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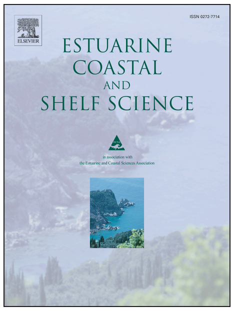

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Investigating the decline of ecosystem services in a production mangrove forest using Landsat and object-based image analysis

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Abstract

The Matang Mangrove Forest Reserve is widely recognised as a sustainably managed mangrove forest. However, recently evidence of multiple ecosystem services decline has emerged. The primary objective of this study was to apply remote sensing techniques to assess the impact of the silviculture in the mangrove forest reserve on the provision of ecosystem services. It applied an object-based approach to classify multi-temporal Landsat imagery. The classified images enabled the study to characterise and analyse the spatiotemporal changes in the distribution of stand age composition and structure over a 35 year period. Links were established between the classified images and the ecosystem services assessment based on the assumption that the classification results provided a reliable proxy for an indirect analysis on the temporal and spatial distribution of aboveground biomass of the mangrove forest reserve. The relationship between the potential impacts of the observed changes derived from the classified images with the data obtained from the ecosystem services assessment were analysed. The analysis showed that the fluctuation in greenwood yield was affected by varying rates of regeneration, exposure to excessive thinning and delays in harvesting. The production of blood cockles around the mudflats of the mangrove forest reserve was determined to be influenced by both timber extraction and natural coastal erosion. An undetected ecological change in the late eighties and anthropogenic disturbances were possible key factors behind the decline in the population of the Milky Stork and migratory shorebirds. The study highlights the importance of understanding and managing the trade-offs between wood production and ecosystem services in a managed mangrove forest and provides an important reference for the future management of the Matang Forest Reserve and other multiple-use wetland forests.

Keywords: Ecosystems, man-induced effects, Forest industry, Ecological balance, Satellite sensing

1. Introduction

The Matang Mangrove Forest Reserve (MMFR) is the largest tract of contiguous mangrove forest in Peninsular Malaysia. It has been primarily managed for timber production for more than a century (Chong, 2006, FAO, 2007). Apart from being recognised as a well-managed production mangrove forest, it is also one of the best studied mangrove ecosystems in Southeast Asia (Alongi et al., 2004). Over the years, through the integration of new advancements in knowledge and technology, the forest management strategy for the MMFR has slowly evolved, from one that was strictly focused on production, to one that incorporates wider ecological objectives (Gan, 1995, Azahar and Nik Mohd. Shah, 2003, Jusoff, 2008).

The MMFR has had a long history of sustainable yield production of wood for charcoal and poles, maintaining a stable average extent of just over 40,000 ha although this has the potential to mask substantial change in the overall health of the ecosystem (Giri et al., 2007). The implementation of production management strategies have had a distinct and complex influence over the provision of the ecosystem services generated by the MMFR (Duncker et al., 2012). The production of commodities such as timber has often resulted in some form of degradation in the provision of one or more forest ecosystem services (Nalle et al., 2004). The management objectives of producing commodities such as charcoal, often conflict with protecting or improving ecosystem health. Moreover, degradation of ecosystem services can also occur as a result of many other different causes and it is often difficult to determine if the management strategies implemented were the cause of forest degradation (Carpenter et al., 2009).

In this study, three key ecosystem services (the greenwood yield, the production of blood cockles and the habitat for migratory birds) were identified in the MMFR that have either been in a state of decline or have exhibited states of periodical decline. A combination of remote sensing techniques were used to determine the change in stand-age composition and structure over time. The analysis was based on the assumption that the observed changes in stand age composition and structure derived from classifying multi-temporal Landsat Thematic Mapper scenes in this study provides a reliable proxy for the spatial and temporal distribution of aboveground biomass at the MMFR. The analysis was used to infer the potential causes of the deterioration of ecosystem services.

Remote sensing, object based image analysis and the Landsat archive has been widely used to map and monitor natural mangrove forests with complex stand structures and abundant species composition (Nascimento et al., 2013, Vo et al., 2013, Jia et al, 2015, Kamal et al., 2015, Son et al., 2015). This study, however, provides a unique perspective to the available literature as a result of several key characteristics of a managed mangrove forest. The application of silvicultural standards, which has resulted in large pockets of even-aged stands ranging from 1 to 30 years and largely homogenous mangrove forest stand structure, has enabled the analysis to be conducted in a much less complex environmental setting compared to previous studies. It also makes a significant contribution to the literature due to the preliminary attempts of establishing links between the classified images and the ecosystem services outcome.

2. Study area and data

2.1 Study area

The MMFR is located in the State of Perak in Peninsular Malaysia. Timber extraction activity is concentrated in 73.6% of the forest and limited timber extraction is carried out in 7.1% of the forest while 19.3% is totally free from any human induced forestry activity (**Fig. 1**). The management strategy of the MMFR is implemented based on a 10 year working plan formulated and published by the Perak State Forestry Department (Gan, 1995, Azahar and Nik Mohd. Shah, 2003, Roslan and Nik Mohd. Shah, 2014). The forest is divided into 108 compartments and within each compartment lies coupes (management units) that are further segmented into sub-coupes which essentially represent the smallest forest management unit in the MMFR. The management employs a clear felling and planting silviculture system. The forest is clear felled on a 30 year rotation. Intermediate felling (thinning) is carried out twice, first between the stand ages of 15 years to 19 years and second between the stand ages of 20 years to 24 years. The management and silvicultural practices have resulted in large areas of the managed forest to mainly compose of the commercially valuable *Rhizophora* forest (Alongi et al., 2004).

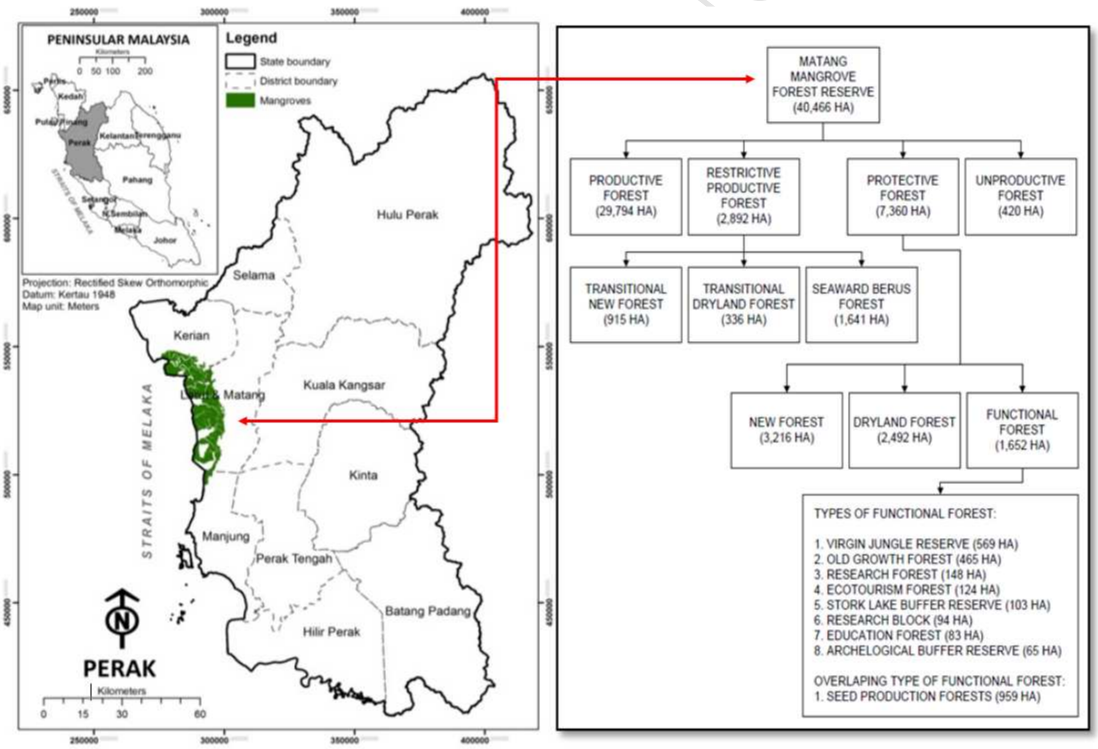


Fig. 1. The location of Matang Mangrove Forest Reserve (left) and the breakdown of the management defined forest classes (right). ***Source:*** *Adapted from (Azahar and Nik Mohd. Shah, 2003, Hamdan et al., 2013)*

2.2 Data

The satellite images used in this study were cloud-free subsets of the MMFR derived from nine Landsat scenes: (1) Multispectral Scanner (MSS) scene, acquired on November 26, 1978; (2)

Thematic Mapper (TM) scene, acquired on May 26, 1988; (3) TM scene, acquired on June 14, 1989; (4) TM scene, acquired on February 7, 1995; (5) Enhanced Thematic Mapper Plus (ETM+) scene, acquired on December 12, 1999; (6) ETM+ scene, acquired on March 3, 2001; (7) TM scene, acquired on December 14, 2009; (8) Landsat 8 scene, acquired November 23, 2013 and (9) Landsat 8 scene, acquired on February 11, 2014. The latter two Landsat 8 images needed to be combined to create the latest cloud-free image of the MMFR.

This study also integrated forest management spatial data as an ancillary data set to provide additional information and spatial attributes. This includes a management zone map adapted from the Perak State Forestry Department working plans of 2000-2009 (Azahar and Nik Mohd. Shah, 2003). These data contain information on the compartments, coupes and sub- coupes boundaries, the stand age, the type of activity that the coupes will undergo and the year that activity is to be implemented. Detailed record keeping by the Perak State Forestry Department enables the estimation of stand age in the any particular coupe to within three years of the actual age (Gong and Ong, 1995).

The reference map used to validate the classifications of this study was adapted from the base map produced for the 2000 – 2009 working plan (Azahar and Nik Mohd. Shah, 2003). The stratification process for the map was based on the photo-interpretation of 1989 and 1998 aerial photographs with the scale of 1:20 000 of the study area. The historical records and previous field inventory surveys conducted contributed further in enhancing the accuracy of the produced map.

3. Methods

3.1 Image pre-processing

Image pre-processing reduces environmental and remote sensing distortions of the image data sets utilised in this study. Geometric and radiometric corrections were performed to correct and produce an image that resembles the true radiant energy and spatial characteristics of the data set at the time of acquisition to maximise the probability of extracting useful information from the data sets (Lu et al., 2002, Schowengerdt, 2006). The image was georeferenced to the local topographic map series L 7030 that has scale of 1: 50 000 acquired from the Department of Survey and Mapping Malaysia (JUPEM) with RMS less than 0.5 pixels. The raw digital numbers obtained from the image dataset, which included errors caused by changes in sensor performance and interferences from atmospheric effects (Riano et al., 2003), were converted to radiance and then to at sensor reflectance using an exo-atmospheric model as prescribed by NASA (Chander et al., 2009). The improved image-based dark object subtraction (DOS) model was used to implement the atmospheric correction (Chavez Jr, 1988, Chavez, 1996). The resulting at surface reflectance values ranged from 0 to 1 but was rescaled to the range of 0 and 1000 to facilitate the object- based image analysis.

3.2 Image classification

A comprehensive assessment on the potential of using Landsat archive for ecological monitoring and management of the study area conducted by Ammar et al. (2015) demonstrated that the object-based approach was more effective in stand age delineation than both the supervised and unsupervised pixel-based approach. The classified images produced by the pixel-based methods were negatively affected by the salt and pepper effect. The object-based approach was found to be primarily effective because of the unique forest stand structure and canopy characteristics of the study area. Large pockets of even-aged and homogenous mangrove forest stand structure creates non-complex study elements that are larger than the image resolution cell of the image datasets, made it ideal for the application of object-based approach.

Due to space limitations, a specific and detailed explanation of the image processing involved in this study could not be included. However, this can be obtained from Ammar et al. (2015) and a more general description of the application of an object-based approach can be obtained from Kamal et al. (2015). Based on the findings of Ammar et al. (2015), three classes of stand age groupings were used: (1) young mangrove forest, comprise stands of 13 years old and below; (2) mature mangrove forest, comprising stands of 14 years and above; and (3) clear felled areas. The classification method was applied using the eCognition software package.

3.3 Error and accuracy assessment

Prior to analysing and establishing links between the ecosystem services assessment and the classified multi-temporal Landsat images, it was crucial to ensure that any inferences on the geospatial information gathered is based on accurate and reliable maps. Error and accuracy assessment is an integral component of this study to ensure that the analysis is based on a classified map that has been generated with an acceptable level of accuracy (Foody, 2002, Thompson et al., 2007). The error matrix was employed to calculate the overall accuracy, user accuracy and producer accuracy for the designated classes. The error and accuracy assessment was conducted on the Landsat Thematic Mapper (TM) image acquired in 1999 to correspond to the year the reference map was produced. The stratified random sampling points were generated in ArcGIS and constrained to areas where stand age data was available. The young mangrove forest class was assigned 50 random sample points while the mature mangrove forest was assigned 150 random sample points proportionately based on its area of coverage of the study area.

3.4 Assessment of ecosystem services

Ecosystem services of interest in this study were estimated based on secondary data collected from the relevant state government agencies and supported by data obtained from published sources. Blood cockle culture data were derived from the Perak Fisheries Statistics and supported by the findings in Ellison (2008). The secondary survey data of migratory shorebirds were compiled by Li et al. (2006a, b, 2007) and the survey results are supported by the urgent plea to investigate the decline of the Milky

Stork in the west coast of Peninsular Malaysia issued by Ismail and Rahman (2012). The greenwood yields were derived from the Working Plans of the MMFR issued by the Perak State Forestry Department. The fluctuating yields were noted in Putz and Chan (1985) and Gong and Ong (1995).

4. Results

4.1 Changes in the composition of the forest stand structure over time (1978 – 2014)

The results showed that the areal percentage of the clear felling area in the forest ranged between 10.37% and 16.60%, the young mangrove forest area ranged between 13.76% and 21.06% and the mature mangrove forest area ranged between 64.21% and 75.87% (**Fig. 2**). In all the classified images, the clear felled areas were consistently the smallest area between the three designated classes. Most importantly, the overall results indicated a clear trend of stability in the overall composition of the forest stand structure.

During the study, the two highest number of kilns in operation was in the 1970-1979 and the 2010-2019 working plan periods. Based on the number operating of kilns in the 1970 – 1979 period which peaked at 393, the stability in the composition of the forest stand structure seemed to be unaffected by the number of kilns. Although it should be noted that the effects of increasing the number of kiln by 40% to 489 kilns in the 2010-2019 working plan can only be fully evaluated once the cycle of the management plan ends in 2019. More importantly, the reccommended maximum amount of operating kilns at the MMFR has been determined to only be 418 (Noakes, 1952, Haron, 1981).

The average yield per hectare of greenwood extracted for the production of charcoal corresponding to the year of the acquired Landsat images also depicted a similar scenario. The large fluctuation in yield, ranging from 124 to 262 tonnes per hectare, showed no relation to the composition of the forest stand structure which had remained stable throughout the observed study period.

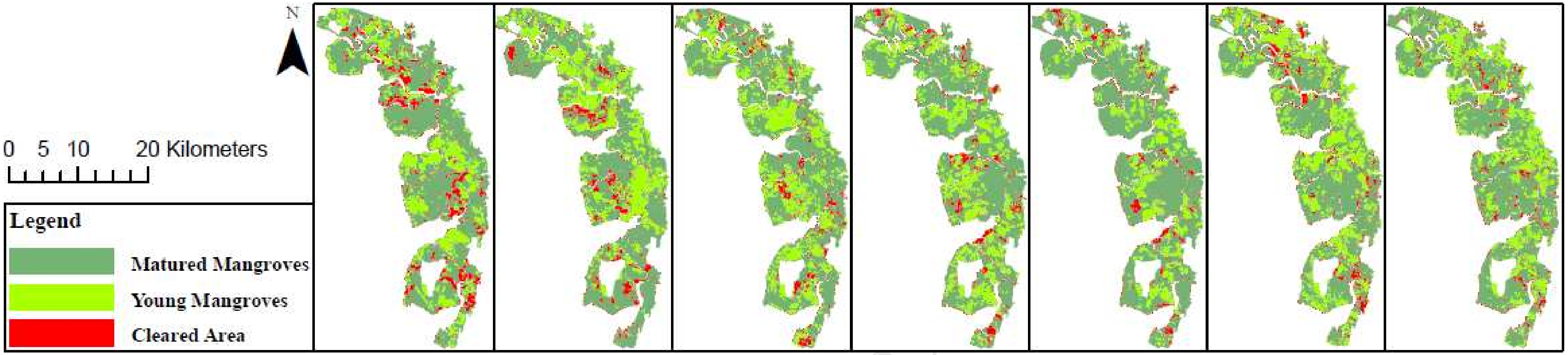


IMAGE YEAR	1978	1988	1995	1999	2001	2009	2013/2014
Total Area (ha)	41186.88	40862.25	40593.33	40623.84	40651.20	40607.64	40418.19
Mature Mangrove (ha)	27415.80	26239.32	27488.97	28175.58	30842.37	27403.47	28899
Young Mangrove (ha)	6933.24	8604.72	7915.41	7526.43	5594.22	7777.35	6803.19
Cleared Area (ha)	6837.84	6018.21	5188.95	4921.83	4214.61	5426.82	4716
Mature Mangrove (%)	66.56	64.21	67.72	69.36	75.87	67.48	71.5
Young Mangrove (%)	16.83	21.06	19.50	18.53	13.76	19.15	16.83
Cleared Area (%)	16.60	14.73	12.78	12.12	10.37	13.36	11.67
Number of kilns	336 - 393	316	336	336	348	348	489
Average yield per (ton/ha)	NA	180	177	124	154	262	NA

Fig. 2. Changes in land cover from 1978 to 2009 derived from classifying multi-temporal Landsat imagery with management statistics.

4.2 Error and accuracy assessment

The accuracy assessment result indicated an overall accuracy of 90% (**Table 1**). The mature mangrove forest class had the lowest omission and commission error at 7% and 6% respectively. The young mangrove forest class had an 18% omission error and a 21% commission error. The Kappa coefficient of 0.74 fell within the substantial agreement range of 0.61 – 0.80 according to Landis and Koch (1977). After scrutinizing the misclassified group of pixels, it was discovered that the errors were partly caused by problems of spectral segregation of areas that had successfully regenerated and comprised of stand age that ranged from approximately three to five years old. These areas had spectral signatures that mimicked those of a matured mangrove forest. The misclassification was also caused by a delay in harvesting or an extended re-growth period.

Table 1

The error matrix for the object-based classified Landsat 1999 image *versus* the reference map.

	Reference data			Producer's	User's
Classified Map	Cleared	Forest	Total	Accuracy	Accuracy
Cleared	139	9	148	93%	94%
Forest	11	41	52	82%	79%
Total	150	50	200		
Overall Accuracy	90%				
Kappa Coefficient	0.74				

The initial assessment could not compute an error matrix which included an evaluation of the classified clear felled areas. The reference map merely indicated the year that clear felling would take place but considering the fact that harvesting could have taken place at any time during the determined year, it would have been almost impossible to reclassify the reference map to include the clear felled areas that corresponded to the date of the selected images.

In order to include a quantitative method of evaluating and validating the results for the classified clear felled areas, 50 random points were generated each for forested and clear felled areas in ArcGIS on a Landsat 8 subset imagery of the MMFR. These sample points were than verified through a field validation exercise. The sample points were constrained to accessible areas of the forest and in cloud free segments on the imagery. The proportionate sampling method was not replicated as this error and accuracy assessment involved actual on the ground validating exercise and it would have been difficult to conduct the verification of larger sampling points especially in a mangrove forest.

Table 2

The error matrix for the object-based classified Landsat 8 2013 image *versus* field validation.

	Reference data			Producer's	User's
Classified Map	Cleared	Forest	Total	Accuracy	Accuracy
Cleared	46	4	50	96%	92%
Forest	2	48	50	92%	96%
Total	48	52	100		
Overall Accuracy	94%				
Kappa Coefficient	0.88				

The accuracy assessment result indicated an overall accuracy of 94% (**Table 2**). The clear felled area had a producer's accuracy of 96% and an omission error of 4%, which meant that 4% of the clear felled areas were mistakenly classified as forest. It had a 92% user's accuracy and a commission error of 8%, which meant that 8% of the forest was designated as clear felled areas. The Kappa coefficient of 0.74 fell within the almost perfect agreement range of 0.81 – 1.00 based on Landis and Koch (1977).

In summary, the findings in the assessment of delineating stand age using Landsat imagery point towards a clearly successful delineation of three categories of the forest based on the proposed age group. Clear felled area (no trees), young mangrove forest (stand age up to 13 years) and mature mangrove forest (stand age above 13 years) were able to be effectively and distinctively categorised. Due to the unavailability of additional reference data, an error and accuracy assessment evaluation on the remaining Landsat images could not be performed.

4.3 Ecosystems services assessment

4.3.1 The greenwood yield

The MMFR has been susceptible to periodical declines in the average yield of greenwood extraction (Putz and Chan, 1986, Gong and Ong, 1995, Ellison and Farnsworth, 2000, Iftekhar and Islam, 2004). Although average yields increased in the second (1990-1999) and third (2000-2009) 10-year period of the second rotation, yields declined in the second (1960-1969) and third (1970-1979) 10-year period of the first rotation. It is crucial to note that the declines in those periods were preceded by an increase in the number of charcoal production kilns (**Table 3**).

Table 3

The number of kiln and the corresponding yield of greenwood.

Year	Rotation	10 year Period	Kilns	Yield (t/ha)
1950 – 1959	First	1^{st}	418	NA
1960 – 1969	First	2^{nd}	494 - 561	158
1970 – 1979	First	3^{rd}	336 - 393	136
1980 – 1989	Second	1^{st}	316	174
1990 – 1999	Second	2^{nd}	336	170
2000 – 2009	Second	3^{rd}	348	182
2010 – 2019	Third	1^{st}	489	NA

Source: *Adapted from (Gan, 1995, Azahar and Nik Mohd. Shah, 2003, Roslan and Nik Mohd. Shah, 2014).*

Currently, the first (2010-2019) 10-year period of the third rotation has a total of 489 approved kilns which represents an increase of 40% from the previous 10-year period (Roslan and Nik Mohd. Shah, 2014). Whilst this will not necessarily result in the reduction of future greenwood yield, the increase in the number of kilns, combined with other factors, will undoubtedly exert additional pressure on the coastal ecosystem.

4.3.2 The production of blood cockles (Anadara Granosa)

The rate of decline in the cockle seeds and adult cockle production for Perak, the state in which the MMFR is located, has been very alarming. The cockle seed production has been non-existent since 2004 and the adult cockle production levels are now less than a quarter of its historic high of 104,963 tonnes in 1980 (Ellison, 2008). Perak has accounted for more than half of the total cockle production in Malaysia. Although the area for the production of cockle has generally increased since 1990, the yield of cockle per ha has been declining steadily (DOFM, 1995; DOFM, 2012).

The overall trend of decline in the production of cockle (*Anadara Granosa*) at the State of Perak suggest that there is a corresponding decline in production from the MMFR, because production from the State of Perak is dominated by production from the MMFR (**Table 4**). The production of cockle seeds is dependent on parts of the coastal mudflats adjacent to the MMFR that act as natural spatfall areas (also known natural cockle beds). On the other hand, the main culture areas for cockle are concentrated on the estuaries of the MMFR.

Table 4

The cockle culture landing at the fisheries district located at the Matang Mangrove Forest Reserve (MMFR).

Year	MMFR Production of Cockles (tonnes)	Area of the Production of Cockles in MMFR (ha)	MMFR Production of Cockles (tonnes/ha)	Perak Production of Cockles (tonnes)	Perak Percentage Contribution of Production
2000	40,558.57	4,726.30	8.58	43,382.17	93.5%
2011	17,615.00	3,891.00	4.53	21,759.37	81.0%

Source: *Adapted from the (Azahar and Nik Mohd. Shah, 2003, Roslan and Nik Mohd. Shah, 2014)*

In the year 2000, the MMFR accounted for more than 90% of the total cockle production in the entire state of Perak. It declined to 81% in 2011. The total production of cockles at the mangrove forest reserve in 2011 has declined 57% from the total production in 2000. Even the average production rate per ha has been in steady state of decline. At 4.53 tonnes per ha, it is well below the 20 year state average (1990 – 2010) of 11.49 tonnes per ha.

4.3.3 Habitat for migratory birds

The MMFR is also an important habitat to a total of 154 species and of this, 49 species are migratory birds (Othman 2004). Despite incorporating management strategies which includes the creation of permanent bird sanctuaries and increased efforts in the preservation of mudflats (Azahar and Nik Mohd. Shah, 2003), which is also the natural habitat for the diminishing blood cockles, there have been evidence of a catastrophic decline in the population of waterbirds. It was estimated that between 1989 and 1992, the coastal ecosystem supported approximately 18,526 to 31,520 waterbirds annually, but in 2002 only 1,015 to 4,057 waterbirds were recorded (Li et al., 2006a, Li et al., 2007). This constituted a 75 – 95% decline in the overall wintering waterbird population at the MMFR. The population of the Vulnerable Milky Stork (*Mycteria cineria*) recorded a 90% decline (Li et al., 2006b). Only five individuals were recorded during an observation in 2009 and there is an urgent need for interventions to conserve the species (Ismail and Rahman., 2012).

5. Discussion

5.1 Exploring the effects of timber extraction on the ecosystem services

The analysis indicates that there has been some form of deterioration in the provision of several critical ecosystem services in the MMFR. It is therefore important for us to develop an understanding of the relationship between the structural changes of mangrove forest reserve and the delivery of these ecosystem services. Whilst all the observed negative impacts on the flow of certain ecosystem services at the MMFR may or may not be a direct result of the production of charcoal and poles, it does highlight the need to study the effects of the silvicultural practices at the MMFR on the provision of these ecosystem services.

The role of biomass in the carbon cycle, nutrient allocation and habitat provision has long been established. It is a result of the productivity of forests, and plays an important role in shaping ecosystem functional characteristics and in many cases, the provision of ecosystem services (Lu, 2006). Therefore, it plays a key role in connecting the image classification analysis and the ecosystem services assessment in this study. Information on the spatial and temporal distribution of biomass could provide the study with vital clues on the factors that may be affecting the delivery of key ecosystem services at the MMFR.

However, as current research has yet to effectively and accurately relate aboveground biomass estimation derived from ground sample plots with the spectral reflectance derived from Landsat MSS or TM image datasets (Clark and Kellner, 2012), the established classes (young mangrove forest, mature mangrove forest and clear felled area) are used as proxies to provide a general overview of the spatial and temporal distribution of biomass at the MMFR. The changes detected from the classified Landsat MSS and TM time series scenes were assessed in relation to the data obtained from the ecosystem services assessment to analyse any impact it might have had on the provision of these services.

5.1.1 The greenwood yield

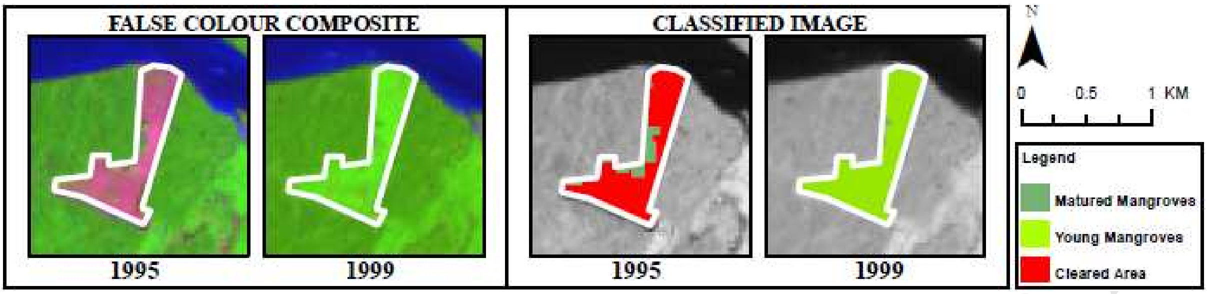
It can surmised from the analysis that overexploitation and unsustainable management practices could not have been the major cause for the fluctuations in the yield of harvested greenwood recorded at the mangrove forest reserve. Over the observation period, there has always been a stable and substantially larger areal percentage of mature mangrove forest – ensuring sustainable supply of greenwood in each working plan. In all the classified images analysed, it had consistently covered more than two thirds of the total forest reserve. Overexploitation and unsustainable management of the forest reserve would have resulted in an unstable composition of the forest stand structure and a much larger areal percentage of the clear felled areas, both of which were not indicated in the classified results.

This shows that the issue mainly lies in the composition of the mature mangrove forest itself, an issue best analysed by directly analysing the biomass of the mature mangrove forest area over time. As the study is able to accurately estimate the stand age composition of the forest, the information extracted is used to indirectly analyse the biomass spatial distribution. Upon closer examination of the Landsat MSS and TM images and the classified image datasets, valuable information were obtained and several factors that could have contributed to the fluctuation of greenwood yield at the MMFR were identified.

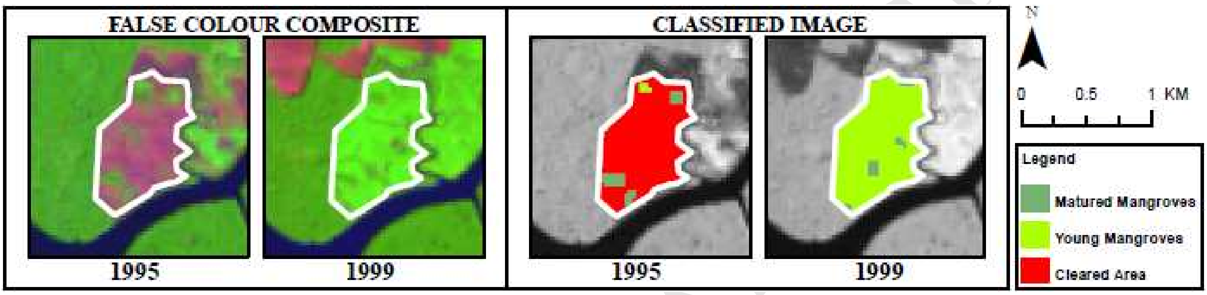
The first factor is related to the different rate of growth or regeneration of the clear felled areas. This can be seen by comparing the subset of the Landsat images and the produced classified image datasets of the clear felled areas in the mangrove forest reserve (**Figs. 3a and 3b** which depicts two areas that exhibit good rate of regeneration). Both the areas were designated for clear felling in 1993. By 1999, a fully restocked mangrove forest with no sign of cleared area that is void of vegetation can be seen. On the other hand, **Figs. 3c** and **3d** shows an example of two clear felled areas that have not regenerated as well as the areas shown in **Figs. 3a** and **3b**.

To demonstrate the varying degrees of regeneration, an area that was designated for clear felling in 1990 have been included (**Fig. 3d**). The area was clear felled three years earlier than the other areas highlighted in **Figs. 3a, 3b** and **3c**. The selected area still displayed some cleared area across the middle of the highlighted area even though nine years had passed since clear felling. In fact, it was observed that there were other areas within the forest that shared similar marks, best described as 'scarring', that was clearly visible on false coloured composite images. These 'scarred' areas took a significant amount of time to regenerate compared to its surrounding area.

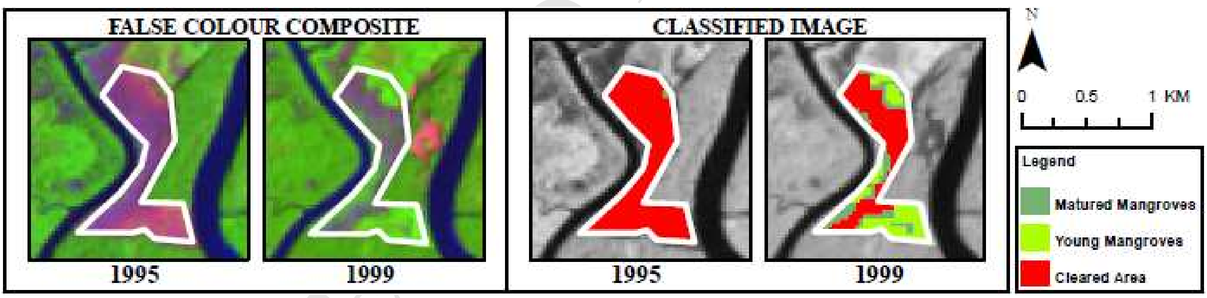
Clear felling in 1993 (Good rate of forest regeneration)



a) Clear felling in 1993 (Good rate of forest regeneration)



b) Clear felling in 1993 (Poor rate of forest regeneration)



c) Clear felling in 1990 (Extremely poor rate of forest regeneration)

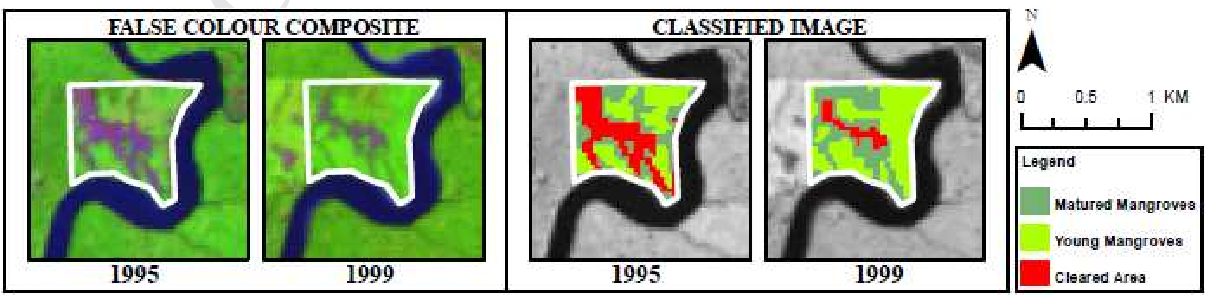


Fig. 3. The highlighted areas represent subset of areas that have been clear felled. Comparison in made between 1995 and 1999. For comparison purposes, the 1995 and 1999 subset false colour

composite image and the corresponding classified image of the area has been placed side by side. a) and b) depict the changes two areas that exhibit good rate of generation. c) was designated for clear felling during the same period as the first two images but exhibited poor regeneration. d) depicts an area that was clear felled in 1990 but exhibit extremely poor rate of regeneration.

Signs of late regeneration would mean that in certain clear felling areas, thinning and clear felling activities may have actually taken place at a much earlier age than planned. This could have caused these areas to have much lower greenwood yield than those that have recovered in a timely manner. Generally, slower growth rates can be attributed to environmental factors such as soil properties and nutrient status (Komiyama et al., 2007). As a result of the silvicultural practices in the MMFR, regeneration and the establishment of new stands face two challenges that are probably not prevalent in natural mangrove forests – areas that are exposed to deep flooding and areas that are prone to monkeys and crabs (Azahar and Nik Mohd. Shah, 2003, Cannicci et al., 2008). The analysis of the images shows that there could still be areas that are not benefiting from the artificial restocking or manual replanting activity which include the propagule and the potted seedling technique.

To demonstrate an extreme case of poor regeneration of the forest, a subset of an image that depicts a severe case of poor regeneration around a concentrated area of two designated clear felling areas has been included (**Fig. 4**). The top half of the highlighted area was designated for clear felling in 1993 while the bottom half was cleared 2 years earlier in 1991. The 1988 image shows the condition of the forest prior to the clear felling activity. Once the areas were clear felled, some areas within the highlighted area can be seen to remain classified as clear felled areas that are void of vegetation until early 2014.

The pattern of the late regeneration could indicate that clear felling activities could be affecting or changing the landscape of the designated areas causing slow or poor regeneration. After all, it has been observed that clear felling causes a disruption in the mud-trapping function of the stilt rooted mangrove trees. This leads to the erosion of surface mud and higher elevated soils will eventually dry out and become extremely acidic. This eventually causes the retardation of regenerating mangrove tress (Johns, 1997).

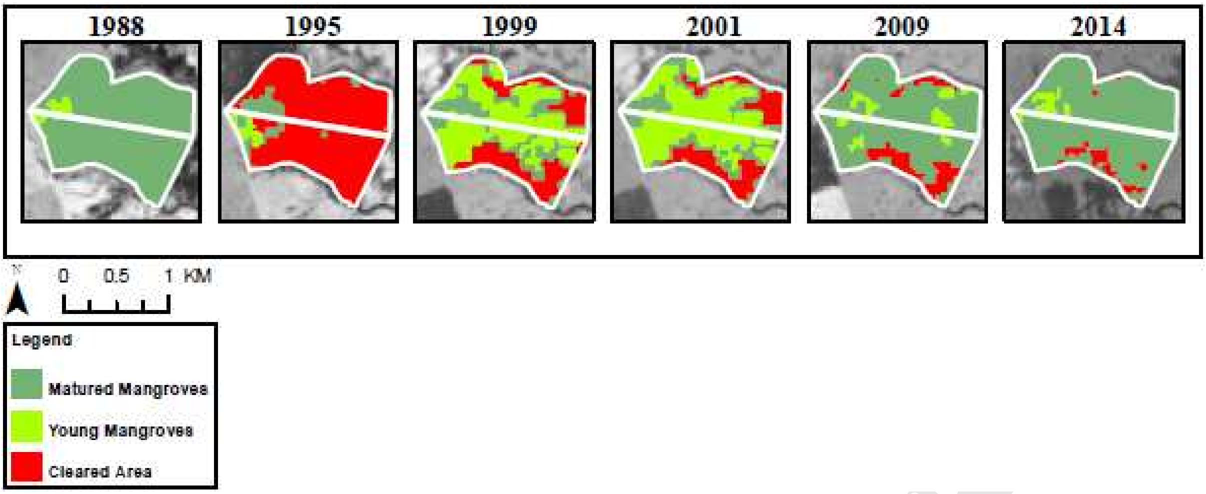
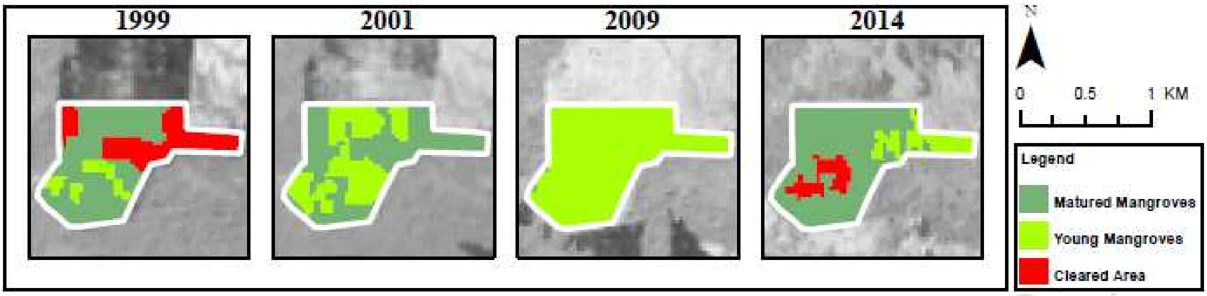


Fig. 4. The two highlighted areas in the subset of classified image represent two clear felling areas designated to be clear felled two years apart. The highlighted area of the top half was clear felled in 1993 while the bottom half was clear felled in 1991.

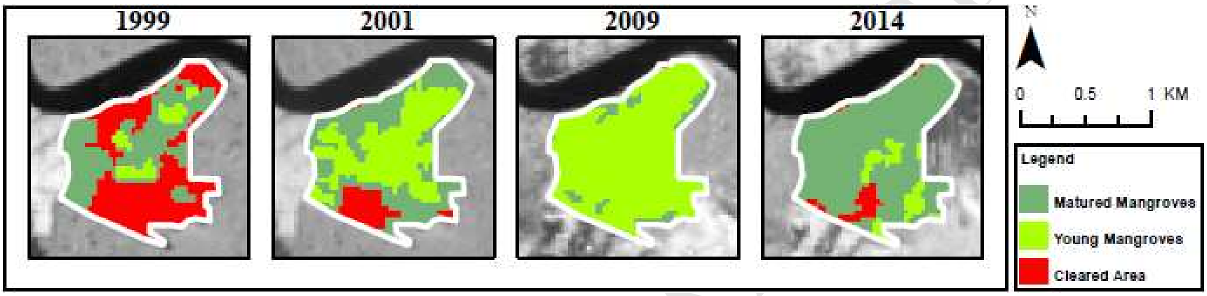
Excessive thinning could be the second factor that is contributing to the observed fluctuation in greenwood yields at the MMFR (**Fig. 5** depicts four areas in different parts of the mangrove forest that were designated for clear felling in 1996). As reflected in the management records, these areas were scheduled for the first thinning in 2011. It can be seen that in 2014, almost three years after the first thinning there are clear indications of areas void of vegetation (**Figs. 5a and 5b**).

These areas were fully restocked in 2009 and the cleared areas only appeared after the thinning processes were performed. For comparison purposes, classified images of two other areas that were designated for clear felling and underwent its first thinning at the same period as the areas have also been included (**Figs. 5c and 5d**). These areas were not affected by the presence of areas that were void of vegetation. It can be postulated that greater care was taken during the first thinning in these areas as opposed to the ones presented in **Figs. 5a and 5b** which shows clear signs of excessive thinning.

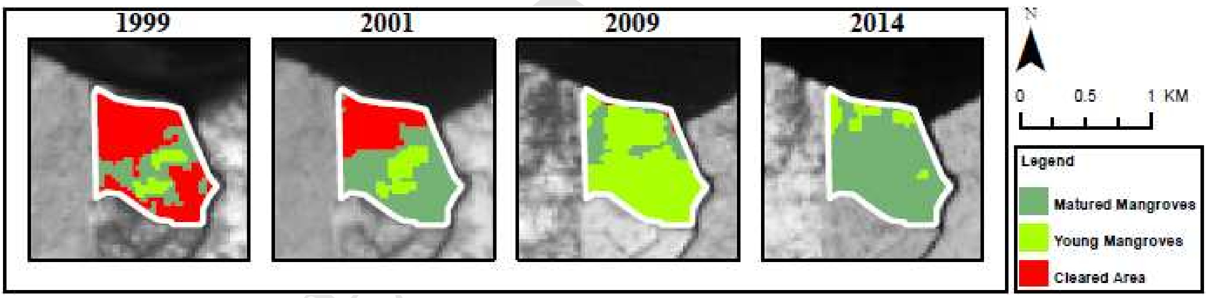
a) Clear felling in 1996 (Signs of excessive thinning)



b) Clear felling in 1996 (Signs of excessive thinning)



c) Clear felling in 1996 (Signs of excessive thinning)



d) Clear felling in 1996 (Signs of excessive thinning)

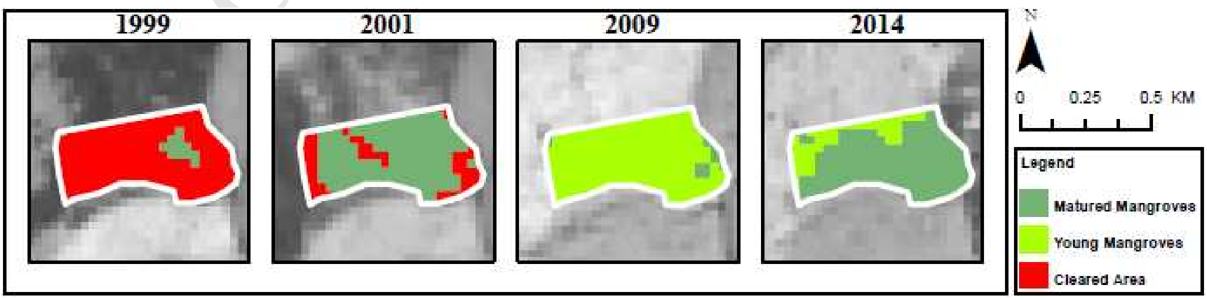


Fig. 5. Subset of areas that are clear felled in 1996 and scheduled for first thinning in 2011. a) and b) are examples of areas that have may have been exposed to excessive thinning. c) and d) are examples of areas with the same forest activity schedule but does not exhibit any signs of excessive thinning.

The third factor contributes to the increase rather than decrease in the yield of greenwoods at the mangrove forest reserve. Records in the working plan already clearly states that there are clear felled areas that exceed 30 years of age. This will often result in an increment in greenwood yield and contribute to the observed fluctuations. However, a quick scan also revealed an area that was designated for first thinning in 2007 but the time series data seemed to show that the area has never been clear felled since 1978 (**Fig. 6**). This would make the area 14 years older than reported. In fact, there are signs of an unexplained incursion into the area in the 2014 image that is signified by the cleared area in the compartment which needs to be investigated.

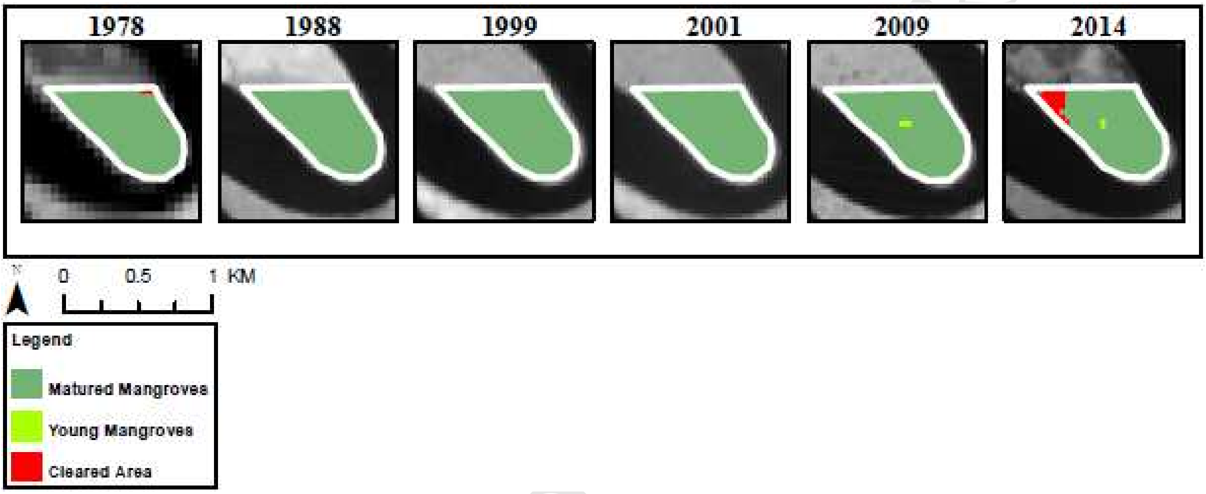


Fig. 6. The classified images show that the area that was designated for its first thinning in 2007 has not been clear felled since 1978.

By linking the results of the classified images to the fluctuations of the greenwood yield at the MMFR, the study has identified several of the contributing factors. It is important to note that these factors need to be analysed further and the current analysis does not provide a comprehensive explanation of the observed fluctuations. However, the findings and conclusions do identify basic research that could be expanded upon. It also signifies the importance and effective role Landsat can play in monitoring the mangrove forest reserve.

A further and investigation needs to be carried out to recalibrate the true age of the trees. This will ensure that the greenwood yield can be monitored effectively. The example of harvesting coupes that are perceived to be 30 years old but which are actually older – not only gives a much higher yield but more importantly could give a wrong impression of the condition of the total forest regrowth or restocking activity.

5.1.2 The production of blood cockles (Anadara Granosa)

The Perak Fisheries Department has attributed the decline in the production of cockle seeds and adult cockles to the post-2004 tsunami effects on sediment and water quality and to an unidentified threat that has caused an unusually high mortality rate among young cockles (Roslan and Nik Mohd. Shah, 2014). On the other hand, Ellison (2008) suggested that the decline at the MMFR could be related to the continued management of the mangrove forest reserve. To date, the underlying cause of decline has yet to be conclusively determined.

The lack of scientific research on the possible causes of this decline raises a huge cause of concern because anthropogenic pressures have been found to affect macro benthic communities stronger and much earlier than trees (Cannicci et al., 2009, Bartolini et al., 2011, Dahdouh-Guebas et al., 2012). Macro benthic communities, in this case blood cockles, function as an indicator to the state of health of an ecosystem and acts as a natural early warning system for ecosystem degradation (Ellison, 2008). Linking the blood cockle production data and the image classification results has also been complicated by the fact that there have been limited research on blood cockles in general, both in terms number and scope (Lee, 2012).

In order to establish a link between the classification results and the decline in the production of cockle seeds and adult cockles at the MMFR, several possible causes that have been put forth in the literature were looked at to identify those that could be analysed with the information extracted from the classified images. The threats to cockle seed and adult cockle production include salinity, turbidity, water temperature, nutrient contents, overharvesting of cockles, human development, pollution, predators and disturbance or destruction of adjacent mangrove forests (Pathansali and Soong, 1958, Broom, 1985, Din and Ahamad, 1995, Rönnbäck, 1999, Ellison, 2008, Ong and Gong, 2013).

The threat of disturbance or destruction of mangroves adjacent to the natural cockle spatfall areas was the only factor that was observable from the produced set of classified images and ancillary data available in the study. The occurrence of such an event would have adverse effects such as slower growth of the cockles and lead to the deterioration or destruction of natural spatfall areas which are essentially the most valuable asset in the multimillion-dollar industry (Ong and Gong, 2013).

The natural cockle spatfall areas are concentrated in the Larut-Matang fishery district. The total area of the natural spatfall is estimated to be 1,300 ha. Sector 1 is estimated to be 300 ha, Sector 2 is estimated to be 750 ha and Sector 3 is estimated to be 250 ha (Roslan and Nik Mohd. Shah, 2014). Despite the large estimate of cockle spatfall areas, there have been no recorded production of cockle seeds in the area since 2004 except for 2011 when only 27.08 tonnes were produced. The rapid decline began in 1993, after a record 9971.31 tonnes was produced.

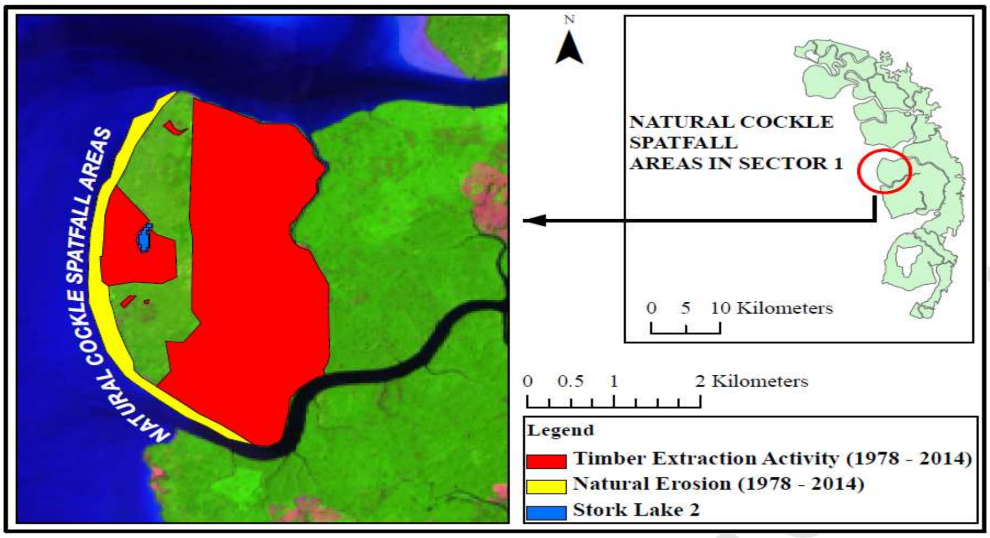
To determine if the systematic management of the MMFR could be one of the possible direct causes of the decline in the production of cockle seeds and adult cockles, the time series classified images of the mangrove forests adjacent to the natural cockle spatfall areas were analysed. The objective was to investigate if there had been any disturbance or removal of mangrove forests in these areas during the period of 1978 to 2014 which could have led to the decline in the cockle seed production.

Some parts of the mangrove forest adjacent to the natural cockle spatfall area in Sector 1 have been exposed to timber extraction activity (**Fig. 7a**). Although some parts of the area have been designated as protected areas, it was found to have been clear felled several years prior to 1988. The surrounding area has also been severely eroded from the period of observation from 1978 to 2014. It has been estimated to have lost a total coastal border of 91 ha.

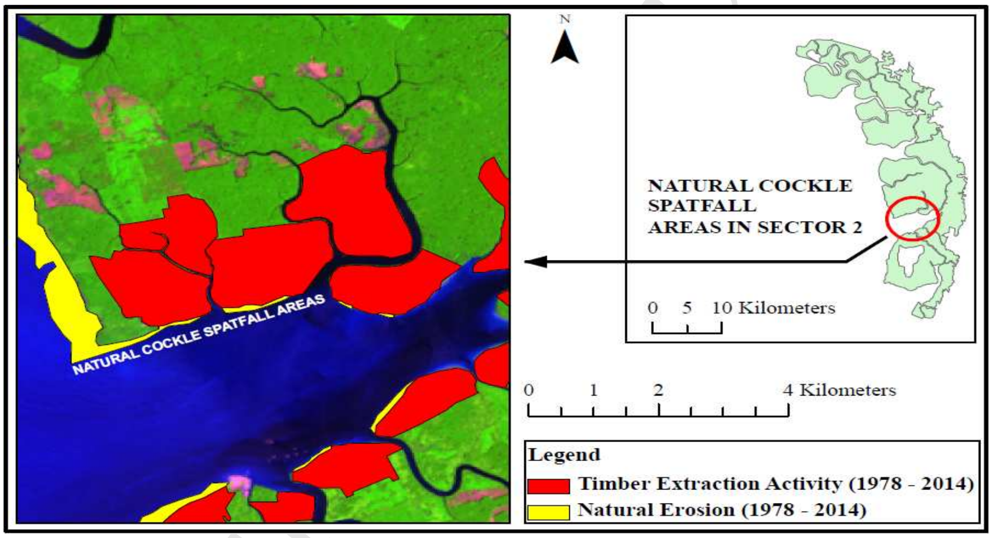
Sector 2, which has the largest estimated area of natural cockle spatfall area, is almost completely surrounded by adjacent mangrove forests that have been designated as a production forest (**see Fig.7b**). There has been a substantial amount of erosion in the coastline north-west of the natural cockle spatfall area totalling a loss of a 269 ha between 1978 and 2014. Only a total of 33 ha have been loss to erosion in the areas adjacent to the natural cockle spatfall area.

Interestingly, in contrast to the natural cockle spatfall areas previously analysed, Sector 3 has significantly large areas of adjacent mangrove forests that have not been designated as a production forest (**Fig. 7c**). The only area adjacent to the spatfall area that has disturbed was an area that was clear felled in 1978; none has been exposed to any form of timber extraction since. It was also the only area that showed an increase of mangrove forest area due to accretion – it reclaimed 33 ha of land. However, relative to the estimated natural cockle spatfall size of area, Sector 3 suffered the largest loss of an adjacent mangrove forest due to erosion. It was subjected to a loss of 200 ha of coastal borders.

a)


NATURAL COCKLE SPATFALL AREAS
N
NATURAL COCKLE
SPATFALL
AREAS IN SECTOR 1
0 5 10 Kilometers
0 0.5 1 2 Kilometers
Legend
Timber Extraction Activity (1978 - 2014)
Natural Erosion (1978 - 2014)
Stork Lake 2

b)


NATURAL COCKLE SPATFALL AREAS
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NATURAL COCKLE
SPATFALL
AREAS IN SECTOR 2
0 5 10 Kilometers
0 1 2 4 Kilometers
Legend
Timber Extraction Activity (1978 - 2014)
Natural Erosion (1978 - 2014)

c)

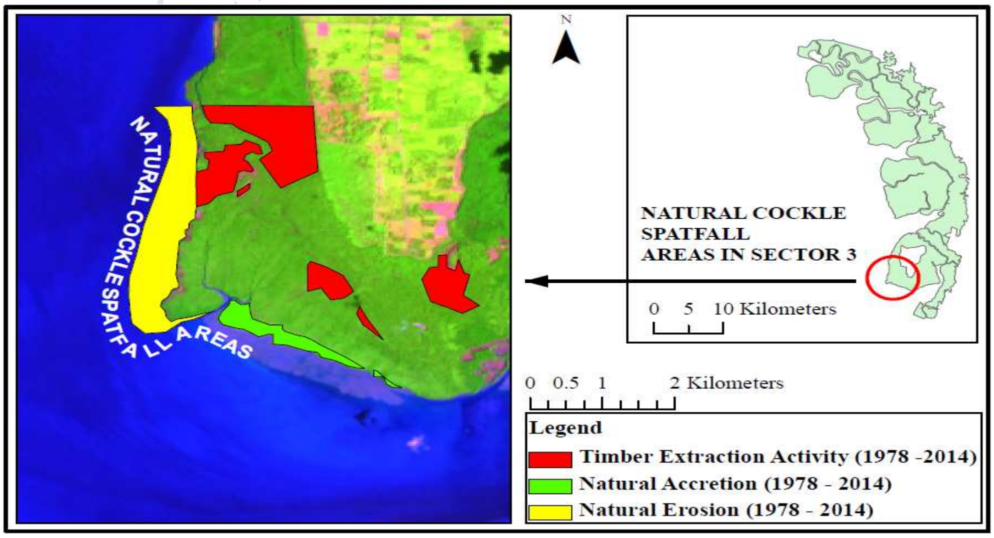
NATURAL COCKLE SPATFALL AREAS
N
NATURAL COCKLE
SPATFALL
AREAS IN SECTOR 3
0 5 10 Kilometers
0 0.5 1 2 Kilometers
Legend
Timber Extraction Activity (1978 -2014)
Natural Accretion (1978 - 2014)
Natural Erosion (1978 - 2014)

Fig. 7. The estimated natural cockle spat fall areas in a) Sector 1, b) Sector 2 and c) Sector 3 viewed on a Landsat image dataset acquired on the 11th of February 2014.

From the analysis, it can be concluded that large areas adjacent to the spatfall area in the MMFR were either subjected to timber extraction or natural coastal erosion and at times, to both factors simultaneously. This could have possibly deprived spatfall areas of the presence of adjacent mangrove forest that regulates and maintain good water quality which abates fluctuations in salinity and turbidity and reduces concentration of pollutants (Rönnbäck, 1999) and control nutrient levels by providing the area with much needed nutrient replenishment (Holguin et al., 2001, Niiyama et al., 2012, Mohd Fadzil Shuhaimi and Faizal Riza, 2013). In addition, if the presence of both these factors in the natural cockle spatfall areas caused interference in the normal pattern of water circulation then it could be the case that the cockle spat were also hindered from settling in the cockle beds (Ong and Gong, 2013).

Habitat for migratory birds

The management regime has taken great efforts to preserve the mudflats and protect the two natural lakes generally referred to as Stork Lake I (located in Pulau Kelumpang) and Stork Lake II (located in Pulau Trong Utara) to provide high quality refuge and feeding ground for migratory shorebirds and the highly endangered Milky Stork (Azahar and Nik Mohd. Shah, 2003). Despite the intensification of these efforts, assessments based on data gathered from previous research have shown an alarming trend of decline in the population of these birds over the past 25 years.

A century of continued management of the MMFR could have resulted in the accumulation of direct and indirect anthropogenic disturbances possibly causing the degradation in the quality of the stopover sites. This could have eventually affected the migratory shorebird prey population, foraging rates and use of foraging and roosting sites (Koch and Paton, 2014). Prolonged or intense direct anthropogenic disturbance have been found to have caused the complete abandonment of stopover sites (Pfister et al., 1992).

A stable food supply for shorebirds is crucial in maintaining regular shorebird migration and it is interesting to note that wading shorebirds have been reported to be important predators of small blood cockles (Broom, 1985, Iwamatsu et al., 2007). A link has been established between the decline in the number of young migratory shorebirds and low food supply in the form cockle and mussel stock levels (Atkinson et al., 2003). Since predation has been found to be an unlikely cause of variation or decline in cockle spatfall (Dare et al., 2004), it is therefore important for future research to investigate the impact of diminishing supply of cockle seeds on the decline in migratory shorebirds at the MMFR.

In contrast, the lack of food has not been identified as a potential factor in the decline of the Milky Stork population at the mangrove forest reserve (Swennen and Marteijn, 1987). Among the factors that have been found to be the leading cause of the decline in the Milky Stork population at the mangrove forest reserve are hazardous chemicals, habitat destruction, poaching by humans, high rates of predation and disturbance, and most importantly, the lack of mature trees for nesting (Li et al., 2006b, Ismail and Rahman, 2012). An old growth dependent species, the Milky Stork uses tall trees between the height of 8 to 14 m and nests are usually placed at the height of 6 to 12 m (Verheugt, 1987). Forestry activities have been found to be the main source of habitat disturbance and alteration which threatens the existence of the Milky Stork population (Luthin, 1987, Verheugt, 1987, Li et al., 2006b).

The key factors in this study that are crucial in establishing the links between the classified images and the assessment of the potential habitat for migratory birds at the MMFR are the analyses of habitat disturbance and alteration and the changes in the vegetation structure with respect to the availability of tracts of undisturbed and tall mature mangrove trees. These are factors that could be observed and analysed through the output of classified images with a focus on the decline of the Milky Stork population mainly because of its requirement of tracts of undisturbed and tall mature mangrove trees for roosting and breeding.

The two lakes in Pulau Kelumpang and Pulau Trong were identified as an important feeding, roosting and breeding area at the MMFR during two different time periods (Verheugt, 1987, Li et al., 2006a). Based on surveys carried out at the mangrove forest reserve, Li et al. (2006a) was of the opinion that Stork Lake II appeared to be more of an alternative site for the Milky Stork during periods when the lake at Pulau Kelumpang is too disturbed or dry. An equal emphasis were placed on both the areas in the analysis and discussion of this study.

The first signs of disturbance of the bird habitats were uncovered in the previous analysis on blood cockles in which there was evidence of clear felling that occurred around the area encompassing Stork Lake II several years before 1988. The visible boundaries surrounding the change in vegetation shows that it had been a coordinated destruction of the mangrove forest surrounding the habitat. This destroyed large tracts of matured and tall mangrove trees. In the 1988 classified image, large parts of the area are seen covered by the growth of young mangrove trees (**Fig. 8**).

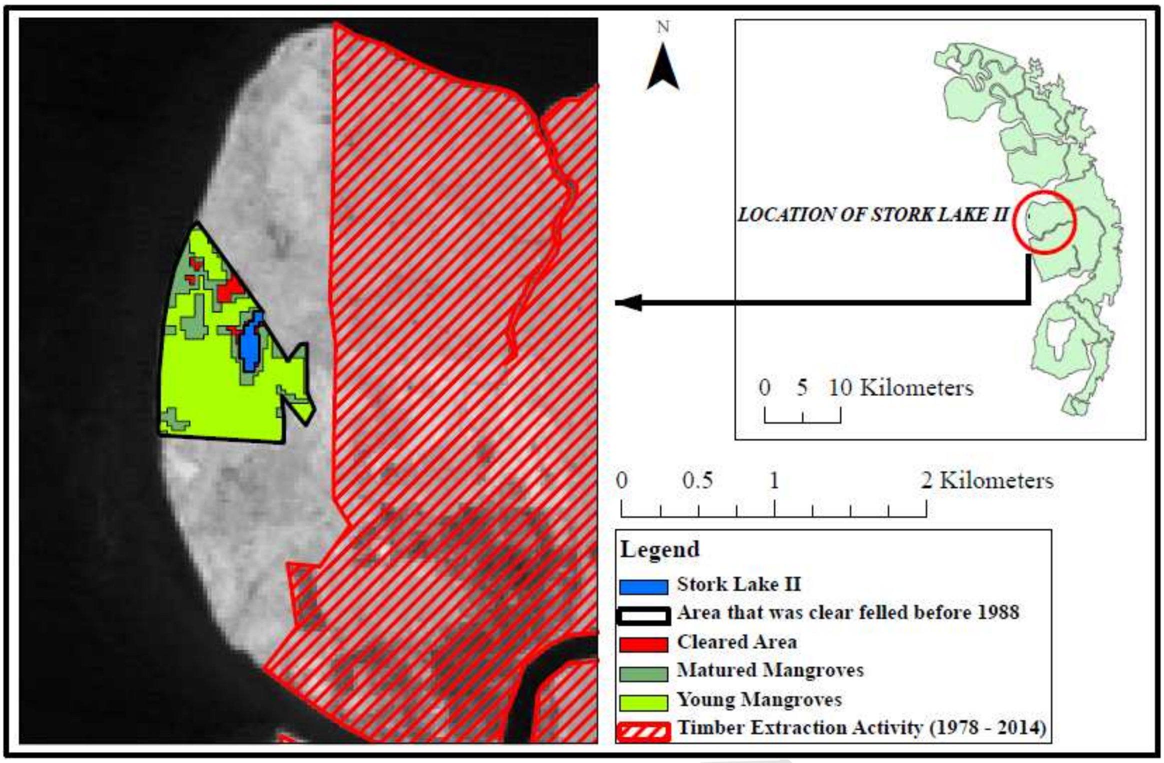

Fig. 8. The composition and overlay of subsets of the ancillary data, the classified image output and the 1988 Landsat 8 satellite image depicting the location and surrounding of Stork Lake II.

There were also signs of recently cleared area north-west of Stork Lake II in the 1988 classified image subset. Twenty six years later, in the 2014 classified image, that particular area remained clear of vegetation due to changing conditions on ground level probably causing issues such as deep flooding which inhibits the growth of new mangrove trees. This is yet another form of evidence indicating that timber extraction activity can permanently change the landscape of the mangrove forest reserve. This time, unfortunately, the change is in close proximity of a sensitive and important bird sanctuary.

In addition to the close proximity land clearing issue, timber extraction activities are also carried approximately 600 m away from the bird habitat. This can be also be a crucial threat as Milky Storks are very sensitive to disturbance and have been reported to take flight at the presence of approaching surveyors at a distance of between 100 to 200 m (Li et al., 2006b). The combination of the lack of mature and tall mangrove trees and the close proximity of timber extraction activity at Stork Lake II may have made it a less likely destination for the Milky Stork population in the late eighties.

The analysis on Stork Lake I uncovered a significant ecological change in 1988 that may have gone undetected and has therefore never been specifically put forth as a possible cause in the decline of migrating birds, including the Milky Stork population. The area surrounding Stork Lake I is under a management zone classified as Protective Forest (**Fig. 9**). Despite being free from timber extraction activities, large areas of the forest were found sharing similar spectral characteristics of cleared areas found in the Productive Forest management zones indicating the absence of mangrove trees, especially the tall and mature ones.

The multi-temporal classified images of the area surrounding Stork Lake I shows that the problem continued to deteriorate a year later in 1989 as seen in **Fig. 9 (*bottom*)**. The forest recovered naturally 10 years later as reflected in the 1999 image subset. However, in 2009 signs of the problem recurring in the area north-east of Stork Lake I are detected, close to areas that have been designated as a Productive Forest management zone. A more recent subset image of 2014 shows the problem spreading wider towards the areas in the east and south-east of the important bird sanctuary. Based on the time series observation of mangrove forest cover in 1988-1989 and the effects it may have had on the population of migratory birds at the Stork Lakes, the more recent detection of a decreasing forest cover is a cause for serious concern and merit further and intensive investigation.

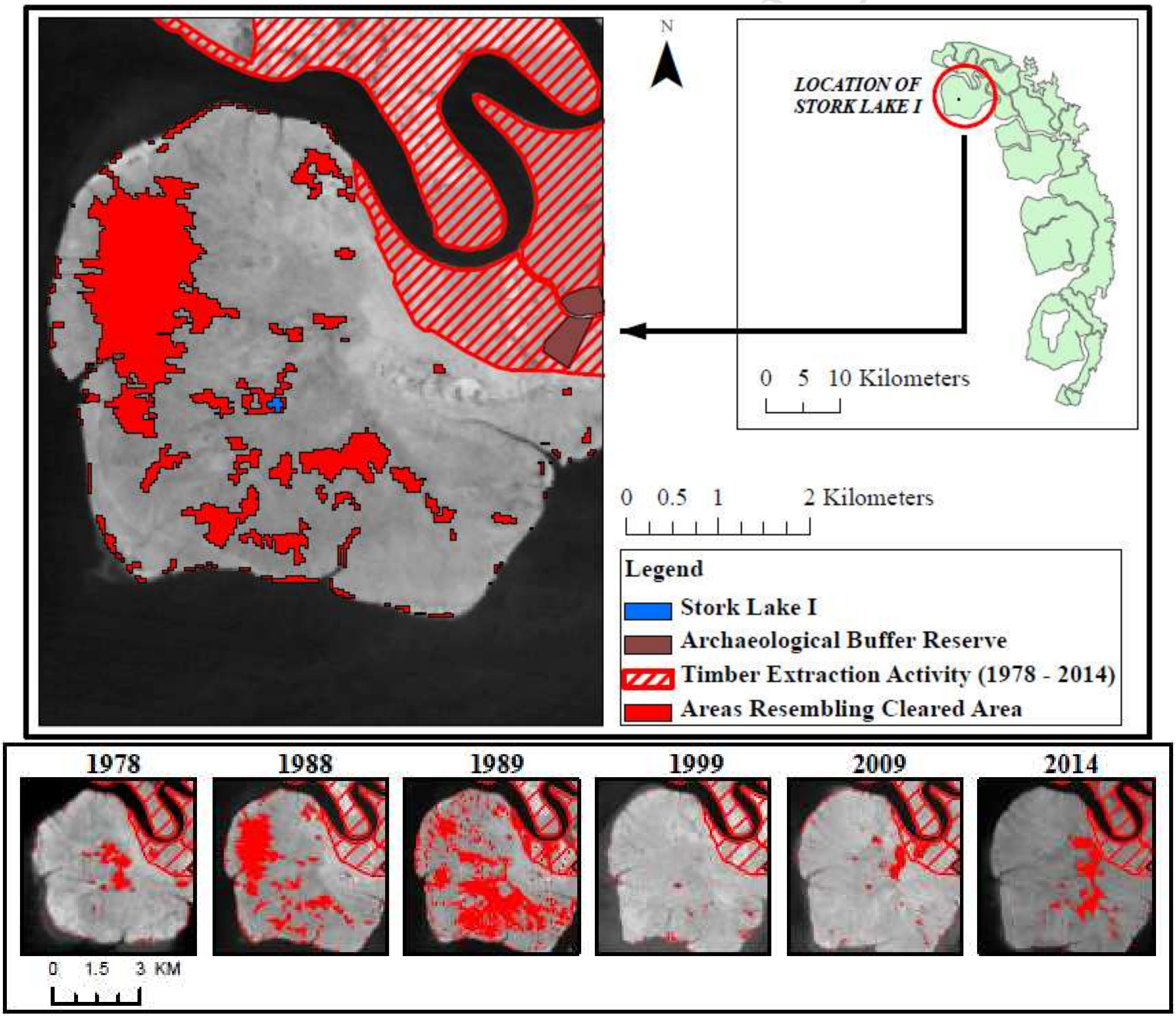

Fig. 9. (*Top*) The composition and overlay of subsets of the ancillary data, the classified image output and the 1988 Landsat 8 satellite image depicting the location and surrounding of Stork Lake I.

(*Bottom*) The ecological change during the period 1978 to 2014 surrounding Stork Lake 1 derived from classifying multi-temporal Landsat scenes.

The findings of the analysis are in direct contrast to that of Li et al. (2006) who suggested that the mangrove forest vegetation structure surrounding Stork Lake I and Stork Lake II changed little in the last two decades preceding the study period. Evidence suggests that systematic clear felling was carried prior to 1988 at Stoke Lake II and an unknown cause had led to the deterioration of the mangrove forest vegetation surrounding Lake I. The findings concur with the observation made by Verheugt (1987) with regards to the absence of immatures in the area. The fact that both these factors had occurred during the same time period could have only spelled disaster for the population of the Milky Stork and perhaps some species of the migratory birds.

5.2 External pressures exerted on to the mangrove forest reserve

There are mangrove forests that share borders or are located within the MMFR that have not been designated as Permanent Reserved Forests. These areas are either privately or stated owned lands that do not fall under the jurisdiction of the Perak State Forestry Department. Because of the complex and dynamic relationship shared between the designated mangrove forest reserve and the surrounding mangrove forest, it is important to briefly mention some results of interest that were derived from the multi-temporal land use change analysis.

Since 1978, a total of approximately 546 ha of mangrove forest within or adjacent to the mangrove forest reserve were detected to have been cleared for aquaculture and approximately 146 ha had been cleared for agriculture. The startling fact is that more than half of the areas cleared for aquaculture, totalling approximately 301 ha, were cleared within the past 5 years. Although limited operation may not have significant impacts on the mangrove forest reserve (Rönnbäck, 1999, Alongi, 2002), it could exert more unnecessary pressure on the delivery of other ecosystem services that are already showing multiple signs of deterioration. Some of the direct and indirect problems of pond aquaculture include blockage of tidal creeks; alteration of natural tidal flows; alteration of the groundwater table; increase in sedimentation rates and turbidity in natural waters; release of toxic wastes; overexploitation of wild seed stocks; development of acid sulphate soils; reduced water quality; introduction of excess nutrients; and alteration of natural food chains (Robertson and Phillips, 1995, Alongi, 2002). These are all factors that could negatively impact all three of the ecosystem services that have been assessed in this study.

5.3 Uncertainties

The analysis of the classified images in this study includes a certain degree of uncertainty. Therefore, it is important to identify and understand the source of these uncertainties that are associated with the analysis prior to any form of utilization of any extracted information from the study.

Firstly, the 1978 classified image were derived from an MSS image that has a spatial resolution of 80 m and four bands. All the other classified images were derived from images with a spatial resolution of 30 m and six bands. The incorporation of the data, although much coarse compared to the other image datasets, was however necessary to ensure a multi-temporal analysis that spanned more than 30 years – the time that would take to complete the cycle of a single rotation at the MMFR. In addition to that, the study area is a managed mangrove forest with sub-coupes that have a minimum size of 2 ha. This would compensate or negate the amount of information that could potentially be lost by incorporating a lower resolution image dataset.

Secondly, a close examination of the classified data showed that the classification results of areas of young mangrove trees between the ages of three and five years would sometimes be misclassified as mature mangrove forest due to the vegetation structure. Based on the ancillary dataset and the management records, it is estimated that there is a possibility of an over estimation of mature mangrove forest and an under estimation of young mangrove forest by approximately 2400 ha. Apart from that age group, the study was able to conclusively separate the younger mangrove stands (dense stands) from the mature stands (sparse stands).

6. Conclusion

An object-based approach was applied to classify and analyse multi-temporal Landsat imagery of the MMFR from 1978 to 2014. Although the analysis showed that the management have maintained a relatively stable area of clear felled areas, young and mature mangrove forests throughout the observation period, the results of the accompanying ecosystem services assessment disclosed signs of deterioration in the provision of several critical ecosystem services at the mangrove forest reserve. The state of these ecosystem services reflect the real underlying challenges faced by the management of the mangrove forest reserve in achieving optimum balance between sustaining high yielding timber extraction activity and preserving the ecologically sensitive coastal ecosystem.

By establishing links between the classified images and the ecosystem services assessment, possible causes for the deterioration were identified. The findings suggests that the fluctuation in greenwood yield could be negatively affected by varying rates of regeneration and exposure to excessive thinning. The delay in harvesting on the other hand, may have led to positive increases in greenwood yield. Timber extraction and natural coastal erosion were identified as some of the possible causes in the drastic decline in the production of blood cockles around the mudflats of the mangrove forest reserve. An undetected ecological change in the late eighties and anthropogenic disturbances were uncovered as the possible key factor behind the decline in the population of the Milky Stork and migratory shorebirds. The study also emphasized the dangers of the recently detected change in the vegetation structure in the surrounding areas of Stork Lake I.

In addition to the multiple signs of deterioration in ecosystem services highlighted, the MMFR is also exposed to pressures exerted from activities along its borders. Due consideration must be given to these ecosystem services as a whole to enhance our understanding of the relationship that exist between these services. These flow of services, if left unmonitored, could cause a subtle but yet devastating degradation of the entire coastal ecosystem. It could lead to a decline in the ecosystem functions and disrupt the flow of critical ecosystem services to the community.

Further research is needed to better understand the underlying causes of late regeneration of mangrove trees and its effect on greenwood yield overtime. The decline in the production of blood cockle seed and adult blood cockle also needs to be investigated to identify possible management actions to promote sustainability. Investigating the possible links between blood cockles and migratory birds at the MMFR bird sanctuaries and determining an effective conservation plans for the population of migratory birds and Milky Storks are also important actions to be considered.

Future research will be able to take full advantage of the recently launched Landsat 8. The availability of a constant source of image datasets will allow the recalibration of the classification to increase its accuracy and effectiveness. The impact of change in vegetation structure on spectral signatures of designated plots can be closely monitored. Overall, future research should focus on priority management issues. It is crucial to link science to management in order to have an effective and efficient mangrove management. The findings of future research can be used to underpin the management of sustainable ecosystem services at the mangrove forest reserve in future.

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