UNIVERSITI PUTRA MALAYSIA

GEOSPATIAL MAPPING AND MODELLING OF MANGROVE ECOSYSTEM HEALTH AT MATANG MANGROVE FOREST RESERVE

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By

RHYMA PURNAMASAYANGSUKASIH PARMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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GEOSPATIAL MAPPING AND MODELLING OF MANGROVE ECOSYSTEM HEALTH AT MATANG MANGROVE FOREST RESERVE

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Chair : **Norizah Kamarudin, PhD**
Faculty : **Forestry and Environment**

Among the multi-functional ecosystem provided by mangrove forest, the health like biotic and abiotic variables represent the most challenging components to be monitored due to their diverse characteristics and spatially distributed over mangrove area. Since the biotic and abiotic variables factors are vital for the mangrove ecosystem health (MEH), the information of remotely sensing data and spatial analysis were integrated to evaluate the health condition of mangrove. The objective of this study was (1) to examine mangrove vegetation cover by integrating NDVI and SAVI, and (2) to model the MEH using ordinary kriging (OK) for the entire MMFR.

Supervised classification, NDVI and SAVI were performed to determine vegetation coverage. Since SAVI requires a suitable *L*-factor to be used to distinguish the vegetation areas, four different *L*-factors *viz*. 0.1, 0.25, 0.5 and 0.75 were tested with the multiple linear regressions using the stepwise regression method of backward elimination. The relationship of NDVI and SAVI in detecting mangrove vegetation covers were examined with correlation-Pearson analysis. For Objective 2, eight variables from Faridah-Hanum et al. (2019) were used as preference factors to determine the MEH. Semivariogram model and interpolation method of OK were used to generate spatial autocorrelation of MEH. Prediction accuracy was examined through ME, RMSE and RMSSE. All variables were then overlay and combined via linear weight regression (LWC) to see the overall health status. Reclassification was conducted to standardise the health value *viz*. 1 (worst), 2 (poor), 3 (moderate), 4 (good) and 5 (excellent). In order to verify the health status, NDVI analysis performed in Objective 1 were used to support the accuracy of MEH.

Supervised classification was observed with good accuracy; Kuala Sepetang (71.8%; K=0.668), Kuala Trong (83.8%; K=0.798) and Sungai Kerang (73.5%; K=0.681). SAVI with *L*-factor 0.75 was found to be significant to be used for MMFR. The vegetation indices (VIs) resulting from NDVI and SAVI demonstrate the classification variations when compared to the initial supervised classification. In Objective 2, all variables had an overall prediction accuracy with 85.16% (AGB), 90.78% (crab abundance), 97.3% (soil C), 99.91% (soil N), 89.23% (number of phytoplankton species), 95.62% (number of diatom species), 99.36% (DO) and 87.33% (turbidity). The spatial prediction autocorrelation delineating an area of 307.9 ha for excellent MEH, 15935.68 ha for good MEH, 5224.34 ha for moderate MEH, 17795.63 ha for bad MEH and 715.55 ha for worst MEH. This study modelled the overall MEH through OK with selected semivariogram model and comparison to VIs consequently promoting the restoration affects, relevant management and facilities distribution, and therefore improving the MEH over the entire MMFR.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PEMETAAN GEOSPATIAL DAN PERMODELAN KESIHATAN EKOSISTEM HUTAN PAYA BAKAU DI HUTAN SIMPAN PAYA BAKAU MATANG

Oleh

RHYMA PURNAMASAYANGSUKASIH PARMAN

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Di antara ekosistem pelbagai fungsi yang disediakan oleh hutan bakau, kesihatan seperti pemboleh ubah biotik dan abiotik merupakan komponen yang paling mencabar untuk dipantau kerana ciri-cirinya yang pelbagai dan tersebar secara spasial di kawasan bakau. Oleh kerana faktor pemboleh ubah biotik dan abiotik sangat penting untuk kesihatan ekosistem paya bakau (KEPB), maklumat data penderiaan jarak jauh dan analisis spasial disatukan untuk menilai keadaan kesihatan bakau. Objektif kajian ini adalah (1) untuk memeriksa penutup vegetasi bakau dengan mengintegrasikan *NDVI* dan *SAVI*, dan (2) untuk memodelkan KEPB menggunakan *Ordinary Kriging* (OK) untuk keseluruhan HSPBM.

Pengelasan yang diselia, *NDVI* dan *SAVI* dilakukan untuk menentukan liputan vegetasi. Oleh kerana *SAVI* memerlukan faktor *L* yang sesuai untuk digunakan untuk membezakan kawasan tumbuh-tumbuhan, empat faktor *L* yang berbeza. 0.1, 0.25, 0.5 dan 0.75 diuji dengan regresi linear berganda menggunakan kaedah regresi linear berganda langkah demi langkah ke belakang. Hubungan NDVI dan SAVI dalam mengesan penutup tumbuh-tumbuhan bakau diperiksa dengan analisis Korelasi-Pearson. Untuk Objektif 2, lapan pemboleh ubah dari Faridah-Hanum et al. (2019) digunakan sebagai faktor pilihan untuk menentukan KEPB. Model semivariogram dan kaedah interpolasi *OK* digunakan untuk menghasilkan autokorelasi spasial KEPB. Ketepatan ramalan diperiksa melalui *ME*, *RMSE* dan *RMSSE*. Semua pemboleh ubah kemudian dilapisi dan digabungkan melalui kombinasi berat linear (LWC) untuk melihat keseluruhan status kesihatan. Pengkelasan semula adalah dijalankan untuk menyeragamkan nilai kesihatan iaitu 1 (sangat tidak sihat), 2 (tidak sihat), 3 (sederhana), 4 (sihat) dan 5 (sangat sihat). Untuk mengesahkan keadaan kesihatan, analisis *NDVI* yang dilakukan dalam Objektif 1 digunakan untuk menyokong ketepatan KEPB.

Pengelasan yang diselia diperhatikan dengan ketepatan yang bagus; Kuala Sepetang (71.8%; K=0.668), Kuala Trong (83.8%; K=0.798) and Sungai Kerang (73.5%; K=0.681). *SAVI* dengan faktor *L* 0.75 didapati signifikan untuk digunakan untuk MMFR. Indeks-indeks tumbuhan (VIs) yang dihasilkan dari *NDVI* dan *SAVI* menunjukkan variasi klasifikasi jika dibandingkan dengan pengelasan awal yang diselia. Dalam objektif 2, semua pemboleh ubah mempunyai ketepatan ramalan keseluruhan dengan 85.16% (AGB), 90.78% (kelimpahan ketam), 97.3% (K tanah), 99.91% (N tanah), 89.23% (bilangan spesies fitoplankton), 95.62% (bilangan spesies diatom), 99.36% (DO) dan 87.33% (kekeruhan). Ramalan autokolarasi spatial menggambarkan kawasan seluas 307.9 ha untuk KEPB yang sangat baik, 15935.68 ha untuk KEPB yang baik, 5224.34 ha untuk KEPB sederhana, 17795.63 ha untuk KEPB tidak sihat dan 715.55 ha untuk KEPB sangat tidak sihat. Kajian ini memodelkan keseluruhan KEPB melalui *OK* dengan model semivariogram terpilih dan perbandingan *VIs* yang mendorong pemulihan mempengaruhi, pengurusan dan pengagihan kemudahan yang relevan, dan dengan itu meningkatkan KEPB di seluruh MMFR.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AGB	Aboveground Biomass
C	Carbon
CPs	Control Points
DO	Dissolved Oxygen
GCPs	Ground Control Points
GIS	Geographic Information System
GPS	Global Positioning System
M	Meter
ME	Mean Error
MEH	Mangrove Ecosystem Health
MEHD	Mangrove Ecosystem Health Distribution
MLC	Maximum Likelihood Classification
MMFR	Matang Mangrove Forest Reserve
N	Nitrogen
NDVI	Normalised Difference Vegetation Index
OGF	Old Growth Forest
RMSSE	Root-Mean-Square Standardised Error
SAVI	Soil-Adjusted Vegetation Index
SPOT	Satellite Probatoire d’Observation de la Terre
VIs	Vegetation Indices
VJR	Virgin Jungle Reserve

CHAPTER 1

INTRODUCTION

1.1 General background

Mangroves are a form of vegetation that connects the terrestrial landscapes with the sea environment; these sea-land interface forests are commonly found along the coastlines and around estuaries of the tropical and sub-tropical regions (Ewell et al., 1998; Alongi, 2002; Hamdan et al., 2012; Ammar, 2014). These salt-tolerant trees are found in abundance in the tropical Asia, Africa, and the islands of the Southwest Pacific (Hamdan et al., 2012). The unique mangrove ecosystem influences the existence of a diverse range of tree species. Most of the mangrove species survive and even flourish under the high and low tides as the trees have a complex root system to cope with salt water immersion and wave action (Lugo and Snedaker, 1974; Kuenzer et al., 2011; Nowak, 2013). Mangrove forests are difficult to access due to several factors: the presence of aerial root systems that arch high over the water and extend to a wide area; dense tree stands of the mangrove species; and regular occurrence of high and low tides with deep mudflats. Despite the harsh environment (Giri et al., 2011; Rhyma et al., 2016; Wang et al., 2019), this forest ecosystem has many important functions and produces various invaluable goods and services that are beneficial to human well-being. These benefits include availability of timber and forest products (Putz and Chan, 1986; Aschbacher et al., 1995; Alongi, 2002; Ammar, 2014), coastal protection, nutrient and sediment filtration, provision of nurseries and feeding ground for fishes and crustaceans (Barbier, 2003; Mumby et al., 2004; Sharitz and Penning, 2006; Ammar, 2014), supporting coastal fisheries (Gong and Ong, 1990; Aschbacher et al., 1995; Thu, 2006; Heumann, 2011), shoreline stabilisation, climate regulation, water quality maintenance as well as creating recreational and cultural values (Hemminga et al., 1994; Ewel et al., 1998; Alongi, 2008; Kamaruzaman and Dahlan, 2008; Liu et al., 2008; UNEP, 2014; Heumann, 2011). The positive contribution of the mangroves to the human race has been globally recognised; and people are more aware of the coastal security after the Indonesian tsunami disaster in 2004, which affected neighbouring countries such as Thailand and Malaysia.

Globally, approximately 35-36% of the total mangrove forest had been lost in the last two decades (Feller et al., 2017; Carugati et al., 2018) due to natural disasters such as erosion (Thomas et al., 2017), cyclones and typhoons (FAO, 2007; Islam et al., 2018). It is also reported that the mangrove forest area has significantly declined due to anthropogenic activities such as agriculture/rice production (Alongi, 2002; Giri et al., 2011), coastal development (Maiti and Chowdhury, 2013; UNEP, 2014), urbanisation (UNEP, 2014; Richards and Friess, 2016), aquaculture (Richards and Friess, 2016; Islam et al., 2018), over-harvesting/exploitation (Giri et al., 2011; Thomas et al., 2017), tourism (Giri et al., 2011; Islam et al., 2018), forestry (Valiela et al., 2001; Richards and

Friess, 2016), mariculture (Valiela et al., 2001), artisanal and commercial fisheries, human settlements, harbours construction, ports operation, recreation, mining and industrial development (Santos et al., 2014), and pollution (UNEP, 2014; Feller et al., 2017). These human-related activities cause the declining trend in conserving the mangroves ecosystem. According to Carugati et al. (2018), climate changes and anthropogenic activities are the major threats to the mangroves (Van Lavieren et al., 2012; Ellison and Zouh, 2012); they are detrimental to the health of the mangrove ecosystem and would contribute to the functional loss (Duke et al., 2007; Thomas et al., 2017). Generally, mangroves loss is associated with a loss of biodiversity (Polidoro et al., 2010; Carugati et al., 2018). An ecology theory predicts that the functions of an ecosystem can be influenced by biodiversity, and contrasting results are shown through correlative investigation and manipulative experiments (Loreau, 2010; Carugati et al., 2018). An ecosystem functions more often than not, is positively related to biodiversity (Cardinale et al., 2012; Carugati et al., 2018); therefore, a loss of biodiversity could result in a reduction in the ecosystem functioning and negatively affect the capacity of the ecosystem to provide goods and services to humans (Worm et al., 2006; Danovaro et al, 2008; Bulling et al., 2010; Cardinale et al., 2012; Carugati et al., 2018). This is particularly evident in the tropical ecosystem, which hosts an important fraction of the coastal biodiversity such as mangroves, and is among those that will experience the earliest emergence of the impacts of global changes (Solan et al, 2006; Carugati et al., 2018).

The remote sensing technology has revolutionised the way ecological research is conducted; ecological datasets from field data which include land cover classifications and vegetation indices at local to global scales, can be collected through the remotely sensed imagery analysis or derived by using the GIS techniques (Cohen and Justice, 1999; Rushton et al., 2004; Miller and Rogan, 2007). The integration of these pieces of information has been proven (Pimm et al., 2015; Marvin et al., 2016) effective, and the innovative data gathering procedure expands the boundaries of the traditional ecological inference and conservation strategies (Snaddon et al., 2013; Marvin et al., 2016). According to Kerr and Ostrovsky (2003), the estimation of ecosystem functions cannot be easily converted from field-based measurements covering an entire system; however, the integration of the remotely sensed data can provide simultaneous estimates of the ecosystem functions over a wide area. This statement concurs with views of Miller and Rogan (2007), who opine that the integration of remotely sensed data can improve the data quality and integrity of a GIS database (field-based measurement), which can then be employed to describe the actual ground conditions. The remotely sensed measurements such as synoptic view, temporal frequency and repeatability are valuable for detecting and monitoring changes to ground conditions (Rogan et al., 2003; Miller and Rogan, 2007).

Over the past 20 years, remotely sensed data have been used extensively to map and monitor mangrove environments (Heumann 2011; Kuenzer et al., 2011). The remote sensing technology provides key advantages for mangrove studies, which include the following: (i) indirect access to mangrove habitats in areas that are temporarily inundated and often inaccessible due to geographical location in intertidal zones (Ramsey III and Jensen 1996; Davis and Jensen 1998); (ii) observation results at specific sampling sites can be extrapolated to encompass an entire image extent (Hardisky et al. 1986); (iii) providing a synoptic overview and repeated coverage of mangrove sites (Giri et al. 2007); and (iv) delivery of data at multi-scale levels to address key problems in coastal areas (Malthus and Mumby 2003). The recent developments of the remote sensing and image processing technologies provide new avenues of exploring various types of image datasets as well as types of mapping techniques or combinations of them, to map mangrove environments (Heumann 2011; Kuenzer et al. 2011). Problems could arise when there is a need to match the scale of an analysis to the scale of the phenomenon under investigation because environmental inferences are scale-dependent (Wiens, 1989). As such, there are many knowledge gaps in dealing with remote sensing approaches for mapping mangrove forests, which include knowing the type of mangrove information that can be mapped from specific image resolutions and the level of detail in that information.

In Malaysia, the applications of remote sensing and geographical information system (GIS) have been deployed for different purposes in managing the mangrove forests. Many researches have been undertaken using these two modern data-collecting technologies and below are some examples of the studies: (i) mangrove mapping and monitoring in Terengganu (Sulong et al., 2002), Selangor (Khali Aziz et al., 2009), the entire Peninsular Malaysia (Hamdan et al., 2012), Kelantan (Che Ku Akmar et al, 2009, Satyanarayana et al., 2011), Penang (Beh et al. 2011), Perak (Roslani et al., 2014), and Selangor (Samad et al., 2011); (ii) species identification via spectra examination in Selangor (Jusoff, 2006), and Perak (Zulfa et al. 2020; Beh et al., 2015); (iii) canopy density identification in Kedah (Mohd Hasmadi et al., 2008) and Johor (Mohd Hasmadi et al., 2011); (iv) mangrove ecological and ecosystem monitoring and production management in Perak (Ammar et al., 2015a; Ammar et al., 2015b; Ammar et al. 2016), Kedah (Khuzaimah, 2015; Khuzaimah et al., 2017; Otero et al., 2017; Faridah-Hanum et al., 2019; Otero et al., 2019; Rhyma et al., 2020); (v) carbon stock and biomass assessment in Perak (Hamdan et al., 2014; Hamdan et al., 2013; Otero et al., 2018); and (vi) soil quality assessment in Selangor (Jeyanny et al., 2018).

Vegetation indices are one of the analysis with satellite imageries. This analysis works by transforming the spectral metric contains in the satellite data for measuring the presence and examining the state of vegetation (Bannari et al., 1995; Khan et al., 2018). This analysis has widely adopted by a number of researchers for monitoring forest states for example, Kefalas et al. (2018) used Enhanced Vegetation Index (EVI), Normalised Difference Vegetation Index (NDVI), Normalised Difference Moisture Index (NDMI) and Modified Soil Adjusted Vegetation Index (MSAVI) in heterogeneous landscape (forest stands are mixed with cultivations), Tian et al. (2016) and Zhang et al. (2020) used NDVI in dryland, Xulu et al., (2020) used NDVI and Normalised Difference Vegetation Infrared Index (NDVII) in plantation forest, Oon et al. (2019) used NDVI in peatlands, and Ren et al. (2018) and Hashim et al. (2019) used NDVI in urban forest. Khan et al. (2018) mentioned the high indices value indicates healthy plants that exhibit high infrared reflectance and low red reflectance due to absorption of red light by chlorophyll. Analysing vegetation cover is first step in assessing ecosystem health (Liao et al., 2018), and VIs were simple algorithm and effective tools used to measure vegetation status (Xue and Su, 2017). Therefore, Liao et al. (2018) suggested VIs measure can be used to facilitate measure for ecosystem health.

Geostatistical analysis is a common spatial modelling technique used to help in decision making by making an evaluation and prediction from sample data (Towfiqul Islam et al., 2017). This analysis has been widely used by various fields for example on vegetation to assess variation of carbon density (Pan et al., 2019) and quantification carbon stock for mangrove soil (Castillo et al., 2017), on soil to assess soil quality for regenerating mangrove forest (Jeyanny et al., 2018), and water to assess spatial variability of water quality for development and rehabilitation of the mangrove trees (Lotfinasabasl et al., 2018) and to determine habitat suitability for predicting lionfish (*Pterois volitans*) distribution (Bernal et al. 2015). Estimating the ecosystem health has also one of the fields that applied geostatistical analysis. Due to the complex environmental data and evolution of spatial data analysis with advances algorithm analysis, geostatistical analysis is treated as the best tools to help in ecosystem services decision making (Obida et al., 2018; Dai et al., 2018; Shaheen and Iqbal, 2018). Since there are unique ecosystem of mangrove forests, estimation on the mangroves health can also be investigated with geostatistical analysis, by taking an advantages that the spatial data of mangroves is worth wile. Forest managers may find these investigative results helpful: assessment of the ecosystem services for a huge area by prediction analysis as well as vegetation indices mapping and modelling through a selected point. Armed with the useful data, the forest managers are able make informed decisions and take necessary actions in managing the mangrove forests to the best conditions and protect the mangrove ecosystem when it is at risk. The simultaneous use of geospatial analysis, modelling of remotely sensed imagery data, and GIS is a method of utilising all available data to monitor the vegetation and ecosystem health as well as providing the current status of the mangrove forest at a given site. Therefore, this study is conducted for the purpose of mangrove mapping and monitoring by using the geospatial modelling.

1.2 Problem statement

Despite the large number of studies of mangrove mapping and monitoring reported in the literature, no complete assessment technique has been found that incorporates the crucial aspects of mangrove health. Biotic and abiotic evidences are known as an indicator to determine the health of an ecosystem. By examining the conditions of the mangroves, the acceptable health level can be updated and the adversely affected part of the ecosystem can be verified. However, there is a limitation in collecting accurate information which is unevenly distributed over space and in different times; such situation necessitates obtaining information about the biotic and abiotic conditions. The environmental measurement is based on samples at specific locations, and provides useful information to predict the outcome of the samples in a studying area. With the advances of the image and geostatistical analysis algorithm, data taken from a specified location may represent the conditions of the examined variable adjacent to it. However, reliable estimates or predictions of the mangrove ecosystem health need to be examined.

Therefore, the current study is undertaken to investigate the vegetation health distribution by using two procedures: first, examine the indices of vegetation through the remotely sensed imagery data; second, apply the geostatistical analysis with data interpolation to interpret areas attributed to different ecosystem health indexes. The vegetation indices represent reactions to photosynthetic activity and determine the health of vegetation; the higher the NDVI value, the greater the vegetation covers will be (Xiao et al., 2020). While SAVI helps to correct the influences on soil brightness and subpixel classification to improve the classification by identifying different places in single spectrum. The findings of this study are crucial in reducing the manpower, time and cost of monitoring the mangroves; the current practice of manually checking the timber stock volume as an indicator of the mangrove health is labour-intensive, time-consuming and high-cost. Moreover, data collected with the use of modern methods like geostatistical analysis, especially pieces of information about tidal events in relation to the unique mangrove forest characteristics, are reliable and accurate; and it can be carried out within a short time, less laborious and less costly. Methodology applied in this study is also expected to be useful for forest managers and/or stakeholders to make similar ecosystem health monitoring in other forest types due to no limitation designed in this study to be applied specifically in mangrove forest.

1.3 Aim and Objectives

The aim of this study is to monitor the ecosystem health of MMFR. The specific objectives are as follows:

1. To examine the mangrove vegetation cover by integrating NDVI and SAVI of the Matang Mangrove Forest Reserve.
2. To map and model the health of the mangrove ecosystem of the Matang Mangrove Forest Reserve.

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LIST OF PUBLICATIONS

Articles

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