MODELLING SEAGRASS BLUE CARBON STOCK IN SEAGRASS-MANGROVE HABITATS USING REMOTE SENSING APPROACH

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Built Environment and Surveying
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AUGUST 2020

DEDICATION

This thesis is dedicated to my mother Hajiya Hassana Alikote, and my beloved wife, Badiya Salele.

ACKNOWLEDGEMENT

I like to commence by expressing my profound gratitude to the Almighty ALLAH for making all this affords accomplished and for sparing our life's to see this particular moment. Similarly, my indebtedness to appreciate my supervisor, Prof. Dr, Mazlan Hashim for his continuous guidance, fatherly advice, valuable assistance, constant support with endless encouragement throughout the research period. I would also, convey my sincere appreciation to my co-supervisor Dr Mohammad Shawkat Hossain for his much-esteemed suggestions and advises.

I also wish to extend my most profound gratefulness to my wife, Badiya Salele, for her support and prayers for my success and bright future. Members of my family, particularly my late father, Alh. Aliyu Sani, my mothers Hajiya Hassana Alikote, Maria Alikote, my daughters Badia and Mariya, my brothers Yusuf Aliyu and Mikail Suleman Miko and my sisters Asmau Aliyu, Amina Ladan, Samira Aliyu, Sauda Miko and Aisha Aliyu for their support, encouragement and continuous prayers.

I want to express my gratitude to the entire staff in the Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia for the extreme cooperation given to me at the period of my research. Finally, I wish to acknowledge so many special persons whose names are so many to be stated here. Even though, have assisted both academically and morally during the study period.

ABSTRACT

Modelling seagrass blue carbon stocks are essential to complement the satellite-based remote sensing in detecting the underground seagrass carbon stocks. The green carbon initiatives have for long reported the detailed mapping and estimation procedural as well as the audit protocol of the global terrestrial carbon stocks. Research on the blue carbon mapping and its related modelling and estimation, on the other hand, is rarely if ever published as part of its importance is realised but remained scattered. Therefore, this study aimed at investigating blue carbon stocks in seagrass habitats by estimating the total carbon stored in seagrass using the satellite-based technique. The specific objectives are to : 1) assess and adapt some selected models for deriving seagrass total above-ground carbon (STAGC); 2) formulate new approach based-on selected models to combine with in-situ data, to model and estimate blue carbon stocks from seagrass total below-ground carbon (STBGC); 3) develop a novel technique using the selected models with soil organic carbon (SOC) to model and estimate the blue carbon stocks from seagrass total soil organic carbon (STSOC); and 4) integrate all the models (STAGC, STBGC, and STSOC) to produce a framework for the mapping and estimation of seagrass total blue carbon stock (STBCS). Suitable logistic functions were selected and applied on the satellite images to investigate seagrass, and soil carbon stocks along the seagrass meadows of Peninsular Malaysia (PM) coastline All the Landsat ETM+'s shortwave visible bands (blue, green, red) were employed for detecting and mapping seagrass stocks boundary within the coastline of PM. The derivation of STAGC was adopted from the existing bottom reflectance index (BRI) based technique via establishing a strong relationship between BRI with seagrass total above-ground biomass (STAGB). While for STBGC estimation, the $STAGB_{BRI}$ (STAGB obtained from BRI image) were correlated with seagrass total below-ground biomass derived from in-situ measurement ($STBGB_{IN\text{-}SITU}$). Both these $STAGB_{BRI}$ and $STBGB_{IN\text{-}SITU}$ were converted into STAGC and STBGC using a conversion factor. Furthermore, the derivation of seagrass total soil organic carbon derived via laboratory test ($STSOC_{LAB}$) was achieved through correlating BRI values with corresponding in-situ samples of soil organic carbon (SOC) obtained from the laboratory analysis by the Carbon-Hydrogen Nitrogen Sulphur (CHNS) analyser. These models were generated from the three major sample areas (Johor, Penang, and Terengganu), which were used to estimate the entire seagrass carbon stocks in the coastline of PM. The models revealed a robust correlation results for BRI versus STAGB (R^2 = 0.962, p≤ 0.001), $STAGB_{BRI}$ versus $STBGB_{IN\text{-}SITU}$ (R^2 = 0.933, p≤ 0.001,), and BRI and STSOC (R^2 = 0.989, p≤ 0.001) respectively. The STBCS for the whole seagrass meadows along the coastline of PM was finally realised, demonstrating a good agreement in accuracy assessment (Root Mean Square Error (RMSE) = +- <1MtC/ha^1,). It is, therefore, concluded that the new approach introduced by this research on STBGC and STSOC estimation was tested and proved significant on the entire STBCS quantification for the PM coastline. The contributions are critical to fast-track the United Nations Framework Convention on Climate Change (UNFCCC) agreement to report the STBCS contents. Hence, this study has managed to propose a new fundamental initiative for estimating STBCS for speedy realisation of 2020 agenda on targets 14.2 and 14.5 of United Nations' Sustainable Development Goal 14th (life below the water).

ABSTRAK

Pemodelan stok karbon biru rumput laut adalah penting untuk melengkapkan ketidakupayaan penderiaan jarak jauh berasaskan satelit dalam memetakan stok karbon rumput laut bawah tanah. Inisiatif pemetaan terperinci karbon hijau dan prosedur anggaran serta protokol audit karbon daratan di peringkal global telah lama dijalankan. Kajan mangenai pemetaan karbon biru, pemodelan dan anggaran yang berkaitan jarang sekali diterbitkan kerana sebahagian kepentingannya dapat direalisasikan tetapi sangat terpencil. Oleh itu, kajian ini bertujuan untuk menyelidik stok karbon biru dalam habitat rumput laut dengan menganggarkan jumlah karbon yang disimpan dalam komponen biofisik rumput laut menggunakan teknik berasaskan satelit. Objektif khusus adalah untuk: 1) menilai dan mengadaptasi beberapa model terpilih untuk memperoleh jumlah karbon rumput laut di atas tanah (STAGC); 2) merumuskan pendekatan baru berdasarkan model terpilih untuk digabungkan dengan data dalam-situ, untuk model dan menganggarkan stok karbon biru dari jumlah rumput laut di bawah tanah (STBGC); 3) membangunkan teknik baru dengan menggunakan model terpilih dengan karbon organik tanah (SOC) untuk memodelkan dan menganggarkan stok karbon biru dari jumlah karbon organik tanah rumput laut (STSOC); dan 4) mengintegrasikan semua model (STAGC, STBGC, dan STSOC) untuk menghasilkan rangka kerja untuk pemetaan dan pengiraan jumlah stok karbon biru rumput laut (STBCS). Model logistik yang sesuai dipilih dan digunakan pada imej satelit untuk mengkaji rumput laut, dan stok karbon di sepanjang rumput laut di pesisir pantai Semenanjung Malaysia (SM). Semua jalur bergelombang pendek (biru, hijau, merah) daripada Landsat ETM+ digunakan untuk mengesan dan memetakan sempadan stok rumput laut dalam garis pantai SM. Penerbitan STAGC diterima pakai dari teknik berasaskan *Band Reflectance Indeks* (BRI) yang sedia ada, dengan mewujudkan hubungan yang baik antara BRI dengan jumlah biojisim rumput laut di atas tanah (STAGB). Sementara untuk anggaran STBGC, $STAGB_{BRI}$ (STAGB yang diperoleh dari imej BRI) dikolerasikan dengan jumlah biojisim rumput laut di bawah tanah yang berasal dari pengukuran dalam-situ ($STBGB_{IN\text{-}SITU}$). Kedua-dua $STAGB_{BRI}$ dan $STBGB_{IN\text{-}SITU}$ ditukar kepada STAGC dan STBGC menggunakan faktor penukaran. Selanjutnya, perhitungan jumlah karbon organik tanah rumput lautyang diperoleh melalui ujian makmal ($STSOC_{LAB}$) dicapai melalui korelasi BRI, dengan sampel karbon organik tanah (SOC) di kawasan sepadanan, yang diperoleh daripada analisis makmal oleh Karbon-Hidrogen Nitrogen Sulfur (CHNS). Model-model ini dihasilkan dari tiga kawasan sampel utama (Johor, Pulau Pinang, dan Terengganu), yang digunakan untuk menganggarkan seluruh stok karbon rumput laut di pantai SM. Model-model ini menghasilkan korelasi yang sangat baik untuk BRI berbanding STAGB (R^2 = 0.962, $p \leq 0.001$), $STAGB_{BRI}$ berbanding $STBGB_{IN\text{-}SITU}$ (R^2 = 0.933, $p \leq 0.001$,) dan BRI lawan STSOC (R^2 = 0.989, $p \leq 0.001$). STBCS untuk seluruh rumput laut rumput di sepanjang garis pantai SM akhirnya direalisasikan, menunjukkan persetujuan yang baik dalam penilaian ketepatan (punca min ralat kuasa dua (RMSE) = +- <1MtC/ha^1). Oleh itu disimpulkan bahawa pendekatan baru yang diperkenalkan dalam kajian ini terhadap STBGC dan STSOC diuji dan terbukti signifikan untuk pengiraan STBCS keseluruhan bagi garis pantai SM. Sumbangan kajian ini sangat penting untuk mempercepatkan perjanjian Konvensyen Rangka Kerja Konvensyen Pertubuhan Bangsa-Bangsa Bersatu mengenai Perubahan Iklim (UNFCCC) untuk melaporkan kandungan STBCS. Oleh itu, kajian ini berjaya mencadangkan inisiatif asas baru untuk menganggarkan STBCS untuk merealisasikan agenda 2020 pada sasaran 14.2 dan 14.5, Matlamat Pembangunan Mampan Pertubuhan Bangsa-Bangsa Bersatu ke-14 (kehidupan di bawah air).

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
B	-	Blue
BRDF	-	Bidirectional Reflectance Distribution Function
BRI	-	Bottom Reflectance Index
C	-	Carbon
CO_2	-	Carbon Dioxide
CM	-	Centimetre
CASI	-	Compact Airborne Spectrographic Imager
DN	-	Digital Number
DII	-	Depth-Invariant Index
EMR	-	Electromagnetic Radiation
ETM+	-	Enhanced Thematic Mapper Plus
GIS	-	Geographical Information System
GPS	-	Global Positioning System
G	-	GREEN
HA	-	Hectare
IPCC	-	International Penal on Climate Change
KM^2	-	Kilometre Squire
LK	-	Likelihood
MLC	-	Maximum-Likelihood Classifier
MG	-	Mega
MtC	-	Metric Tonnes of Carbon
PM	-	Peninsular Malaysian
R	-	Red
REDD+	-	Reduce Emission Deforestation and Forest Degradation Plus Conservation
ROI	-	Region of Interest
RS	-	Remote Sensing
RMSE	-	Root Mean Square Error
RT	-	Radiation Transfer

STAGB	-	Seagrass Total Above-Ground Biomass
STAGC	-	Seagrass Total Above-Ground Carbon
STBGB	-	Seagrass Total Below-Ground Biomass
STBGC	-	Seagrass Total Below-Ground Carbon
STBCS	-	Seagrass Total Blue Carbon Stocks
STSOC	-	Seagrass Total Soil Organic Carbon
SOC	-	Soil Organic Carbon
SDG	-	Sustainable Development Goals
UN	-	United Nations
UNEP	-	United Nations Environmental Programme
UNFCCC	-	United Nations Framework Convention on Climate Change"
UTM	-	Universal Transverse Mercator
WQC	-	Water Quality Checker
WGS	-	World Geodetic System

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Modelling of seagrass blue carbon stocks is essential to derive the underground seagrass carbon stocks using a remote sensing approach. The green carbon initiatives have for long reported the detailed mapping and estimation procedural as well as the audit protocol of the global terrestrial carbon stocks (Atwood *et al.*, 2017, 2018; Chappell *et al.*, 2016). The blue carbon mapping and its related modelling and estimation especially in seagrass habitat; on the other hand, is rarely if ever published, a part of its importance is realised but remained scattered. Therefore, it's necessary to use satellite-based modelling and estimation of seagrass total blue carbon stocks (STBCS) for reporting total carbon stocks in the seagrass meadows. Even though these meadows have been declining due to human activities.

Since 1850, human has discharged roughly 480 Gt of carbon dioxide (CO_2) into the sky via fossil fuel consumption and changes in land use (Aaheim *et al.*, 2015; Gasser *et al.*, 2018). These changes have prompted atmospheric CO_2 fixations that are higher than at any other point throughout the previous twenty million years (Crutzen and Andreae, 2016; Hutchins *et al.*, 2019). While fossil fuel emissions may represent a critical piece of global carbon emissions, the deforestation, and flames related to them make up a great extent of aggregate emissions (Bond, 2018; Cruz-López *et al.*, 2019). Blue carbon habitats typically seagrasses play a critical role in the global carbon cycle since these habitats sequester a substantial proportion of carbon into its biophysical components (Sani *et al.*, 2019b; Thomas, 2014). In general, seagrass meadows are among the most vital global blue carbon storage (Fourqurean *et al.*, 2012; Lavery *et al.*, 2013; Pendleton *et al.*, 2012a). Even though comprehensive statistics on the quantity of carbon sequestered by these meadows is insufficient, the existing discoveries suggested that they could be a globally significant surface reserve of carbon (Arias-Ortiz *et al.*, 2018; Atwood *et al.*, 2015).

However, the ecosystems are measured among the most vulnerable and rapidly vanishing natural environments worldwide and Malaysia in particular (more than 15 species) (Hossain et al., 2019; Lewis et al., 2018). This deterioration of seagrass is the consequence of anthropogenic activities (Hashim et al., 2017; Musa et al., 2017; Vierros, 2017). In these regards, precise estimations of seagrass total carbon stocks are required for better understanding of the ocean carbon cycle and global warming. Equally, information on seagrass total carbon stocks is expected to assist in attaining sustainable coastal resource management.

In general, seagrass carbon is stored in soil and biomass (aboveground biomass (AGB) leaves and belowground (BGB) roots) (Apostolaki *et al.*, 2019; Fourqurean, *et al.*, 2012). Due to the difficulties in field data gathering and the inability of satellite remote sensing to detect the BGB, most of the researches have been concentrating only on seagrass AGB/carbon estimation (Koedsin *et al.*, 2016a; Lyons *et al.*, 2015a; Tang *et al.*, 2018). Usually, national as well as local scale seagrass carbon estimation have been conducted using ground-based methods (Johnston, 2019). Even though in-situ-based approaches have been permitting estimates in several areas (Sani, et al., 2019), these methods still have some limitations. These limitations involve the little proportion of the seagrass species that are sampled and difficulties in gathering suitable data due to the time and logistics associated with ground inventories (Kauranne *et al.*, 2017; Mahabir *et al.*, 2018). Therefore, these limitations can be solved at a sequence of scales by employing remote sensing (RS). RS data can effectively provide a synoptic view of large locations (Dierssen, 2016; Raitsos *et al.*, 2017).

The recent advancements in scientific information on the climate change impacts resulting from anthropogenic activities along the marine environment triggered the augmented attention in seagrasses meadow (Holmer, 2019). This development is possible because of their competencies in carbon capture and storage as revealed by some studies (Dierssen *et al.*, 2019; Pham *et al.*, 2019; Wicaksono *et* *al.*, 2019b). Similarly, more efforts have been invested in mapping and quantification of the seagrass carbon via hyper and multi-spectral satellite images (Hwang *et al.*, 2019b; Wicaksono*, et al.*, 2019b). Seagrass total above-ground carbon (STAGC) mapping and changes detection (Misbari and Hashim, 2016; Mohamed *et al.*, 2018; Roelfsema *et al.*, 2014), mapping meadows cover extents (Saunders *et al.*, 2017; Traganos *et al.*, 2018) monitoring and estimating changes within multi-species of seagrass (Evans *et al.*, 2018; Kovacs *et al.*, 2018). These studies mainly reported only on a single component of seagrass, leaving the other two components namely the seagrass total belowground biomass (STBGB) and the soil carbon. However, to estimate seagrass total blue carbon stocks in seagrass meadows involve estimation of the three major components: (a) seagrass total aboveground carbon (STAGC); (b) seagrass total belowground carbon (STBGC); and (c) seagrass total soil organic carbon (STSOC) (Sani*, et al.*, 2019b).

At the current state of the art, the substrate leaving radiance of seagrass meadows have been detected after applying water column correction using bottom reflectance index (BRI) model (Hashim*, et al.*, 2017; Hossain *et al.*, 2015a; Misbari and Hashim, 2016; Rahmawati *et al.*, 2019; Traganos*, et al.*, 2018). However, the satellite-based carbon stocks derivation from belowground and soil carbon are yet to be reported. Consequently, comprehending the global seagrass carbon cycle remains inadequate (Barrell *et al.*, 2015). Ultimately, the precise estimate of seagrass underground carbon remains a challenging task. This wide gap could commonly be associated with the ability of the satellite sensor only to detect the surface/canopy of vegetation.

Hence, this research bridged the gap by estimating carbon from all the 3 components (STAGC, STBGC, and STSOC). The combined components were used to estimate seagrass total blue carbon stocks (STBCS) along the entire coastline of Peninsular Malaysia. This new initiative of seagrass total carbon stocks estimation using remotely sensed images is required to speedy the realisation of "United Nations Framework Convention on Climate Change" (UNFCCC) agreement to all participant nations to account on their STBCS contents. The STBCS estimate significance can enhance the incentives as well as practices in sustainable coastal management, which are essential for seagrass carbon stocks management. Equally, this carbon estimate could motivate the accomplishments of Sustainable Development Goals 14 (SDG) (life below water), targets 14.2 and 14.5 set by the United Nations (UN), to fast track the conservation and restoration of the coastal ecosystem, which is set to be realised in the year 2020 and 2030.

1.2 Problem Statement

Satellite-based seagrass carbon estimation has successfully offered a synoptic view. Incredibly increase productivity and usefulness of the limited conventional techniques used for estimating carbon stocks within the seagrass research domain. This advancement in satellite technology triggered various researchers to invest more efforts on STAGC estimation (Hashim, *et al.*, 2017; Misbari and Hashim, 2016). However, the STBGC and STSOC estimation have been ignored because of challenges in gathering in-situ data. More so, the ability of a satellite sensor to detect only the surface of vegetation it another factor. The STBGC and STSOC are among the most critical in seagrass carbon pool, yet they have been ignored even though the STSOC sequesters a significant proportion of carbon (>90%).

Although several wide gaps have existed as identified by reliable literature (Hossain, *et al.*, 2019; Sani, *et al.*, 2019b). These gaps include: 1) Limited publications on seagrass total blue carbon stocks, particularly, in STBGC and STSOC estimation; 2) No framework estimate seagrass total carbon stocks using satellite-based and statistical analyses have never been reported; 3) Specifically in Malaysia, no documented research relates the fast-tracking of the SDG 14 to the STBCS estimation via satellite data. Therefore, this research has bridged the gaps by estimating the three components of seagrass meadows (STAGC, STBGC, and STSOC) using RS and statistical approach. To this motive, this research could serve as supporting initiatives for seagrass total carbon estimation.

1.3 Research Question

(a) What are the models available to derive blue carbon stocks from seagrass total aboveground biomass (STAGB)?

(b) To what extent can the established models of bottom reflectance index (BRI) and depth-invariant index (DII) for STAGB derivation be combined with in-situ of seagrass total belowground biomass (STBGB) to estimate STAGC? and

(c) How can the selected BRI-based model be combined with in-situ of STSOC to formulate a new approach for modelling blue carbon stock from the soil?

1.4 Research Aim and Objectives

This research aims at estimating total blue carbon stocks of seagrass using satellite-based approach within Malaysian coastal water. The following objectives were set to accomplish the aim of the research:

(a) To assess several models and adapt the best model for deriving total blue carbon stocks from STAGB in seagrass meadows;

(b) To formulate a new approach based on the selected models above and combined them with in-situ biophysical parameters to estimate STBGC; and

(c) To develop a novel model for estimating STSOC based on the selected models from a and b and in-situ data.

1.5 Scope of the Research

(a) Only three (3) sets of seagrass in-situ samples were collected along the coastline of Johor, Penang, and Terengganu (Merambong, Gazumbo, and Setiu). The 3 samples locations were chosen to have different seagrass compositions in eastern, southern, and northern part of Peninsular Malaysian (PM) coastline, which represent that the entire seagrass meadows. These samples were used for mapping seagrass spatial distribution and modelling to estimate the total blue-carbon stocks for along PM shoreline. The three developed models from the selected sites were used to test the local effects of the models as they are site specific. Whereas, for testing the global effects the three models of each seagrass components were integrated to estimate STBCS. The motive behind selecting coast of PM as a case study is due to its significance in providing ecological and economic benefits. Satellite-based remote sensing via Landsat-7 enhanced thematic mapper's (ETM+) short visible bands (red, green, and blue) were used together with geographical information system (GIS) approach to investigate on seagrass total blue carbon stocks (STBCS) along the entire Malaysian coastline. The ETM+ images were used due to their spatial (30 m) and spectral (8 bites) capabilities of covering a large area such as PM.

(b) The derivation of seagrass total carbon stocks was realised by adopting BRI-based model modified by Misbari and Hashim (2016). This model was used to detect the seagrass occurrences along the study area. The selection of this BRI model is due to its ability of not only improving the level of accuracy for retrieving seagrass in clear water types I - II but as well dealing with turbid and low transparency waters (type II to III) (Sagawa *et al.*, 2010). Maximum likelihood classification techniques were used to identify the precise seagrass boundary, which was used for mapping and estimation of STAGC along the existing meadows in the coastline of PM. This classification method was used because of its efficiency in distinguishing seagrass and non-seagrass areas (Hossain *et al.*, 2015b). The motives behind STAGC estimation in the entire Peninsular Malaysian coastal are: (a) seagrass upper component is the second-largest carbon storage after soil pool in a seagrass meadow. Similarly, no published knowledge reported large-scale STAGC estimation using satellite data for the entire coastline of PM.

(c) Estimation of STBGC contents was first of its kind as a new model was developed, and many researches ignored it due to its insignificant carbon contents. However, to obtain STBCS in a meadow, STBGC must be included for precise quantification as suggested by UNFCCC (Sani *et al.*, 2019a).

(d) Seagrass soil organic carbon was derived directly from the BRI image as the model was already established with the capability of detecting substrate leaving radiance of sea bottom features such as soil, seagrass and coral (Sagawa, *et al.*, 2010). Therefore, STSOC contents are needed as >80% of seagrass blue carbon is obtained from the soil (Phang *et al.*, 2015).

(e) Furthermore, during the data preparations for modelling and accuracy assessments, the 216 samples (for the 3 sample areas) obtained in each of the seagrass components (STAGC, STBGC, and STSOC) were divided into two mutual sets. The datasets 50% for induction (control) to establish a relationship using the logistic model. Whereas, the second 50% was used for accuracy assessment as deduction (training). Root mean squire error (RMSE) and the R^2 coefficient determination were applied to evaluate the model's performance in STAGB, STBGB, and STSOC prediction. This assessment methods were utilised to achieve precise quantification of STBCS along PM coastal waters.

1.6 Research Significance

Indeed, efforts have been invested, within the last two decades, to map the spatial extents of seagrass habitat. These efforts were made via employing a conventional approach, and very few used RS. These approaches did not consider incorporating estimation of seagrass total carbon stocks, particularly in a large coastal area. This research, therefore, seeks to broaden the knowledge by proving the capabilities of the RS and statistical model to develop a procedure, which could be utilised for seagrass total carbon stocks derivation. This development is to improve

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