# Supplementary Material S1

# A re-evaluation of wetland carbon sink concepts and measurements: A diagenetic solution down sediments

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Orcid ID 0000-0003-4715-5387.A re-evaluation of blue and teal carbon stock and sequestration concepts with solutions for climatic scales

## Introduction

The following is a description of the model, evidence of its robustness, and its application used to hindcast and project the losses of sedimentary organic carbon. Two examples with the required data were drawn from the literature (i.e., a geochronology, C concentrations, the fractions of organic sources to the total C content, and black carbon directly or taken from a similar system). The results of the model are then used to estimate net ecosystem production over time, and assert that the same model can be used to estimate changes in stocks of 1 m thickness over time. For stocks, this is provided the depth of the sediment core is sufficient, or the variability in carbon is not captured within a time dictated by the length of the sediment core.

## **Determining carbon accreditation concepts of a tropical mangrove and seagrass ecosystem**

### Data acquisition

For the mangrove, Gonneea (Gonneea et al., 2004) kindly supplied the mangrove sediment horizon ages, sediment accretion rates, dry bulk density, and organic carbon contents, required for hindcasting and projection of organic source concentrations. The fractions of mangrove, seagrass and microalgae as surface particulate matter (SPM), were extracted digitally from a pdf (Adobe™) into Graph Grabber™ from a figure within Gonneea et al. (2004) for Chelem Lagoon station 9.

For the tropical seagrass, the organic carbon contents, their carbon stable isotope and N/C molar signatures, dry bulk densities, and accretion rates, horizon ages of the surface 0-2 cm and 20-22 cm, as a mix of 20 cores adjacent cores, came from Chuan et al. (2020). Additional data for the 8-10 cm horizon was taken from an unpublished thesis, supplied by Chew (Swee Theng Chew, 2019). The sediment core had been taken previously within the core sampling site used by Chuan et al. (2020). The proportions of mangrove, seagrass, and microalgal carbon were calculated using a three source carbon stable isotope N/C used across tropical lagoons (Gonneea et al., 2004). The microalgae–SPM source signature was taken from as the microalgal endpoint (Gonneea et al., 2004). The organic source endpoint signatures for mangrove detritus was taken from one of the study lagoons from Gonneea et al (2004). The lagoon supported the mangrove *Avicennia sp.*, consistent with that of surrounding the seagrass meadow. However, the seagrass organic carbon signature endpoints were replaced with local *Enhalus sp.* as the average of three sites from nearby coastal study area from 3 locations within Sepanngar Bay (Kota Kinabalu, Sabah, Malaysia), as supplied by Tzuen Kiat Yap (δ13C -8.6 ‰ and molar N/C 0.0435). This was part of the Ministry of Science, Technology and Innovation grant (FRG0424-SG-1/2015) “Increasing the resilient of sandy beach to erosion by replanting seagrass beds” (Research Supervisor John Barry Gallagher). The dried seagrass shoots ( 9 to10 shoots per site) were combined and scaped to remove epibionts, dried at 50 ⁰C, ground with a porcelain mortar and pestle, and fumed with concentrated HCl before. After further drying, the samples were immediately packaged within 5 cm3  Eppendorf vials and sealed while warm before vacuum sealing all the vials in a plastic bag for transport to the specialised laboratory SINLAB (Canada) (17YAP 001-039 SINLAB.xls). The accuracy was confirmed using standard peach tea and the matrix standard.

All the extracted data can be found in Supplementary Material S4, as inputs for the spreadsheet templates that sets out the calculations for *NEP*, organic carbon accumulation, and stocks.

### Site descriptions

The tropical mangrove Chelem lagoon station 9 supported a scrub mangrove forest near the seaward entrance of the lagoon, being impacted by its proximity to a rural population. Its sediments were sandy with relatively low organic carbon contents of around 2.5% dry wt over the last 100 years of deposition, and low carbon accumulation rates (Gonneea et al., 2004). As such, the forest could be expected to support rates of *NEP* within the lower quartile of a global distribution.

The tropical seagrass meadow occupied the upper embayment of the Salut Mengkbong lagoon, located north of Kota Kinabalu, Sabah, a major population centre. The meadow was a subaquatic shallow system composed entirely of *Enhalus sp.*, in which around a quarter of the leaf length could be seen floating on the water surface during spring low tides (Gallagher et al., 2020). The surface waters were generally turbid due to tidal washout out from the surrounding mangrove shoreline. As a consequence, the seagrass sediments supported a relatively high organic content of around 5.5% dry wt to 23 cm deep (Supplementary material S4). Below 23 cm was the remnants of mangrove roots mud and shell detritus deposited from a rare storm surge event (Chuan et al., 2020).

## Carbon accreditation model

### Hindcasting and projecting sedimentary carbon losses

The advantages of using the sedimentary record for carbon accreditation components for expected variability or trend have been outlined in the manuscript. The question arises can the components within Equation (8) be successfully modeled to produce an accurate estimate? Along with the more familiar geochronology and a discriminatory organic source mixing model, it requires a general decomposition model. The model should be sufficiently robust for hindcasting and projecting organic source losses across different sedimentary environs to determine the *NEP* and carbon accumulation throughout the sediment column. We applied the parameters from the power model constructed by Middelburg (Middelburg, 1989) and modified by Gallagher (2015). Middelburg (1989) found that there was a continuous decrease in the rate of decomposition of sedimentary organic matter that reflected a strong relationship between a first-order decay constant (*k*), and the sum of deposition time (*t*) and the apparent age (*a*) of organic source or sedimentary mixtures of sources (9). The apparent age is a concept of intrinsic time that matches the degree of recalcitrance at the start of decomposition. This starting value is required to determine changes in real-time, that is, the more labile microalgae will have a younger apparent age than the more recalcitrant mangrove leaves containing a higher proportion of lignocelluloses and phenolics. The model was found to be robust as it was constructed from first-order decay constants determined and calculated from a variety of laboratory and *in situ* sediment experiments and sedimentary profiles. Furthermore, these were determined under a variety of anoxic and oxic conditions, temperatures, sediment types, organic sources mixtures, and deposition times over eight orders of magnitude.

The power model has also been successfully (i.e., validated from long-term monitoring data sets) applied by Zimmerman and Canuel (Zimmerman and Canuel, 2002) to disentangle the initial of organic source supply from decomposition sensitive to change of the late Anthropocene. Although, it should be noted that Middelburg did not have access to data for coastal canopy sediments, where the microalgal fraction would not be as dominant. Nevertheless, the work of Janssen on which the model was based (Janssen, 1984), followed the same logarithmic construct, irrespective of large additions of a wide range of more recalcitrant organic sources to soils (i.e., green matter, straw, litter, manure, fir needles, sewage, and various peats).

*k* = 0.16(*a + t*)-0.95 (9)

Where the first-order rate constant (*k*) determines how much of the organic matter with its particular state of recalcitrance remained after a small period (*Ct*).

(10)

Gallagher (Gallagher, 2015) extended the application from sediment organic carbon to individual plant sources deposited to sediments (i.e, phytoplankton, seagrass, macroalgae, deciduous leaves). This was conceptually the same as Janssen's (1984) additions of materials to soils with relatively low organic matter contents. The initial first-order decomposition constants (*k*) and *cal* associated apparent ages (*a*), for the plant sources were taken from a compilation of data of decomposition experiments fitted to a first-order rate of decay as a function of their N content (Enríquez et al., 1993). A broad agreement was found with the only two studies that have a sufficient temporal range. A decomposition curve constructed from repeated sampling of sediment cores over 27 years (Gälman et al., 2008) dominated by microalgal supply (*cal* 23.4% remaining after 100 yrs *cf* 22.4% to 29.1% from Gallagher (2015)). A study used diagenetic profiles of dissolved metabolites over depth and time (Alperin et al., 1992). Alperin found the amount of seaweed and phytoplankton carbon remaining after 100 years was 10.2 ± 2% and 21 ± 5% respectively. Although, the remaining seaweed was less than predicted by the power model (22.4% –29.1%). However, the divergence may be specific to seaweeds. Enríquez (Enríquez et al., 1993) also found a greater expected rate of decomposition of the kelp as predicted from its nitrogen content. It was suggested that this may be the result of the bacterial preference of carbohydrate-rich kelps, less chemical alteration before deposition, and a macroscopic surface suitable for bacterial colonisation. These attributes are not shared with seagrass and perennial deciduous leaves, which followed the expected hierarchy of an increasing amount remaining after 100 years of deposition (i.e., between 27.8% to 29.2% and 30.6% to 45.7% respectively) (Gallagher, 2014; Gallagher, 2015).

For this study, the total organic carbon lost after the time of deposition and from the age surface horizons age was calculated from the individual component losses as their weighted fractions. This removes the problem in calculating the apparent age (*a*) of the depositional mixture for non-steady-state accumulation (Middelburg, 1989). The allochthonous component was identified by the nature of the ecosystem and its immediate surroundings and the original amount deposited hindcast along its decomposition curve (Figures 2 and 3).

The model solutions and instructions are presented in three separate Excel™ worksheets.

### Sequestration and carbon accumulation vectors

* First, the decomposition curves for individual organic components were constructed (Supplementary material S1). The time steps to calculate ‘the first-order decay constants ‘*k’* (9) over 100 years for an apparent age ‘*a* and matching initial ‘*k’* taken from Enrichez (Enríquez et al., 1993). An upland soil decomposition constant was added to the model for future applications (Supplementary Materials S3). The values of *k* were then substituted into (10), and the amount of carbon remaining for that particular organic source was calculated (Supplementary Material S2). Time steps were set to 10 000 for computational stability. The iteration produced 100 000 time steps resulting in additional losses after 100 years < 0.1% (Supplemental Material S?). Instructions on how to start the simulation for individual organic sources and the model’s iteration sensitivity analysis are set out in text boxes within the worksheets (Supplemental S2 and S3).
* Second, the above process for individual allochthonous organic sources and the sum of the fractions of total organic carbon for all organic sources at selected horizon dates can be then used to hindcast and project carbon accumulation after 100 years of deposition for *NEP*. These are set out in stages as inputs within the columns of the Excel™ template (Supplementary Material S4). To run the program, the input data consisted of accretion rates and /or age of the sediment horizon, carbon contents, dry bulk density, the fractions of organic carbon sources, and the results of the individual organic components decompositional losses overtimes that match the ages of the sediment horizons. These are readily filtered out from the decomposition curve simulations (Supplementary Material S2).

### Standing stocks over time

An assessment of past stocks may also require extended sampling to should the 100 years of accretion be > 1 m (Fig S1), as it would be unlikely that the rates of supply of organic sources would be constant. Consequently, a correction would also be required to account for losses in carbon contents from those measured today over what the stocks were in the past from a deeper horizon (Figure S1). However, for the core taken from the Salut seagrass meadow, the baseline sedimentation was interrupted by a deposition storm surge event down from 23 cm and likely greater than 52 cm, the bottom core sample (Chuan et al., 2020). Nevertheless, for completeness, we assume that the organic stock to 23 cm today is typical of past values, and around half the stock when integrated to 1 m (Gallagher et al., 2020; Lavery et al., 2013). Similarly, for Mangrove forest at Chelem station 9, it is assumed that the organic stocks today are typical and approximated to twice the amount stored to 42 cm (Donato et al., 2011; Gallagher et al., 2020). Gonneea (2004) recorded a cycle of variability related to oceanographic current changes to around 42 cm over the last 100 years. With the previous cycle seemingly recording organic concentrations marginally elevated over the previous cycle. Corrections for the fraction vulnerable to mineralisation are set to 0.75 between the range suggested by Pendelton et al (2012) over 20 years. Subtraction of allochthonous carbon faction, as BC within the seagrass meadow (11%) comes from direct measurements. Allochthonous BC for the mangrove sediment was set at 5%, as measured for a similar industrial urban environment (Chew and Gallagher, 2018).

*Figure S1. A hypothetical scenario, as measured today and as it was 100 years ago. It shows the stocks to 1 m as a gradient in organic concentrations that fall with depth and time down a sediment column. The illustration implies that 1 m thick stock assessments over time, measured down a sediment column today, require hindcasting the losses over time.*

## Decompositional model

Convergence between independent decay with time models

The decay parameters of Middelburg’s (1989) power model were constructed from measurements of coastal to deepsea sediment cores but outside of canopy ecosystems. Canopy ecosystems are likely to support greater proportions of macrophytes, woody debris and terrigenous organic sources than non-vegetated sediments. Consequently, the model was evaluated from the convergence from the long-term Salut sediment incubation experiment (Chuan et al., 2020). The decomposition experiment modeled parameters using the reactivity continuum model over 500 days sufficient to describe its decay distribution coefficient as the balance between labile and recalcitrance over time. The projected remaining organic carbon contents of 53.2% after 100 years of deposition from the power model from the seagrass surface horizon (0-2 cm) was in close agreement with the reactivity continuum model projections of 51.2% (Chuan et al., 2020). Although, after correcting for the sediment's BC content (around 11%, Chuan et al., 2020), the reactivity continuum model suggested that the remaining labile organic carbon fractions would amount to 45.6% after 100 years of deposition (Supplementary Information (S2)). Nevertheless, the convergence is good suggesting the results are robust and have a common origin outside of theory, and lie in the real world, confirming each of models’ results (Bycroft, 2010).

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