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Author

Eslami-Andargoli, L, Dale, Per, Sipe, N, Chaseling, J

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Mangrove expansion and rainfall patterns in Moreton Bay, southeast Queensland, Australia

L Eslami- Andargoli,[a] PER Dale [a b], N Sipe [a c], J Chaseling [a]

[a] *Griffith School of Environment, Griffith University, Nathan Campus, Nathan Queensland 4111, Australia*
[b] *Centre for Innovative Conservation Strategies*
[c] *Urban Research Program*

Abstract

Changes in rainfall pattern have been suggested as a mechanism for the landward incursion of mangrove into salt marsh. The aim of the research was to assess the relationship between rainfall patterns and the spatial distribution of mangrove forests at study sites in Moreton Bay, southeast Queensland, Australia, over a 32-year period from 1972 to 2004. To identify periods of relatively consistent rainfall patterns points at which rainfall patterns changed (change-points) were identified using the non-parametric Pettitt-Mann-Whitney-Statistic and the cumulative sum technique. The change-points were then used to define the temporal periods over which changes to mangrove area were assessed. Both mangrove and salt marsh area were measured by digitizing aerial photographs acquired in 1972, 1990 (the year with the most significant change-point), and 2004.The rates of change in mangrove area pre-1990 (a wetter period) and post-1990 (a drier period) were estimated. A significant positive relationship was demonstrated between rainfall variables and landward mangrove expansion, but not for seaward expansion. We concluded that rainfall variability is one of the principal factors influencing the rate of upslope encroachment of mangrove. However, the rate of expansion may vary from site to site due to site-specific geomorphological and hydrological characteristics and the level of disturbance in the catchment.

Keywords: mangroves; salt marshes; intertidal environment; rainfall; change-point; Australia, Moreton Bay

1 Introduction

Mangroves are one of the key components of the world's subtropics and tropics inter-tidal zone landscape. The distribution, structure and function of mangrove forests are controlled by environmental factors with varying impacts over different spatial and temporal scales (Duke et al., 1998). At the global scale, temperature limits the distribution of mangroves forest (Alongi, 2002). However at the regional scale, mangrove extent and characteristics may be determined by the cumulative and complex interactions between landscape position, rainfall, hydrology, sea level, sediment dynamics, subsidence, storm driven processes and disturbance by pest or predator (Alongi, 2002, 2008; Cahoon et al., 2003; Field, 1995; Furukawa and Wolanski, 1996; Furukawa et al., 1997; Gilman et al., 2007; Lara and Cohen, 2006; Paling et al., 2008; Smith et al., 1994; Whelan et al., 2005;Woodroffe, 1990, 1995). Changes in any of these factors is likely to affect the spatial patterns and community structure of mangroves.

Mangrove forests are likely to be affected by factors associated with climate change, such as changes in rainfall, temperature, atmospheric CO_2 concentrations, sea-level, high water events, cyclones and storms, and ocean circulation patterns (Gilman et al., 2008). Although a rise in mean sea levels may be the most important aspect affecting the spatial distribution of mangroves in the long term (Field, 1995; Gilman, 2004), changes in regional rainfall and catchment runoff may be more significant in the short term (Snedaker, 1995).

Globally, precipitation over land has increased by about 2% since the start of the 20th century, however, this increase has not been either spatially or temporally uniform (Houghton et al., 2001). Changes in rainfall patterns are expected to affect mangrove growth and its spatial distribution (Field, 1995; Ellison, 2000; Gilman et al., 2008). Higher rainfall and runoff would result in reduced salinity, decreased exposure to sulphates and increased sediments and nutrients supply in coastal areas. These factors can lead to increases in diversity, growth rates and productivity in mangrove forests as well as maintaining the sediment elevations by increasing peat production (Snedaker, 1995; Ellison, 2000; Gilman et al., 2007). Lower rainfall will increase salinity, which will in turn decrease productivity, diversity, growth and seedling survival, thus altering competition between mangrove species. This process may result in reductions in mangrove area with possible increases in the extent of salt flats (Lovelock and Ellison, 2007; Gilman et al., 2008).

Changing patterns of mangrove distribution in eastern Australia are commonly associated with upslope encroachment into the salt marsh, although there may also be seaward expansion due to increased runoff and associated sedimentation (Jupiter et al., 2007). Increase in rainfall has been suggested by McTainsh et al. (1986), Saintilan and Williams (1999), and Saintilan and Wilton (2001) as a mechanism for mangrove incursion into salt marsh. Salt marsh compaction during drought conditions (van Wijnen and Bakker, 2001) may also assist landward mangrove expansion (Rogers et al., 2006). This pattern has also been observed in other parts of the world. For example, McKee (2004) suggested that, in Louisiana, USA, black mangroves may colonise salt marsh, when cordgrass is stressed (e.g. by extreme droughts). Gilman et al. (2008) noted that although rainfall appears to be related to mangrove dynamics, research has only been conducted in a few areas over short timeframes. This paper addresses the issue and adds to the body of research on the relationship between rainfall and mangrove spatial changes by examining multiple sites over longer timeframes.

Monitoring mangrove spatial changes has been limited by the lack of spatial data at a relevant scale and the difficulty of access limiting field survey. Satellite images have a synoptic capability but have not been extensively used for mapping mangrove due to the limited spectral and spatial resolution of conventional imagery (Wang et al. 2004). Such problems may be overcome by the increased spectral resolution of hyper spectral sensors, but the use of this technology is still not cost-effective (D'Iorio et al., 2007) and they are not available over a long enough time frame for long term studies. Thus the use of aerial photos is essential for time series analysis over several decades at the plant community level (Byrd et al., 2004). Due to the advantages offered by the spatial and temporal scale of aerial photos, they are still widely used for mapping mangrove ecosystems (D'Iorio et al., 2007) and provide the most cost-effective approach to accurate habitat mapping in fine scale studies (Manson et al., 2001).

The aim of this research is to investigate the relationship between rainfall patterns and to use historic aerial photographs to identify the spatial distribution of mangrove forests, at multiple sites within a single region, in northern Moreton Bay, Queensland, Australia, over a 32-year period from 1972 to 2004. The specific objectives were to:

1. Analyse rainfall patterns in the study area between 1972 and 2004 to detect any significant change in the pattern (change-points) thereby identifying periods of relatively consistent rainfall patterns;

2. Identify the spatial distribution of mangroves and calculate rates of change; and

3. Identify the relationship between rainfall patterns and mangrove distribution.

2 Methods

2.1 Study area

The study sites encompassed ten locations distributed along 42km of the coastline of northern Moreton Bay (27 °20′ S, 153° 10′ E) between Cabbage Tree Creek and Glass House Creek, south east Queensland, Australia (Fig. 1). Mangroves and salt marshes are the typical inter-tidal vegetation found along Moreton Bay. There are eight species of mangroves present in the bay, covering about 15,000 hectares of inter-tidal wetlands (Manson et al., 2003), and dominated by *Avicennia marina* which comprises 75% of the community (Dowling and Stephens, 2001). Moreton Bay has a subtropical climate and is subject to the effects of El Niño-Southern Oscillation (ENSO), with rainfall and streamflow patterns associated with the different phases of ENSO. Eastern Australia experiences higher rainfall and streamflow, during the cool La Niño phase of ENSO but reduced streamflow during the drier, hotter conditions that prevail during El Niño (Verdon et al., 2004).

All study sites contain substantial stands of mangroves and other wetland vegetation (salt marsh/saltpan), and are classed as ‘middle estuary’ sites, whereby water extends throughout the majority of the estuary with a moderate amount of water movement from fresh water inflows or tidal exchanges (Environmental Protection Agency, 2007). To identify the relationship between rainfall patterns and mangrove distribution, study sites were selected in areas not directly impacted by human development. Also, they were chosen approximately near to each other in order to minimise the variation in rainfall. The study sites are in the catchments of Cabbage Tree Creek, Bald Hills Creek, Pine River, Hays Inlet, Little Burpengary Creek, Burpengary Creek, Caboolture River, Lagoon Creek, Ningi Creek and Glass House Creek.

2.2 Rainfall pattern analysis

Daily precipitation data between 1972 and 2004 for the study sites and their catchments were obtained from the comprehensive archive of Australian rainfall and climate data produced by the Australian Bureau of Meteorology (BoM). The database has been constructed using observational data collected by BoM, and spatial interpolation algorithms to produce interpolated surfaces on a regular 0.05 grid to provide data at locations where there is no direct observational data, or for a specific time period, when observational records do not span the entire period of interest (Jeffrey et al., 2001). For analysis, the following rainfall indices in the periods before and after change occurred were derived: mean annual rainfall; median annual rainfall; and the proportions of rainy days with ≥ 2, 10 and 25 (mm). The number of rainy days was converted to the proportion of rainy days because, after the change-point was identified, the two time periods had different lengths.

To identify the year(s) of any abrupt changes (change-points) in the pattern of annual rainfall between 1972 and 2004, we employed the method of Hoppe and Kiely (1999) which approximates the non-parametric Pettitt-Mann-Whitney-Test and is robust for continuous data. This test is a version of the non-parametric Mann-Whitney two-sample test (Pettitt, 1979) and considers the time series as two samples, the period before a change and the period after.

The probability for a change-point in a time series was calculated, for each site as well as its catchment, to identify the year with the most significant change-point. To confirm the change-points, detected by the Pettitt-Mann-Whitney-Test, the ‘cumulative sum technique’ was also used, which is a method to detect changes in the mean value of a time series dataset (McGilchrist and Woodyer 1975; Page, 1955). Once a change-point was identified, confirmation of the change was obtained by comparing the means of each variable before and after the identified year, using a *t*-test. As well as detecting change-points, the relationships between mangrove changes and the rainfall indices were determined for all sites using simple linear regression.

2.3 Analysis of aerial photos to identify mangrove spatial change

Aerial photos for 1972, 1990 (the most significant change-point identified in terms of rainfall patterns), and 2004 with scales of approximately 1:12000 and 1:24000 were scanned and imported into ArcGIS (ESRI Inc. version 9.2) as digital images at a resolution of 500 and 1,000 dots per inch, respectively. All digital images were registered to the GDA 94, MGA 56 map system using at least five ground control points, and usually 15-20, and were resampled by applying the nearest neighbour function. The georeferenced images had RMS error of less than 0.5 pixel which was considered satisfactory. Visual inspection also confirmed that the overlaid images matched each other well.

The area of each site for the three different dates was fixed using a standardized template with exact coordinates. The boundaries of vegetation types (mangrove, salt marsh and terrestrial) as well as open water were delineated by on-screen digitizing to produce a geo-database of vegetation at each site for 1972, 1990 and 2004. Field validation together with the Southeast Queensland Coastal Wetland Map (Dowling and Stephens, 2001) were used to validate the digital maps. After calculating the vegetation unit area, changes in mangrove extent between 1972 and 2004 were analyzed for both landward and seaward changes using ArcGIS Intersect function. Rates of change in mangrove extent for both periods (pre- and post-1990) were estimated as a percentage of annual increase (Rogers et al., 2006) in the 1972-1990 and 1990-2004 periods. The means of mangrove variables for the two series identified by the rainfall change-point were then compared using a *t*-test.

3 Results

3.1 Rainfall patterns

Both methods of detecting change-points found 1990 to be the most significant year across all study sites. As an example, the cumulative sum and the probability for the change-point using the Pettitt-Mann-Whitney-Test for Bald Hill Creek are given in Fig 2. While we accept 1990 as the change-point year, around that time there were other highly significant years. This indicated a strong change over a few years rather than an abrupt change at a single year. Also, in Fig 2, an apparent high CUSUM in 1976 was not significant because the series length preceding the time point was very short.

Until and including 1990 was a period of relatively high rainfall. From 1991 onwards, the mean annual rainfall across all sites decreased from 1330 mm (sd = 96.77) to 1106 mm (sd = 99.79), a significant decrease of nearly 17% ($p < 0.0001$). There were also statistically significant differences between the two periods (pre- and post-1990) both for median rainfall and proportion of rainy days with ≥ 2, 10, and 25mm, across all sites ($p < 0.0001$). As an example Table 1 shows the pattern for Bald Hills Creek.

3.2 Aerial photo analysis

A general but variable trend of mangrove increases between 1972 and 2004 was observed at all study sites. For example, it varied between 0.17 percent per year in Hays Inlet to 1.83 percent per year in Glass Mountain Creek. Table 2 shows the results for each time period, before and after 1990. The rate of increase was higher in the first, wetter period (pre-1990). The rate of change in mangrove extent before 1990 ranged from increases of 0.38 percent per year in Lagoon Creek to 2.15 percent per year in Glass Mountain Creek. However after 1990 the change in the area of mangrove fluctuated between a 0.38 percent per year decrease in Hays Inlet to a 1.02 percent per year increase in Glass Mountain Creek (see Table 2). There was a statistically significant difference between the pre- and post-1990 means of total mangrove expansion rate (means of 1.12 and 0.45, p = 0.001). It was noted also that large gaps appeared in the mangroves in the second period at some sites (Hay's Inlet, Little Burpengary and Cabbage Tree Creeks). Visual inspection of aerial photographs showed that the gaps had developed as bare mud and were not associated with clearing or other direct anthropogenic activity. There was however no significant difference between the seaward mangrove change pre- and post-1990 (p = 0.563) as exemplified for a typical site in Fig 3.

3.3 Statistical analysis: relationship between patterns of rainfall and of mangrove expansion

The results of the linear regression show there was a significant relationship between the rate of mangrove increase and all rainfall indices at sites and at their catchments (Table 3).There was a significant positive relationship between the rate of change in mangrove area and the median catchment rainfall (p = 0.0004; Fig. 4.). The rate of mangrove increase was also positively related to the proportion of rainy days with precipitation ≥ 10 mm in wetlands (R^2 = 0.3950, p = 0.0030) and the proportion of rainy days with precipitation ≥ 25 mm in the catchments (R^2 = 0.3846, p = 0.0035). The rate of seaward mangrove area change did not have a significant relationship with median catchment rainfall (R^2 = 0.0274, p = 0.4852) or with the proportion of rainy days with precipitation ≥ 10 mm in wetlands (R^2 = 0.0172, p = 0.5812) or ≥ 25 mm in the catchments (R^2 = 0.0058, p = 0.7488). The rate of mangrove area change was negatively related to the salt marsh area change (R^2 = 591, p = 0.0001; Fig. 5.).

4 Discussion

4.1 Changes in rainfall patterns and corresponding changes in mangrove distribution

One of the strengths of this study is that the period over which the rate of mangrove expansion was calculated was based on the intrinsic changes in rainfall patterns as indicated by the change-point analysis, rather than using an arbitrary time scale. Other research (e.g. Wilton, 2002) using simple decadal time frames, did not identify a relationship between mangrove expansion and rainfall. That there was a change-point in rainfall around 1990 is supported by the fact that the 1990s have been dry over most of Queensland, due to a long-running 1991-1995 El Nino-related drought (Bureau of Meteorology, 2000).

Although mangrove distribution at all sites appeared to be increasing over the period, the rate of mangrove increase between 1972 and 1990 was significantly higher than that during the drier period between 1990 and 2004. The relationship between mangrove rate of change and change in rainfall pattern supports Field (1995) and Ellison (2000) who argued that precipitation patterns affect mangrove spatial distribution. This may also be related to higher supply of fluvial sediment and nutrients, lower exposure to sulphates and/or reduced salinity

(McKee, 1993; Field, 1995; Ellison, 2000). In the present study the predominantly landward expansion supports the suggestion that higher rainfall and resulting lower salinity may be a factor contributing to mangrove encroachment into the upper intertidal marsh. This is also consistent with the lower rates of mangrove expansion during the post-1990 (lower rainfall) period. As well, most of the large gaps in mangrove forests at Hays Inlet, Little Burpengary and Cabbage Tree Creeks were created during this lower rainfall period. Drought is considered as one of the factors that may cause the creation of these gaps (Duke, 2001).

4.2 Mangrove expansion and salt marsh decline

The lack of significant differences between the mean rate of seaward mangrove change both pre- and post-1990, as well as the fact that there was no significant relationship between the seaward expansion and rainfall indices, suggests that changes in rainfall patterns primarily affect the rate of landward mangrove expansion ($R^2 = 0.4950$, $p = 0.0005$). This usually occurs at the expense of salt marsh, as indicated in the present research by a significant negative relationship between mangrove expansion and the change in salt marsh area. Thus higher rainfall appears to assist mangrove encroachment into salt marshes (McTainsh, 1986; Morton, 1993; Saintilan and Wilton, 2001). In contrast, Rogers *et al.* (2006) inferred that reduced precipitation was the cause of mangrove expansion into salt marsh. The findings of our research found that, while mangrove encroachment into salt marsh occurred during the post-1990 (drier) period, it did so at a lower rate than in the pre-1990 (wetter) period.

Although we generally found increases in mangrove area, rates of mangrove expansion varied from site to site, whereas rainfall patterns did not. Thus mangrove changes are likely to be also related to factors outside the scope of this research such as site-specific characteristics including wetland microtopography, upland habitat sediment composition, and more general factors such as sea level and tidal range (Semeniuk, 1994; Gilman et al., 2007). For example, at a very local scale, established mangroves may facilitate landward expansion by shading and conserving soil moisture on the landward edge. However that level of detail has not been included in this research. Sea level changes might also explain the mangrove spatial changes. However, for the study area, mean tide height was examined and, although it fluctuated over the period 1972 to 2004, there was no clear trend. At a more general level the degree of catchment modification which ultimately affects the hydrological, sedimentation and nutrients regime of wetlands can impact the rate of change in mangrove extent (Saintilan and Williams, 1999; Saintilan and Wilton, 2001; Nicholls and Ellis, 2002; Harty, 2004; Jones et al., 2004; Williams and Meehan 2004).

5 Conclusion

The results of this study have highlighted a significant relaionship between rainfall pattern and the landward expansion of mangroves in Moreton Bay's subtropical estuaries. It has taken a rainfall pattern based approach by identifying change-points in rainfall to demarcate time periods for analysing mangrove area. In the context of the vulnerability of intertidal systems to changes associated with climate change, identifying the importance of rainfall provides one dimension for assessing impacts. It is suggested that this change-point approach identifying when significant changes occur as a basis for spatial analysis, might be usefully explored for other factors (e.g. sea level change where adequate data were available) and in other places.

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Table 1
Rainfall variables at Bald Hill Creek pre- and post- 1990.

Study level	Variables	Pre-1990 (1972-1990)	Post-1990 (1991-2004)	*p*-value
Wetland	Mean annual rainfall(mm)	1289	1021	0.0174
	Median	1334	931	0.0204
	Proportion of rainy days $\geq$2mm	22%	19%	0.0001
	Proportion of rainy days $\geq$10mm	9%	7%	0.0013
	Proportion of rainy days $\geq$25mm	4%	3%	0.0013
Catchment	Mean annual rainfall (mm)	1293	1057	0.0336
	Median	1306	980	0.0418
	Proportion of rainy days $\geq$2mm	21%	20%	0.0080
	Proportion of rainy days $\geq$10mm	9%	8%	0.0025
	Proportion of rainy days $\geq$25mm	4%	3%	0.0150

Table 2
Area and rate of change of mangrove and saltmarsh vegetation pre and post-1990 at study sites

Study site	Vegetation type	Area at 1972 (ha)	Area at 1990 (ha)	Area at 2004 (ha)	Rate of change pre-1990 (% yr^{-1})	Rate of change post-1990 (%yr^{-1})
Cabbage Tree Creek	**Mangrove**	**45.9**	**55.77**	**59.3**	**1.19**	**0.45**
	Saltmarsh	78.95	59.64	52.79	-1.35	-0.82
Bald Hills Creek	**Mangrove**	**54.82**	**70.47**	**76.3**	**1.58**	**0.59**
	Saltmarsh	84.3	70.13	65.26	-0.93	-0.5
Pine River	**Mangrove**	**66.43**	**71.35**	**71.49**	**0.41**	**0.01**
	Saltmarsh	21.04	20.91	23.86	-0.03	1
Hays Inlet	**Mangrove**	**151.53**	**168.72**	**159.84**	**0.63**	**-0.38**
	Saltmarsh	101.49	91.08	103.22	-0.57	0.95
Little Burpengary Creek	**Mangrove**	**64.92**	**74.76**	**71.6**	**0.84**	**-0.3**
	Saltmarsh	79.01	68.37	73.12	-0.75	0.49
Burpengary Creek	**Mangrove**	**13.53**	**17.64**	**20**	**1.68**	**0.95**
	Saltmarsh	18.98	14.84	12.3	-1.21	-1.23
Southern Caboolture	**Mangrove**	**67.96**	**82.99**	**88.33**	**1.23**	**0.46**
	Saltmarsh	45.29	29.52	23.92	-1.93	-1.36
Lagoon Creek	**Mangrove**	**37.78**	**40.34**	**43.94**	**0.38**	**0.64**
	Saltmarsh	26.09	22.75	19.18	-0.71	-1.12
Ningi Creek	**Mangrove**	**25.85**	**30.91**	**35.31**	**1.09**	**1.02**
	Saltmarsh	32.25	26.93	21.81	-0.92	-1.36
Glass Mountain Creek	**Mangrove**	**37.14**	**51.54**	**58.9**	**2.15**	**1.02**
	Saltmarsh	68.66	51.78	43.98	-1.37	-1.07
Total	**Mangrove**	**565.88**	**664.49**	**684.99**	**0.97**	**0.22**
	Saltmarsh	556.07	455.97	439.39	-1	-0.26

Table 3
Relationship between the rate of mangrove increase and rainfall variables in the study area wetlands and their catchments.

Study level	Variables	*b*	*SE*	*P* value	R-Square
wetlands	Mean annual rainfall	0.0030	0.0008	0.0018	0.4273
	Median	0.0021	0.0006	0.0033	0.3886
	Proportion of rainy days ≥2mm	0.1738	0.0630	0.0130	0.2969
	Proportion of rainy days ≥10mm	0.4731	0.1380	0.0030	0.3950
	Proportion of rainy days ≥25mm	0.7896	0.2510	0.0056	0.3547
catchments	Mean annual rainfall	0.0028	0.0007	0.0006	0.4875
	Median	0.0028	0.0007	0.0004	0.5100
	Proportion of rainy days ≥2mm	0.1236	0.0557	0.0394	0.2152
	Proportion of rainy days ≥10mm	0.2976	0.1115	0.0156	0.2836
	Proportion of rainy days ≥25mm	0.6759	0.2015	0.0035	0.3846

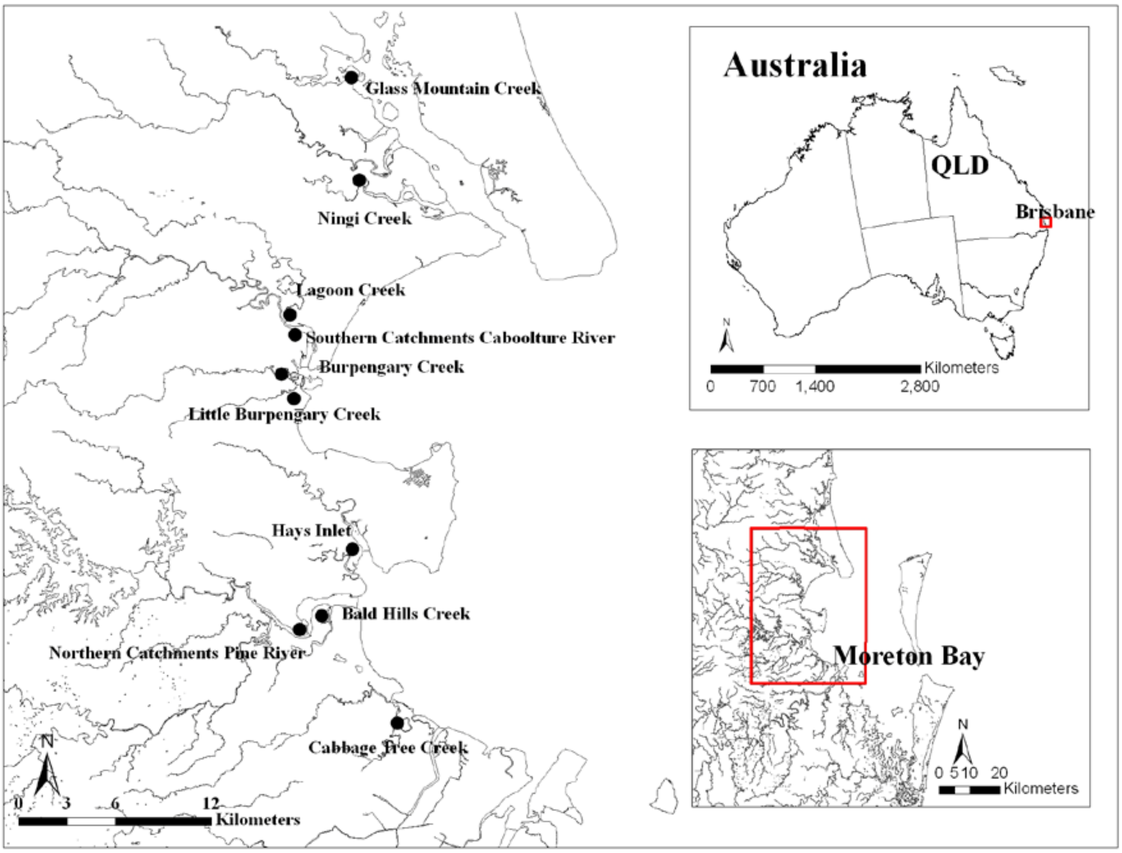

Fig. 1. Locality map of study sites, northern Moreton Bay, Queensland, Australia.

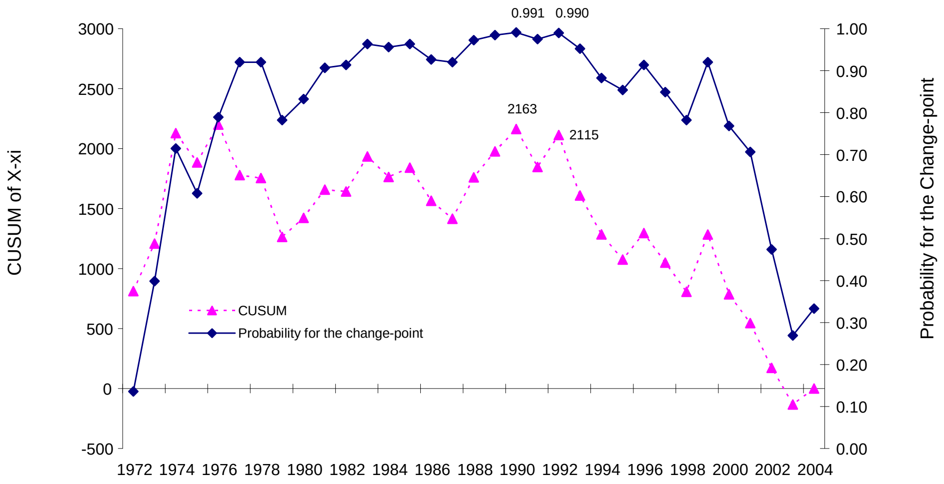

Fig. 2.Result of the Pettitt-Mann-Whitney-Test (probability for the change point) and the CUSUM, for the annual precipitation at Bald Hills Creek 1972-2004

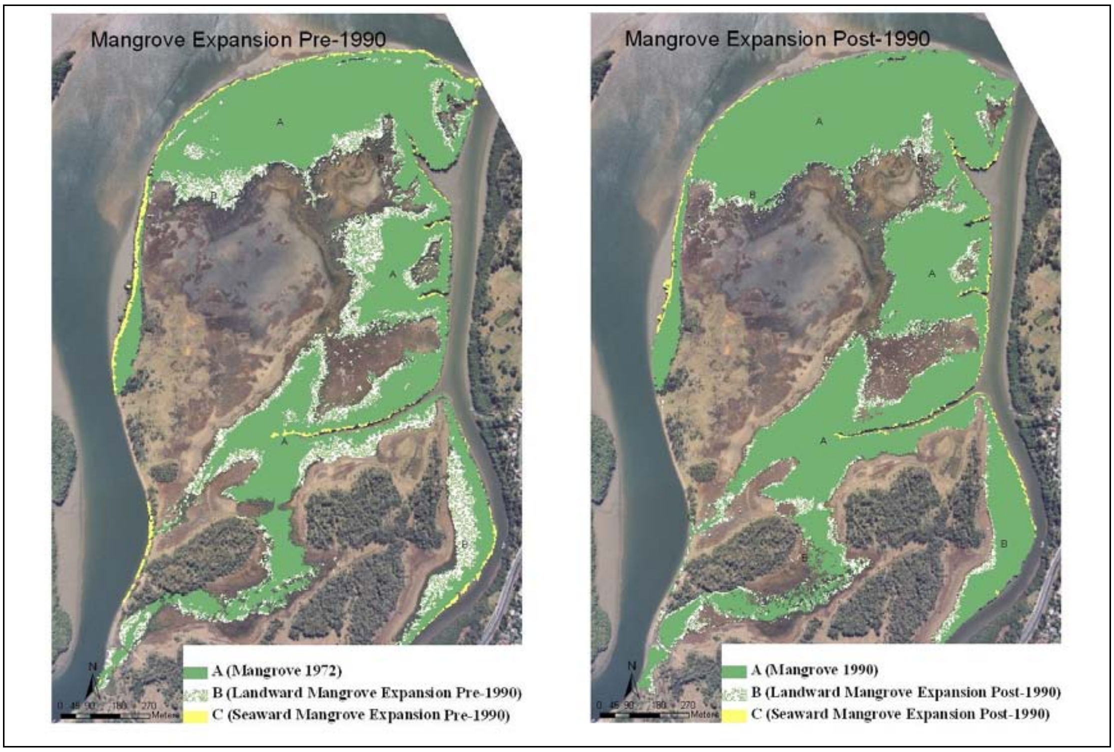

Fig. 3. Landward and seaward mangrove expansion pre- and post-1990 at Bald Hill Creek

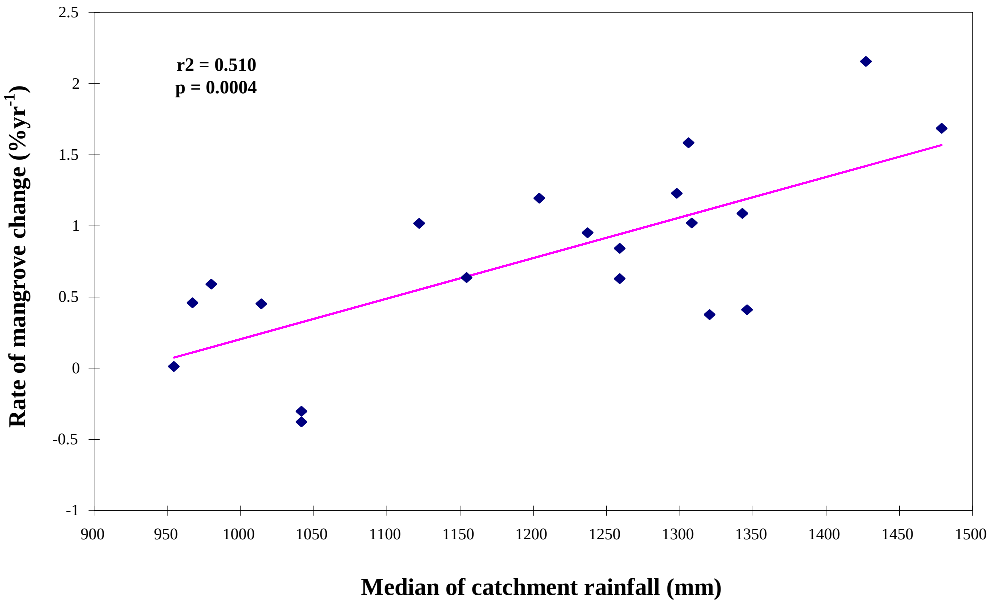

Fig. 4.Relationship between the rate of mangrove increase and median of catchment rainfall

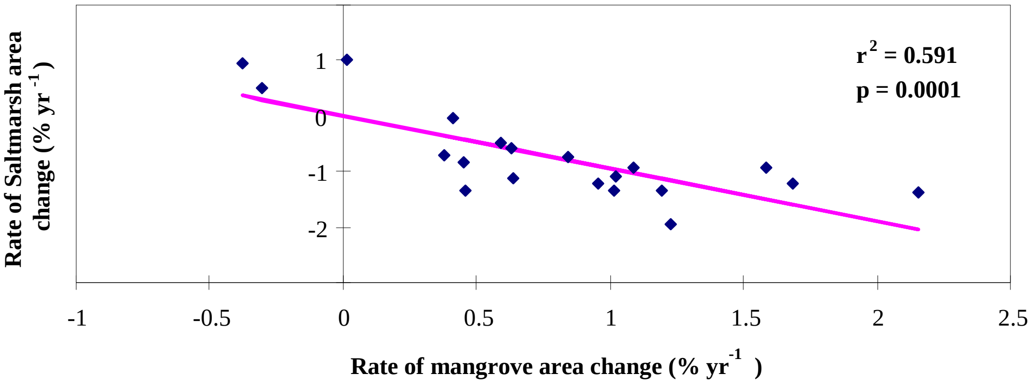

Fig. 5. Negative correlation between change in mangrove and saltmarsh area