

**BLUE AND BLACK CARBON IN SABAH  
SEAGRASS AND MANGROVE SEDIMENTS:  
ITS IMPORTANCE FOR CARBON  
SEQUESTRATION AND STORAGE ESTIMATES**

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**JUDUL:** **BLUE AND BLACK CARBON IN SABAH SEAGRASS AND MANGROVE SEDIMENTS: ITS IMPORTANCE FOR CARBON SEQUESTRATION AND STORAGE ESTIMATES**

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## **DECLARATION**

I hereby declare that the material in this thesis is my own except for quotations, excepts, equations, summaries and references, which have been duly acknowledged.

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## CERTIFICATION

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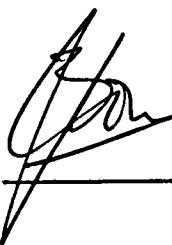
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#### 2. CO-SUPERVISOR

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## ABSTRACT

Blue carbon refers to the carbon stored and sequestered by coastal vegetated ecosystems, for examples, mangroves forest, seagrass meadows and saltmarsh. Along with sequestration, the canopy and rhizome system stabilizes a legacy of hundreds year of buried sedimentary carbon (C) storage from remineralization. The current blue carbon conceptual model estimates C stocks based on the total organic carbon content (TOC) without accounting for deposited allochthonous recalcitrant carbon forms like black carbon (BC). Black carbon is produced outside coastal vegetated ecosystems through the incomplete combustion of fossil fuels and biomass, and is already stable over climatic scales. Hence, a more accurate value of blue carbon storage can only be estimated by subtracting that portion of BC from the TOC. The main objective was, for the first time, to analyze the portion of BC over TOC down the sediment columns of coastal vegetated ecosystem from the seagrass meadows and its adjacent mangrove forest within Salut-Mengkabong lagoon. Black carbon analysis was carried out using two methods, namely, Chemothermal Oxidation (CTO) and Nitric Acid Oxidation (NAO) to isolate the soot continuum and soot to charcoal continuum, respectively. The top meter C stock for seagrass and mangrove sediment estimated ranging from  $6.0 - 203.0 \text{ Mg C ha}^{-1}$  and  $139.4 - 425.5 \text{ Mg C ha}^{-1}$  respectively. For organic carbon (OC) sequestration of *Enhalus acoroides* meadow, estimated ranging from  $1.5 - 5.1 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  for Salut upper lagoon and Mengkabong lagoon over  $\sim 20$  years. However, the results of BC/TOC isolated by CTO and NAO, suggested C stock capacity for seagrass and mangrove will diminish,  $1.8 - 66.6\%$  and  $1.4 - 19.6\%$  respectively. The BC sequestration on the same *Enhalus acoroides* meadows estimated ranging from  $32.6 - 36.0 \text{ g m}^{-2} \text{ yr}^{-1}$ . Moreover, comparison between temperate and tropical blue carbon ecosystems, suggested current carbon stock estimates are positively biased, particularly for sandy seagrass environs, by  $18 \pm 3\%$  ( $\pm 95\%$  confidence interval) and  $43 \pm 21\%$  ( $\pm 95\%$  CI) respectively. In conclusion, it is recommended accounting for BC to be included within the blue carbon conceptual model for more accurate assessments in future carbon trading schemes.



## **ABSTRAK**

### **KARBON BIRU DAN HITAM DALAM ENDAPAN RUMPUT LAUT DAN BAKAU SABAH: KEPENTINGANNYA DALAM KARBON SEKUESTRASI DAN PENYIMPANAN**

*Karbon Biru dirujukan kepada karbon yang disimpan dan disekuestrasi oleh ekosistem persisiran pantai, seperti hutan bakau, rumput laut dan rawang masin. Hal ini kerana, tumbuhan kanopi dan sistem akar mampu menstabilkan karbon (C) yang disimpan dalam sedimen selama beratus tahun dan melindunginya daripada proses mineralisasi. Konsep Model Karbon Biru yang terkini mengganggar stok C berdasarkan kandungan jumlah karbon organik jumlah (TOC), tidak termasuk allochthonous recalcitrant carbon, seperti karbon hitam (BC). BC adalah sisa pembakaran daripada bahan api fosil dan biojisim dan dihasil luar daripada ekosistem persisiran pantai serta mempunyai kestabilan yang tinggi. Oleh itu, pengganggaran stok karbon biru yang lebih tepat hanya boleh dianggar selepas menolak bahagian BC daripada TOC. Kajian objektif utama ini ialah menganalisi peratusan BC dalam TOC yang didapati dalam endapan rumput laut dan juga bakau bersebelahan lagun Salut-Mengkabong. Analisis BC dijalankan melalui dua kaedah, iaitu, Chemothermal Oxidation (CTO) untuk mengasingkan kontinum jelaga dan Nitric Acid Oxidation (NAO) dapat mengasingkan kontinum dari jelaga hingga arang. Pengganggaran stok C dalam sedimen teratas adalah dalam lingkungan 6.0 — 203.0 Mg C ha<sup>-1</sup> dan 139.4 — 425.5 Mg C ha<sup>-1</sup> bagi rumput laut dan bakau masing-masing. Sekuestrasi karbon organik oleh hampuran Enhalus acoroides dianggar dalam lingkungan 1.5 — 5.1 Mg C ha<sup>-1</sup> yr<sup>-1</sup> untuk ~ 20 tahun. Walau bagaimanapun, keputusan BC/TOC yang dianalisi oleh CTO dan NAO mencadangkan bahawa kapasiti stok C rumput laut dan bakau akan berkurang sebanyak 1.8 — 66.6% dan 1.4 — 19.6% masing-masing. Selain itu, sekuestrasi BC dianggar dalam lingkungan 32.6 — 36.0 g m<sup>-2</sup> yr<sup>-1</sup>. Keputusan perbandingan antara ekosistem karbon biru yang meliputi zon iklim sederhana dan tropika, mencadangkan ketepatan penganggaran stok C terkini perlu dikaji semula. Terutamanya, kawasan rumput laut berpasir di zon iklim sederhana dan tropika terdapat BC sebanyak 18 ± 3% ( $\pm$  95% CI) dan 43 ± 21% ( $\pm$  95% CI) masing-masing. Kesimpulannya, BC% perlu diambil kira dalam*



*konsep model karbon biru untuk penilaian stok C yang lebih tepat bagi menjalani skim dagangan karbon pada masa depan.*



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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 The Importance of the Coastal Vegetative Area**

Coastal vegetated ecosystems include mangrove forests, salt marshes, seagrass meadows and seaweed/kelp forests, provide a number of ecological services. Services vary from the biological to the physical, such as nursery grounds for marine organisms (fish and invertebrates), which provide food to ~3 billion people as 50% of the world fishery resources (Nellemann, Corcoran, Duarte, Valdés, De Young, Fonseca and Grimsditch, 2009), reducing the impact of storm events to coastal areas, coastal erosion (Twilley, Snedaker, Yáñez-Arancibia and Medina, 1996; Mumby, Edwards, Arias-Gonza'lez, Lindeman, Blackwell, Gall, Gorczynska, Harborne, Pescod, Renken, Wabnitz and Llewellyn, 2004). It is also more being increasing realise that these ecosystems may also provide an important carbon sequestration services for the mitigation of greenhouse emissions (Nellemann *et al.*, 2009).

In recent decades, the introduction of blue carbon successfully has drawn the attention of various parties that include researchers, policy makers and the private sector. Because of its high carbon storage capacity, on average of 25% (Duarte, Marbà, Gacia, Fourqurean, Beggins, Barrón and Apostolaki, 2010; Gallagher, 2015); or 30—50% (Irving, Connell and Russell, 2011) of world carbon stored and sequestered within small area (~0.05% of land and < 2% of the ocean area ) over long time scales (millennia) (Falkowski, Katz, Knoll, Quigg, Raven, Schofield and Taylor, 2004; Arrigo, 2005; Gonzalez, Fernandez-Gomez, Fernandez-Guerra, Gomez-Consarnau, Sanchez, Coll-Llado, del Campo, Escudero, Rodriguez-Martinez, Alonso-Saez, Latasa, Paulsen, Nedashkovskaya, Lekunberri, Pinhassi and Pedros-Alio, 2008; Simon, Cras, Foulon and Lemée, 2009; Trumper, Bertzky,



Dickson, Van Der Heijden, Jenkins and Manning, 2009). These ecosystems capable of sequestering and storing most of the autochthonous organic carbon produced by the ecosystem as well as allochthonous organic carbon trapped by the canopy. The allochthonous carbon ostensibly washed out from the land and adjacent ecosystems and stored together with the autochthonous forms, through sedimentary burial and within its living biomass. The name given to the carbon associated with vegetated coastal ecosystem is known as "Blue Carbon", in which the sediment components are under the protection from remineralisation and resuspension by the presence of the plant canopy and root system (McLeod *et al.*, 2011).

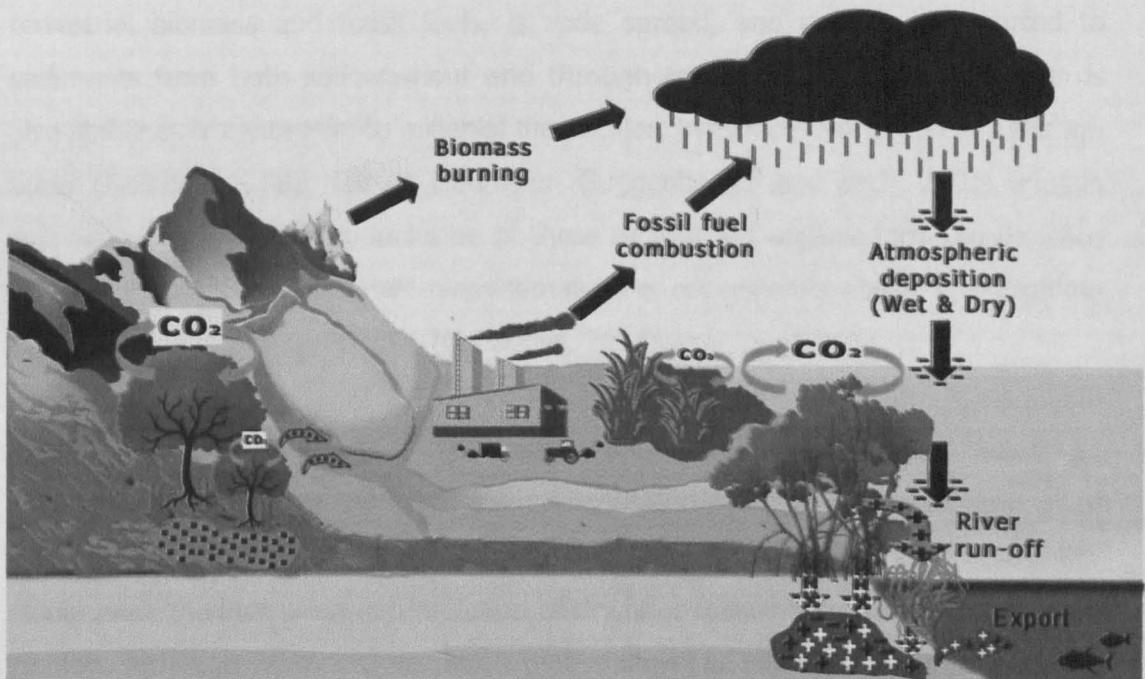
## **1.2 Potential Untested Bias in Estimating Blue Carbon Stock**

Over recent decades, it has become apparent that the coastal ecosystem are vulnerable with losses up to four times quicker than land forests (Duarte, Dennison, Orth and Carruthers, 2008; Duarte, 2009). It has been estimated the loss of seagrass, mangrove, and saltmarshes has resulted in the release of  $\sim 0.15\text{--}1.02 \text{ Pg yr}^{-1}$  of  $\text{CO}_2$  into the atmosphere, an uncertain but significant fraction of current global anthropogenic emissions,  $9.9 \pm 0.9 \text{ Pg yr}^{-1}$  (Pendleton, Donato, Murray, Crooks, Jenkins, Sifleet, Craft, Fourqurean, Kauffman, Marbà, Megonigal, Pidgeon, Herr, Gordon and Baldera, 2012). The large range of uncertainty in  $\text{CO}_2$  emissions from the loss of coastal vegetated ecosystems is, in part, due to under sampling (Donato, Kauffman, Murdiyarso, Kurnianto, Stidham and Kanninen, 2011; Lavery, Mateo, Serrano and Rozaimi, 2013). However, the question of blue carbon stock bias, which additional sampling cannot address, has not yet been fully tested. One source of bias is the implicit inclusion of allochthonous recalcitrant organic matter within sedimentary stock estimates (Gallagher, 2014). Hence, blue carbon ecosystems are not responsible for the recalcitrant carbon formation, and burial does not provide additional protection from remineralisation. Consequently, allochthonous recalcitrant carbon must be excluded from stock estimates as a mitigation service for anthropogenic emissions of  $\text{CO}_2$  (Gallagher, 2015).



### 1.3 The Existence of Allochthonous Recalcitrant Carbon

Allochthonous recalcitrant carbon source refers to highly stable carbon, resistant to oxidation over climatic scales, which is trapped by the blue carbon canopy and roots system, transported from the land via coastal erosion, river runoff and atmospheric deposition (Figure 1.1).



**Figure 1.1:** An augmented blue carbon conceptual model. The model shows saltmarsh, mangrove, and seagrass canopies' ability to trap and store black pyrogenic carbon (BC) washed out from the catchment (green and black) and atmosphere (black), along with detritus produced by those coastal vegetated ecosystems (blue and black). The argument of this study is the failure of removal allochthonous recalcitrants, such as BC, from the coastal vegetated sedimentary carbon stocks could result in overestimated values in mitigating anthropogenic emissions of CO<sub>2</sub>. Icon credit: Tracey Saxby (mangrove) and Catherine Collier (seagrass), Integration and Application Network, University of Maryland Center for Environmental Science ([ian.umces.edu/imagelibrary/](http://ian.umces.edu/imagelibrary/))

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