extreme scenarios of change. Pernetta (1993) estimated on the basis of Thom and Wright's (1983) geomorphological data that in the Purari delta, vertical accretion rates of 0.66–1 mm year^{-1} were occurring, with maximum rates of 1.5 mm year^{-1}. He suggested that the Purari is capable of maintaining its present form under current rates of relative sea-level change. However, Pernetta (1993) also predicted that if rainfall and erosion rates in the Purari remain the same and if current rates of crustal downwarping and sediment compression also remained constant, then under conditions of rising sea level, the rate of progradation of the Purari delta may be expected to decrease. This possible reduction in the rate of progradation of the Purari may also have an impact on the Kikori Delta through a reduction in sediment supply. However, given that substantial quantities of sediment are also entering this system from both the Fly and Kikori rivers, this is likely to have been an oversimplification of a very complex system. Pernetta and Osborne (1990) also expected the mangroves of the Kikori Delta to undergo substantial alteration in their patterns of zonation since the local topography steepens quickly to the north of current mangrove distribution.

Regression of the seaward edge of the Kikori mangrove system has already been recorded (Floyd 1977; Liem and Haines 1977; Cragg 1983; Thom and Wright 1983). Floyd (1977) estimated that at one site on the south of Uramu Island recession was occurring at a rate of 20 m year^{-1}. More recently, Walsh and Nittrouer (2004) compared 1973 aerial photography with Landsat 7 imagery acquired in 2000 at six sites in the Gulf of Papua. Two of these sites were within the Kikori-Purari delta and showed that simultaneous erosion and accretion was occurring in different regions of the delta. They estimated erosion on the coastline of the seaward islands was occurring at ~7.4 m year^{-1} and was an indication of a recent increase in wave attack or local sea-level rise or a combination of both. In the vicinity of the Wame river, at a site within the delta, infilling was occurring along many of the main channels at 3.7–7.4 m year^{-1}. Using steady-state ^{210}Pb profiles, maximum sediment accumulation rates were found to occur in mid-tidal areas at 4.4 cm year^{-1}—a rate far greater than predicted by previous studies. They concluded that the Gulf of Papua mangrove forests may be a significant sediment sink and that as the observed high rates of sedimentation far exceed local sea level rise, it is probable that mangroves can maintain their area within the region.

Measurement of Changes to Mangrove Margins

The measurement of change in the extent and distribution of mangroves is a relatively new field of study. It has been undertaken on Bermuda, where over the last century it was found that the largest mangrove area had lost 26% of its area due to retreat of its seaward edge (Ellison 1993, 1997a). This was deemed to be result of sea-level rising at a rate faster than peat accretion and was determined via the comparison of sea-level measurements and sediment cores. The landward migration of mangroves has been studied in American Samoa through the comparison of co-registered aerial photographs and high-resolution Ikonos and Quickbird imagery (Gilman et al. 2007). The seaward margin was defined as the unbroken canopy edge, thus excluding opportunistic, pioneer mangrove vegetation. There it was observed that landward migration of the seaward edge of mangroves occurred at a rate of 25–72 mm year^{-1} over a 40-year period. The retreat of mangrove zones due to relative sea-level change associated with techtonic subsistence over the Holocene has also been demonstrated using pollen records derived from sediment cores obtained in the extensive coastal swamps of Timika region of West Papua (Indonesia) (Ellison 1998, 2005). Ellison (2005) suggested that while low island mangroves are likely to be the most sensitive to sea-level rise, it is likely that continental margin mangroves will also suffer disruption and retreat particularly in deltas of low relief. The use of aerial photography in the generation of baseline maps of large areas of mangroves was also demonstrated by Lucas et al. (2002) in the Northern Territory of Australia where substantial movements in mangrove distributions over the 41-year study period were documented. While both retreat and progradation were found to occur in different areas of the West Alligator River region, they showed the landward extension of mangrove-flanked creeks occurring at rates of 40 m year^{-1}, perhaps in response to changing saline conditions.

A Spatial Assessment of Mangrove Progradation and Regression in the Northern Gulf of Papua

This study aimed to build upon the findings of Walsh and Nittrouer (2004) by undertaking a regional estimate of decadal change in mangrove area in the northern Gulf of Papua, and where possible, to determine when specifically these changes had occurred.

The study employed a GIS-based comparison of 1973 mangrove extent derived from aerial photography with 2002 mangrove extent derived from Landsat ETM+ imagery acquired during cloud-free conditions in 2002. Within the Kikori Delta, change in mangrove area was expected to occur the fastest at its most southerly point, Cape Blackwood of Ibibubari Island, due to its proximity to the deepest water and its lowest slope (Farr et al. 2007; unpublished Oilsearch bathymetric data). At this location, additional Landsat TM data from 1978, 1988 and 2007 were obtained and analysed to enable the examination of the steadiness of the regression.

MATERIALS AND METHODS

Creation of 1973 Mangrove Map

The '1973' mangrove map was digitized from six colour separations of the Australian Army (T601) 1:100,000 scale vegetation maps. These maps were created by the Australian Army using visual classification and manual delineation of vegetation class boundaries of vegetation types discernible in very high-resolution (1–2 m) stereo aerial photography taken between 1973 and 1974 (Coulthard-Clark 2000). The vegetation classes used in this exercise were tropical rainforest, mangroves, scrub, grassland and water. Within the change analysis, only the digitised boundaries between sea and mangroves were used. The average horizontal accuracy of these boundaries was estimated to be ±25 m (Shearman et al. 2009). It was not feasible to use the 1973 boundaries between rainforest and mangroves as a basis of change detection essentially due to inaccuracies in establishing a boundary in a zone of vegetation transition.

Creation of 2002 Land-Cover Map

In order to create a new mangrove map of the Gulf of Papua, three multi-band images from the Landsat 7 Enhanced Thematic Mapper (ETM+) (path:row 98:65 and 97:65) were acquired. The location and date of capture of each image used is shown in Fig. 1S in the Online Supplementary Materials (OSM). Each satellite image was orthorectified using 10–15 ground control points derived from the 1973 1:100,000 scale vegetation maps (Coulthard-Clark 2000) and a 90-m Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM; Farr et al. 2007). The use of the SRTM data in the rectification process is useful in reducing positional error in the PNG imagery, especially in images that cover a range of topographic conditions. The average Root Mean Square Error (RMSE) for the orthorectified imagery was 25–30 m. All images were georeferenced to the AGD84 UTM55 projection and datum.

Classification was based on the product of a Tasseled Cap and Brovey transformation (Kauth and Thomas 1976) applied to the 2002 Landsat ETM+ imagery. The object recognition software 'eCognition' (Definiens 2000) was used to automatically segment the satellite imagery into spatially continuous and spectrally homogeneous regions consistent with land-cover features, and to vectorize them into individual polygons. Each polygon was classified using expert visual interpretation (Lu et al. 2004) with full methods given in Shearman et al. (2009). Mangroves can be relatively easily distinguished from other vegetation types using high-resolution Landsat ETM+ imagery due to their distinct spectral signature in the near-infrared bands (Rasolofoharinoro et al. 1998). Decision rules used to define land-cover classes are outlined in Table 1 in the OSM and followed the classification system of Paijmans (1976). These were tropical rainforest, swamp forest, mangroves, scrub, herbaceous swamp, non-vegetation and water. The delineation of the boundary between the complex of species categorised as 'mangroves' and the closed canopy lowland rainforest is an approximation but largely follows the northern limit of Nipa Palm distribution. This inclusion follows the approach of Paijmans (1976) and Hammermaster and Saunders (1995) who included Nipa stands within their 'mangrove' classification. Small areas of rainforest may be included within the mangrove distribution, and concurrently, small areas of mangroves are likely to have been excluded.

Change Detection

The 1973 land-cover map was superimposed onto the 2002 map using a geographic information system (MapInfo 7.3), and areas of mangrove loss and gain that have occurred since 1973 were identified and automatically vectorized via a process of 'clipping' one map with another. It was not possible to measure change in the landward boundaries of mangrove extent due to unreliability in the boundary between mangrove and forest in the 1973 classification. Further, in this region, mangroves generally intergrade with swamp forest, before transitioning to rainforest (Paijmans 1976). If there had been landward migration of mangrove species, it would likely occur within this transition zone, hence would not be apparent in the comparison with the 1973 data.

The positional accuracy of the imagery used in the change assessment meant that boundary changes >50–60 m could be detected (Shearman et al. 2009). In order to reduce the impact of this error, all polygons <1 ha in area were removed from the final gain and loss estimates. While many of these areas may have represented real change, they could also have occurred as a result of boundary error.

Assessment of Change at Cape Blackwood

Subsets of images from 1978 (MSS 104:65 17/04/1978), 1988 (TM 98:65, 31/10/1988), 2002 (ETM+ 98:65, 01/12/2002) and 2007 (TM 98:65, 06/06/2007) were co-rectified to the 2002 imagery with an average RMSE of 25 m. Ground control points were generally selected from features that were unlikely to have changed significantly such as creek-junctions within mangrove regions. The seaward margin of mangrove extent was then manually digitised in each image within a GIS system (MapInfo 7.8), and the distance between these vectors measured from the furthest south-easterly point of Cape Blackwood. Manual digitisation was employed due to the small distance that needed to be covered relative to that of the regional change analysis. The maximum error between any two image pairs was expected to be ~50 m (twice the RMSE).

RESULTS

Assuming no landward migration, it was found that there was a net loss in the total area of mangroves of 992 ha over the 30-year period. There were, however, substantial gross changes between 1973 and 2002—an estimated gross loss of 7,191 ha and a gross gain of 6,199 ha.

In total, only 30 ha of loss and 13 ha of gain occurred within regions <1 ha in size, suggesting that the influence of boundary error is minimal. Further, if there was a systematic error associated with the technique, it would be likely that loss or gain would be distributed evenly around each coastline. Instead, as can be seen in Fig. 2, both are distributed asymmetrically.

Within the Kikori Delta, there has been regression of all the seaward margins of the delta islands of between 350 and 1,300 m with an average of 560 m ($n = 12$). The maximum loss occurred at the tip of Cape Blackwood. There, mangroves have receded by ~1.25 ± 0.05 km over the 30-year period (1973–2002)—an average of 42 ± 1.7 m year^{-1}. Overall, the further south-east of the seaward extremity of the lobe, the greater was the distance of regression. The majority of progradation occurred at the mouth of the Purari River (1,435 ha) which extended a further 1,900 m to the south and on the western banks of Bevan Sound (865 ha). Smaller areas of sedimentation and colonisation (<200 m in extension of land margin) have occurred at the northerly, landward edges of most lobes of the delta. These results suggest that the lobes of the Kikori Delta may be migrating to the north, but are overall, probably contracting due to losses at their southern extremities.

While these gains and losses regionally negate each other to a large extent, this is an oversimplification of their implications. The losses within the Kikori Delta were losses of intact mangrove forests dominated by large trees, many decades in age. In contrast, the gains in mangrove area, mostly at the mouth of the Purari River, are a complex of mostly early successional stage vegetation.

Comparison of the extent of mangroves at Cape Blackwood using the time series of imagery from 1973 to 2007 suggests that their loss has not occurred during a single event, but rather has occurred relatively consistently over the 34-year interval (Fig. 3). During this period, mangroves have receded up to 1.43 ± 0.05 km from their most southerly point. The greatest rate of change occurred

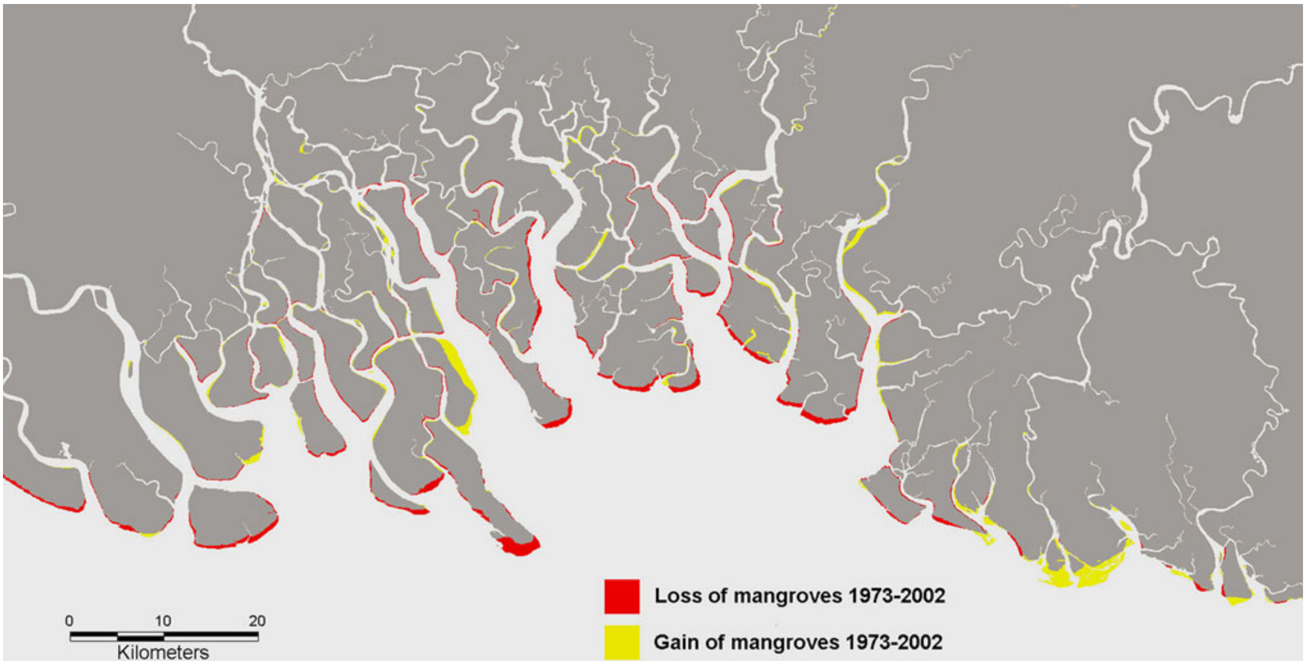

Fig. 2 The distribution of progradation and regression in the mangroves in the Gulf of Papua over the period 1973–2002

in the decade between 1978 and 1988 during which an average regression of 65 ± 1.5 m year^{-1} was recorded.

In contrast, the Purari Delta has continued to extend its seaward margin by an average distance of 63 ± 1.7 m year^{-1}, over the 30-year period.

DISCUSSION AND CONCLUDING REMARKS

The results of this study show that a small but appreciable net loss in mangrove area has occurred within the study period. There has, however, been substantial regression in the extent of mangroves at the seaward margins of the Kikori delta that has been offset in area terms by infilling of channels within the delta and by the progradation of Purari delta. While Walsh and Nittrouer (2004) suggested that these mangrove areas are keeping pace with relative sea-level rise, our findings differ probably because we examined change over the whole coastline, rather than at discrete locations.

The continuation of the loss of mangroves at the seaward margins in the Kikori Delta is likely to be the result of several factors including interactions between sea-level rise, wave attack, storms and sediment supply. It is possible but unlikely that there has been a reduction in sediment induction into the Kikori and Purari Rivers, or that less of the existing sediment from the Purari River is available for transport to and deposition within the Kikori Delta. There is, however, no reason to suggest a decrease in sediment in the water flows in either catchment—indeed it is more probable that the opposite is true (see Fig. 2S in the OSM, a recent aerial photograph of the mouth of the Purari showing a heavy sediment loading). Deforestation has increased over the study period, particularly in the upper Purari Catchment, while large areas of the Kikori Catchment have been subject to the erosive activities of the logging industry (Shearman et al. 2009). The long-proposed Purari Dam near the junction of Wabo Creek has yet to occur. If any change was to have occurred in the sediment budget of either river system, it almost certainly would have been an increase. Thus, net loss of mangrove extent is unlikely to be caused by changes in sediment supply alone. Similarly, there is no reason to suspect a reduction in sediment supply to the Gulf of Papua from the Fly River, where it is believed that the islands are in equilibrium with the current tidal regime and relative sea-level rise (Walsh and Nittrouer 2004).

It is possible that tectonic subsidence has contributed to the net loss of mangroves in the Gulf of Papua. Tectonic subsidence, the lowering of the earth's surface due to the interplay of sediment deposition and crustal warping, has been demonstrated to have occurred during the Cenozoic in the Gulf of Papua (Thom and Wright 1983; Wang and Stein 1992), and over the Holocene in the partially analogous Timika region of West Papua (Ellison 2005). Over long time periods, tectonic subsistence relative to sea level will result in the movement of facies that were deposited in mangrove systems to a depth below which mangroves can no longer survive. Given the low slope of this mangrove region, it is possible that tectonic subsidence is contributing significantly to the observed regression.

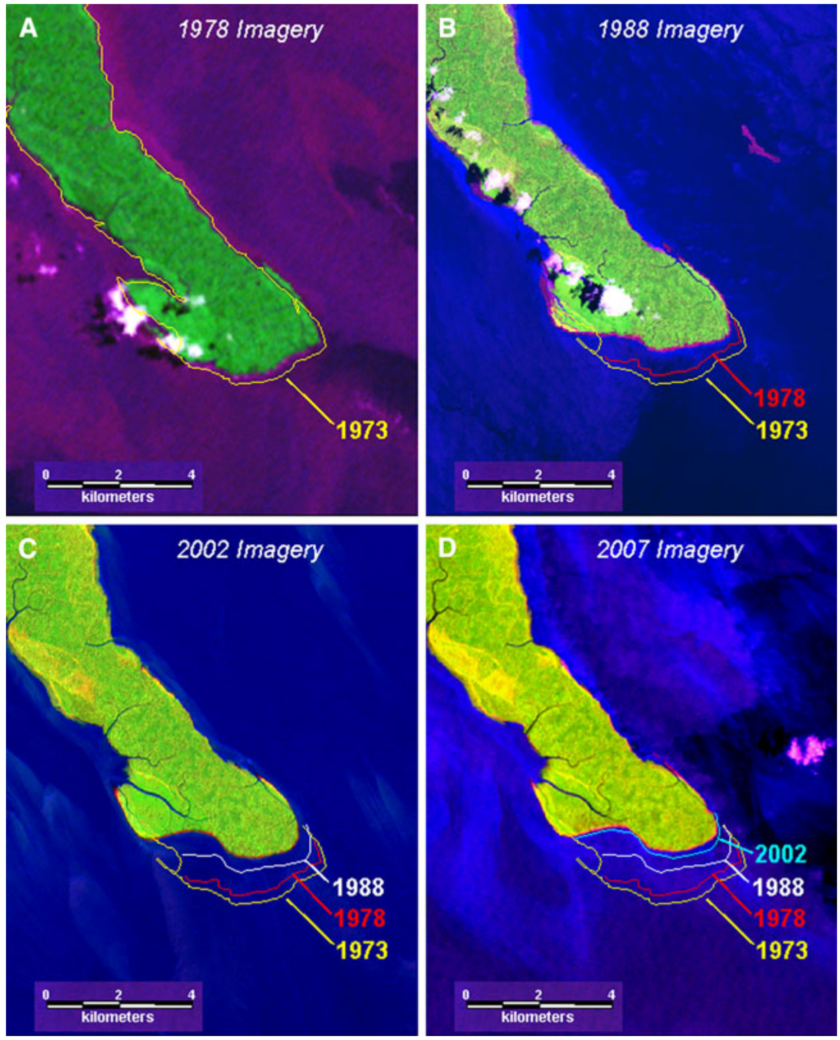

Fig. 3 Images **a–d** show change in the seaward extent of Cape Blackwood from 1973 to 2007

In addition to tectonic subsidence, the net loss of mangroves detected in the Gulf of Papua could be due to sea-level rise. Estimates of global average sea-level rise are around 1–1.5 mm year^{-1} during the twentieth century (IPCC 2007). Loss of mangrove extent, especially at the seaward edge, such as that detected by the present study in the Gulf of Papua, is the expected outcome of sea level rising at a faster rate than sediment accretion. However, it is also possible that the loss of mangroves occurred during several storm events or alternatively through changes in wave climate related to climate change, such as wind forcing or storm frequency, or to a combination of all of these factors.

In summary, the net loss of mangrove extent detected in our study could be due to a combination of tectonic subsidence, sea level rise and changes in sediment supply, although changes in sediment supply alone is unlikely to account for the losses. The trend detected by this study is likely to be accelerated if the predictions of sea level rise over the coming decades do eventuate (IPCC 2007). Conducting a similar regional change analysis in other Global mangrove systems that are subject to different tectonic and sediment dynamics may strengthen conclusions about the role of sea level rise versus that of local factors.

Acknowledgements The author would like to thank J. Ash, J. Bryan, J. Luick and J. Chappell for their insightful comments and Oilsearch Pty Ltd for providing access to their bathymetric data. I would also like to thank the two reviewers for their improvements in the manuscript.

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