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NATALIA BELOTO

BASES PARA A COMPREENSÃO DO POTENCIAL DE CARBONO AZUL EM MANGUEZAIS BRASILEIROS: UM EXPERIMENTO E UMA REVISÃO BIBLIOGRÁFICA

FORTALEZA
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Área de concentração: Ciências Exatas e da Terra

Orientador: Prof. Dr. Luis Ernesto Arruda Bezerra
Coorientador: Prof. Dr. Marcelo de Oliveira Soares.

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Dedico este trabalho integralmente à minha família: Benedeti (mãe), Everaldo (pai), Nadia (irmã) e Felipe (irmão).

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Odociaba, Mãe Iemanjá!

“O feminismo é a ideia radical que sustenta que as mulheres são pessoas”
Angela Davis

RESUMO

Os manguezais estocam grandes quantidades de carbono em seus compartimentos (árvores, folhas, galhos, raízes e solos), em especial nos solos (>70%). Entretanto os fatores e as condições que fazem com que esses ambientes sejam um dos maiores armazenadores de carbono do mundo, ainda não são completamente compreendidos. Entende-se que por serem locais salobros e alagados, a forma como ocorre a decomposição da matéria orgânica (MO) pode ser um dos fatores que potencializa tanto o armazenamento quanto a permanência do carbono no solo, além disto, diversos outros fatores também vêm sendo investigados. Assim, este trabalho realiza análise do processo de decomposição da matéria orgânica no solo (DMOS) de manguezais da região norte e nordeste e consolida um levantamento bibliográfico para identificar lacunas informativas acerca do carbono nos compartimentos dos manguezais. Para tal, na análise da DMOS utilizamos a metodologia *Tea bag index* (TBI), onde saquinhos do chá foram enterrados em manguezais amazônicos e do semiárido nordestino, e posteriormente (~25 e 90-dias) recolhidos para análise. Para a revisão sistemática utilizou-se a metodologia PRISMA, onde artigos foram buscados e triados a partir do uso de três bases científicas. Como resultado, observamos elevados percentuais de DMOS na região norte, comparativamente a nordeste. E diferenças quanto aos fatores de estabilização (S) e taxa de decomposição (k), podendo ser, possivelmente, em resposta às distintas características e condições ambientais dos manguezais amazônicos e do semiárido. Adicionalmente, com a revisão sistemática notou-se diferença entre os estoques de carbono nos compartimentos do manguezal de distintas regiões do Brasil (norte, nordeste e sudeste), e embora estados como o Amapá e Maranhão apresentem extensas faixas de manguezal em seus territórios, observou-se, que ainda não existem dados disponíveis sobre estoque de carbono para tais estados. Com base nos resultados da revisão, atribuiu-se aos manguezais brasileiros uma média de 443 Mg C ha^{-1} de total de carbono no ecossistema (TECS), e ~0.44 PgC para todo o território nacional. Finalmente, os resultados reafirmam a importância dos ambientes de manguezal como eficientes sumidouros de carbono, e destacam a necessidade de avaliação de todas as características dos manguezais para melhor compreensão dos processos de armazenamento de carbono nos mesmos.

Este trabalho está relacionado aos Objetivos do Desenvolvimento Sustentável da ONU, 13 (Ação Contra a Mudança Global do Clima) e 14 (Vida na Água).

Palavras-chave: DMOS. Semiárido. Manguezais. *Tea Bag Index*.

ABSTRACT

Mangroves store large amounts of carbon in their compartments (trees, leaves, downed woods, roots and soils), but especially in soils (>70%). However, the conditions that promote these environments as one of the largest carbon stores in the world are not fully understood. Because of its characteristics salty and flooded, the manner that organic matter (OM) decomposition occurs can be one of factors that enhance carbon storage and permanence in the soil, but others several factors have been investigated to comprehend this high carbon potential. We investigated decomposition of organic matter in soil (DMOS) in north and northeast mangroves and made a systematic bibliographic review to identify gaps in information about carbon in mangrove compartments. To access DMOS, Tea bag index (TBI) methodology was tested, then tea bags were buried in amazon and semi-arid mangroves and later (~25 and 90 days) collected for analysis. And PRISMA methodology was applied to proceed a systematic review, in which articles were searched for and screened using three scientific databases. Results presented higher percentages of DMOS in northern region than northeast. Stabilisation factor (S) and decomposition taxes (k) differed between regions, possibly because of distinct characteristics and environmental conditions of amazon compared to semi-arid mangroves. In addition, systematic review revealed differences between carbon stocks in the mangrove compartments of Brazilian's regions (north, northeast and southeast), and although states such as Amapá and Maranhão have extensive mangrove area in its territories, surprising there are no data available on carbon stocks for these states. Based on results of review, an average of 443 Mg C ha^{-1} of total ecosystem carbon (TECS) was attributed to Brazilian mangroves, and ~0.44 PgC for the entire national territory. Finally, results reiterate the importance of mangrove as efficient carbon sinks, highlighting the necessity to evaluate all mangrove characteristics to better understand carbon storage processes.

This work is related to the UN Sustainable Development Goals 13 (Action against Global Climate Change) and 14 (Life in Water).

Keywords: DMOS. Heterogeneity. Mangroves. Tea Bag Index.

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LISTA DE FIGURAS

CAPÍTULO 1 e CAPÍTULO 2

LISTA DE DEFINIÇÕES

Estoque de C =	Quantidade de carbono estabilizada em compartimento ambiental (vegetação ou solo). Indica o armazenamento ao longo do tempo, e geralmente seu valor aparece expresso em Mg C ha^{-1}.
Sequestro de C =	Geralmente se refere à retirada do CO_2 atmosférico pela atividade fotossintetizante das plantas. Porém também pode ser utilizado para se referir a processos dos solos onde estes incorporam CO_2 por meio da decomposição da MO, fixação biológica de nitrogênio e fotossíntese. No geral, seu valor aparece expresso em Tg C y^{-1}.
Captura de C =	Sinônimo de sequestro de C
Armazenamento de C =	É a diferença entre o quantitativo de entrada de carbono (sequestro/*input*) e de saída (emissão/*output*).
Emissão de C =	Quantidade de carbono que está sendo perdida para o ambiente, tanto por processos naturais, quanto por processos de degradação que potencializam as emissões de carbono.

LISTA DE ABREVIATURAS E SIGLAS

BCEs	Blue Carbon Ecosystem/Ecossistemas de Carbono Azul
DMOS	Decomposição da Matéria Orgânica nos Solos
MO	Matéria Orgânica
MOS	Matéria Orgânica no Solo
COT	Carbono Orgânico Total no Solo
TBI	Tea Bag Index/Índice do Saquinho de Chá
TECS	Total Ecosystem Carbon Stock/Total de Carbono no Ecossistema
AGB	Above-ground Biomass/Biomassa acima do solo (árvores e serapilheira)
BGB	Below-ground Biomass/Biomassa abaixo do solo (raízes e galhos)
DW	Downed-woods/Madeiras e troncos caídos
DOP	Grau de Piritização
LOI	Loss on ignition/Perda na ignição (PNI)
AE	Analisador Elementar
Corg	Carbono orgânico
$CaCO_3$	Carbonato de cálcio

LISTA DE UNIDADES DE MEDIDAS

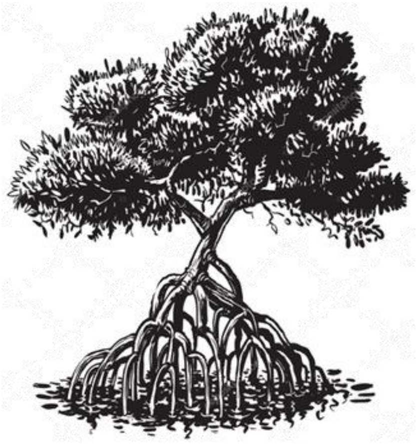
Tg C y^{-1}	Teragramas de Carbono por ano
Mg C ha^{-1}	Megagrama de Carbono por hectare (equivale à tonelada)
T C ha^{-1}	Tonelada de Carbono por hectare
Pg C	Petagrama de Carbono (equivalente a 1.000.000.000 de toneladas)
g/cm^3	Gramas por centrímetro cúbico

SUMÁRIO

CONSIDERAÇÕES INICIAIS

Esta tese será apresentada por meio de um *Referencial Teórico* e *dois Capítulos*, sendo o Referencial Teórico uma contextualização acerca da temática do carbono azul, seguido do Capítulo 1 que se trata da aplicação de um experimento para compreensão dos processos da decomposição da matéria orgânica no solo e sua possível interação com o enterramento de carbono em manguezais e, finalmente o Capítulo 2 que apresentará uma revisão bibliográfica acerca dos valores de estoques de carbono nos compartimentos dos manguezais ao longo da costa brasileira. O percurso para construção deste documento trouxe o entendimento de que os processos relacionados a ciclos biogeoquímicos, tal qual o ciclo do carbono, demandam de contínuo investimento para formação intelectual e consolidação de sua base experimental. A ampla variabilidade de condições ambientais, as questões edáficas e os métodos de avaliação do carbono ainda são itens transponíveis a serem vencidos com pesquisa científica. Manguezais apresentam papel relevante na mitigação climática, agem como protagonistas na eficiência quanto à captura e armazenamento de CO_2, especialmente em seus solos. Com isso, o reconhecimento da importância dos manguezais foi o alicerce para o desenvolvimento do trabalho, o qual buscou por meio de ferramentas disponíveis e dados inéditos, complementar o conhecimento e destacar as potencialidades brasileiras. Os Capítulos 1 e 2 desta tese trazem por meio de evidências científicas informações muitas vezes ignoradas pelos agentes interessados e negociadores de serviços ambientais. E destacam que os manguezais da costa brasileira são diferentes entre si, apresentam processos biogeoquímicos diferentes, e armazenam o carbono de forma distinta. Assim, não é possível afirmar categoricamente que um manguezal **A** terá o mesmo quantitativo de carbono, ou créditos de carbono, que o manguezal **B,** a menos que os valores sejam levantados *in situ*. Também apresentamos com esta tese um afunilamento da questão citada, onde além da percepção acerca das diferenças entre manguezais, no que se refere ao armazenamento e estocagem, destacamos que dentro de um mesmo manguezal há um mosaico de paisagens, que pode refletir no processo de DMOS e consequentemente na passagem do CO_2 para os solos dos manguezais. Dito isto, é importante pensar e questionar alguns pontos que interceptam a temática da tese: (1) Para quais públicos se direcionam as pesquisas acerca dos processos de sequestro e armazenamento de CO_2 pelos manguezais; (2) Quais seriam as soluções práticas da pesquisa experimental para potencializar o sequestro e enterramento de CO_2 pelos manguezais; (3) Se há tantas variáveis influenciando os processos de sequestro e armazenamento de CO_2 no manguezal, não seria ilusório tentar entendê-los em sua totalidade?

REFERENCIAL TEÓRICO



Referencial Teórico

1 REFERENCIAL TEÓRICO

1.1 OS MANGUEZAIS

Manguezal é um ecossistema costeiro que recebe influência do mar e rios adjacentes, fazendo com que haja uma alternância quanto ao seu alagamento, especialmente devido à força das marés, o que altera também suas propriedades salinas. O manguezal, ou mangal, fica geralmente localizado em estuários, enseadas e baías, e conta com a presença de grupos animais e vegetais específicos, tais como caranguejos, aves marinhas, árvores e plantas tolerantes a variações ambientais, etc. (ICMBio, 2018; LACERDA et al. 2002; KATHIRESAN & BINGHAM, 2001).

De acordo com a história natural, a origem dos manguezais ocorreu da evolução de plantas terrestres ou de água doce, e não marinhas. Existe uma hipótese consolidada de que seu surgimento ocorreu Indo-Pacífico Ocidental - local de maior número de espécies vegetais de mangue - e que posteriormente houve sua dispersão por rotas específicas ou via espalhamento generalizado para outras regiões. Entretanto há outra hipótese acerca da origem dos manguezais que defende a ocorrência do processo de vicariância, onde se acredita que todos os manguezais possam ter se originado ao redor do Mar de Tétis, e com a deriva continental separaram-se e mantendo em isolamento esta flora específica (KATHIRESAN & BINGHAM, 2001; LACERDA et al. 2002; BARTH, 1982; MCCOY & HECK Jr., 1976).

Contudo, independentemente de sua origem, o que se sabe hoje sobre manguezais é que esses são ecossistemas extremamente relevantes, considerados um dos mais produtivos do planeta (ALONGI, 2012). Suas árvores, apesar de apresentarem baixa biodiversidade de espécies quando comparadas às florestas tropicais, apresentam estruturas e funcionalidades como nenhuma outra, tendo capacidade de desenvolvimento e sobrevivência em ambientes completamente alagados e de condições extremas (DUKE et al.,1998).

Manguezais são típicos de latitudes tropicais e subtropicais, e se desenvolvem melhor em condições de elevada umidade e temperatura (>20°C) (Figura 1). Atualmente estima-se que cubram uma área de 145.068 km^2 (equivalente à 14.506.800 ha), estando espalhados no formato de faixas ou manchas costeiras. O continente asiático é o que apresenta a maior cobertura vegetal de manguezais, com 39,2 %. Em nível de país, a Indonésia, o Brasil e Austrália, ambos localizados em latitudes tropicais, são os países de maiores quantidades de florestas de manguezal do mundo (KATHIRESAN & BINGHAM, 2001; LACERDA et al., 2002; SPALDING et al., 1997; JIA et al., 2023).

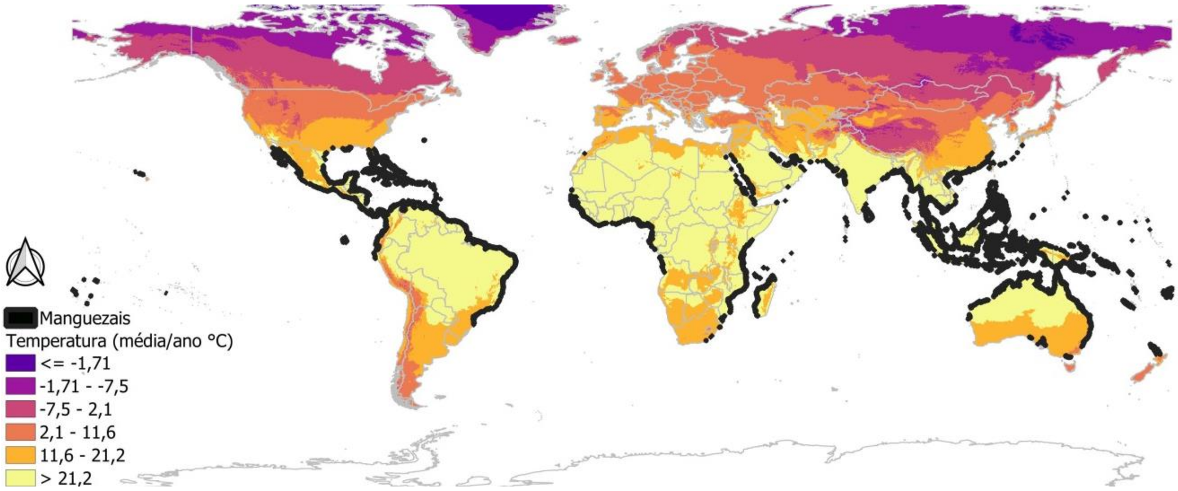


Figura 1 – Distribuição dos manguezais e temperatura média do ar. Elaborado pela autora. Fonte: https://www.worldclim.org/data/bioclim.html.

Especificamente no Brasil, há presença de manguezais em quase todos os estados costeiros, com exceção apenas ao estado do Rio Grande do Sul. Sendo que os locais considerados como os mais relevantes com relação à distribuição de manguezal são os estados do Maranhão, Pará e Amapá, com área contínua representando ~78% dos manguezais do sudoeste do Atlântico (MAGRIS & BARRETO, 2010; ICMBio, 2018; MAPBIOMAS, 2021). Atualmente, ao menos 87% das áreas de manguezais brasileiros estão inseridas dentro de alguma Unidade de Conservação (UC) (Lei n°9986/2000), e ao longo do litoral brasileiro estes manguezais apresentarão características bastante variáveis. Na região norte, por exemplo, os manguezais recebem influência da elevada hidrodinâmica do ambiente devido à amplitude de maré e fluxos de rios, além de recebem elevados volumes de chuvas. Por outro lado, as demais regiões contam com menor amplitude de maré, fluxo de rios e menores regimes de chuvas, o que reflete também em uma menor oscilação da hidrodinâmica desses manguezais (ICMBio, 2018).

1.1.1 OS MANGUEZAIS DO PARÁ

Os manguezais do Pará estão inseridos dentro da Costa de Manguezais de Macromáre da Amazônia (CMMA), área que compreendem ~7.591,09 km^2, indo da Baía de Marajó - PA, até a Ponta do Tubarão - MA. O Estado do Pará, especificamente, tem 850 km de linha retilínea de costa, e um território de ~2.176,78 km^2 de manguezais (SOUZA-FILHO, 2005; ICMBio, 2018).

Características geomorfológicas e sedimentares dos manguezais do norte remontam a um ambiente deltaico, com clima quente de monção (Am) e macromarés (até 7.5 m). Assim, tais características, junto à topografia, as condições de correntes, de ondas e de maré, podem ser os fatores que mais beneficiam a constante expansão territorial de manguezais na região (WORTHINGTON et al., 2020; SOUZA-FILHO, 2005; DUBREUIL et al., 2018).

No Pará, os manguezais ficam localizados na foz do rio Amazonas, adentram estuários, e contam com uma enorme quantidade de sedimentos em suspensão, além de grandes volumes de água doce. Sua vegetação se mistura com vegetação de florestas de várzeas, terra firme e ilhas de vegetação herbácea, essas oscilam sazonalmente conforme períodos de precipitação e paisagem, oscilações que também afetam o desenvolvimento das espécies de mangue e sua produção de serapilheira ao longo do ano (ICMBio, 2018; MENEZES et al., 2008).

1.1.1.1 Manguezal da Resex Marinha de Caeté-Taperaçu-PA

A Resex Caeté - Taperaçu é uma Unidade de Conservação (UC) de uso sustentável criada pelo Decreto s/n° de 20 de maio de 2005 (BRASIL, 2005), conta com uma área de 42.489,17 ha, onde 23.189 ha (54,57%) da Resex correspondem a florestas de mangue. Os manguezais desta Resex são considerados como um dos mais preservados e estudados do país, contemplam áreas do município de Bragança, incluindo a Península de Ajuruteua, e adjacências dos rios Caeté, Taperaçu e Maniteua (ICMBio, 2018; SARAIVA et al., 2012; MENEZES et al., 2008)(Figura 2).

(a) (b)

Figura 2 – Região da Resex Caeté-Taperaçu. (a) Manguezal da Península de Ajuruteua; (b) Vista do Rio Caeté - Bragança. Foto: Autora (2023).

As espécies *Rhizophora mangle, Avicennia germinans* e *Laguncularia racemosa,* são facilmente encontradas na área, geralmente apresentam grande porte, havendo predominância da *R. mangle*. O crescimento das árvores se dá de forma contínua ao longo do ano, e as características do local, tais como inundação e topografia se mostram importante no desenvolvimento das florestas, não obstante, foram observadas que alterações destas características podem ocasionar a mortalidade de árvores, tal como o ocorrido com a construção da rodovia PA-458, área adjacente ao manguezal da Resex (MATNI et al., 2006; KRAUSE et al., 2001).

Além de toda a relevância florística, a Resex Marinha Caeté-Taperaçu funciona como berçário reprodutivo para várias espécies, sendo responsável pela manutenção de diversos recursos pesqueiros, recursos esses necessários para a vida das populações locais e regionais, que seguem dependentes deste ecossistema para sua sobrevivência (SARAIVA et al., 2012; FERNANDES, 2016; OLIVEIRA et al., 2022).

1.1.2 OS MANGUEZAIS DO CEARÁ

No Ceará, os ambientes de manguezais estão presentes em uma área de aproximadamente 176,14 km^2, inseridos no regime climático semiárido. Apresentam dois períodos sazonais bem marcados, um longo e seco (de junho a novembro) e um curto e chuvoso (de dezembro a maio). O período chuvoso recebe forte influência da Zona de Convergência Intertropical (ZCIT), responsável pelos elevados volumes de chuva, enquanto no período seco, há escassez de chuvas, redução do fluxo dos rios, além de alta evaporação. Durante este período de seca, os manguezais permanecem em condições de hipersalinidade (MAPBIOMAS, 2021; CAVALCANTE, 2015; GADELHA, 2014). Sendo assim, o clima semiárido, a longa estação seca, o regime de escoamento intermitente dos rios exorréicos (de drenagem para o mar), a presença de barragens e consequente elevada salinidade dos estuários nos manguezais cearenses, são passíveis de atuar como fatores de estresse para os bosques de mangue, fazendo com que haja pouco desenvolvimento das árvores neste período (SCHAEFFER-NOVELLI et al., 1990; MAIA, 2016).

1.1.2.1 Manguezal do estuário da APA do rio Pacoti

A Área de Proteção Ambiental (APA) do rio Pacoti foi criada por meio do Decreto Estadual Nº 25.778/2000 (CEARÁ, 2000), compreende uma área de ~3000 ha (Figura 3). Neste mesmo ano de criação da APA, também houve a criação do Corredor Ecológico do rio

Pacoti (Decreto Nº 25.777/2000), com intenção de ligar a APA do Pacoti com a Serra de Baturité, em virtude a extrema relevância de ambos ambientes (MAIA, 2016; FIUZA et al., 2010). Dentro da APA do Pacoti ocorrem ambientes de manguezal, cordão de dunas, mata de tabuleiro e ciliar; sua área de mangue, especificamente, corresponde a 158 ha, tendo mostrado recente tendência ao aumento da cobertura vegetal. Esse aumento das áreas vegetadas no estuário do Pacoti vêm sendo atribuído a alguns fatores tais como à desativação de salinas e viveiros de camarão, que deram espaço a uma regeneração natural; a projetos recentes de restauração florestal que promovem o crescimento eficientemente dos bosques; e há também fatores como o avanço do nível médio das marés e regime hidrológico que promovem maior expansão de manguezais, em especial em direção às áreas de apicuns (LACERDA et al., 2007; BARBOSA et al., 2016; FERREIRA et al., 2022, 2023).

(a) (b)

Figura 3 – Região da APA do rio Pacoti. (a) Manguezal às margens do rio Pacoti; (b) Manguezal da APA do rio Pacoti em processo de restauração. Foto: Autora (2022).

E finalmente, mesmo sabendo que o estuário do rio Pacoti é uma área pouco urbanizada em comparação aos demais manguezais da região metropolitana de Fortaleza (rio Ceará e Cocó), há também pressões antrópicas sob este ambiente, tais como: 1) ocupações irregulares; 2) tráfego de veículos; 3) disposição de resíduos, e 4) especulação imobiliária. Tais fatores presentes ameaçam a integridade e funcionalidade dos manguezais, podendo comprometer seus recursos pesqueiros quanto à disponibilidade e qualidade, prejudicando assim, as comunidades locais e o meio ambiente como um todo (MAIA, 2016; FIUZA et al., 2010; SEMACE, 2010).

1.2 OS ECOSSISTEMAS DE CARBONO AZUL

O termo carbono azul se refere ao carbono de ecossistemas marinhos ou costeiros com capacidade de sequestrar, armazenar e estocar elevadas quantidades de carbono em seus compartimentos (vegetação e/ou solos). Atualmente existem três ambientes que mais se destacam quanto a isso, são eles: 1) os prados de angiospermas, 2) os pântanos salgados e 3) **os manguezais** (VANDERKLIFT et al., 2019, MURRAY et al., 2011; DONATO et al., 2011; GORDON et al., 2011). Porém recentemente, vêm sendo reivindicado para que outros ambientes marinhos também sejam inventariados e considerados quanto a seu potencial de sequestro, armazenamento e estocagem de carbono, são estes: a plataforma continental, os bancos de rodolitos, os apicuns, os bancos de macroalgas e as florestas marinhas (SOARES et al., 2022; BELOTO, NASCIMENTO, BEZERRA, 2023).

Quantitativamente falando, embora os manguezais ocorram apenas em algumas áreas restritas do mundo, sabe-se que esse apresenta estocagem superior aos outros tipos florestais e ecossistemas, sendo seus solos reconhecidos como o compartimento de maior estocagem (NÓBREGA et al., 2019; FOURQUREAN et al., 2012; ALONGI, 2014; HOWARD et al., 2014) (Figura 4).

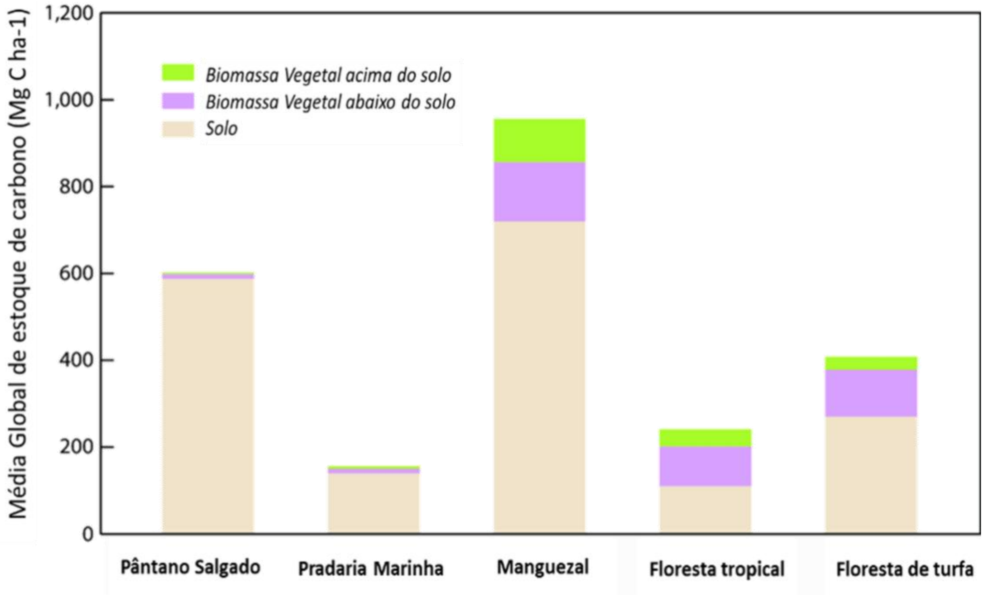


Figura 4 – Média global de estoque de carbono por ecossistema. Fonte: adaptado de Howard et al., 2014.

Desta forma, diante da imensa potencialidade dos manguezais frente aos outros ambientes, diversos estudos vêm buscando informações sobre estes estoques de carbono ao redor do mundo. Conquanto, a nível nacional, ainda são escassas as informações acerca do potencial de armazenamento, estocagem e até mesmo emissão de carbono por mangues brasileiros, havendo inclusive lacunas informativas sobre estoques de carbono em diversos estados brasileiros (Amapá, Maranhão Paraíba, Pernambuco, Alagoas, Sergipe, Paraná e Santa Catarina) (BELOTO et al., 2023; MARIANO NETO & SILVA, 2023).

1.3 CARBONO AZUL NO SOLO DE MANGUEZAL (COS)

Dentro de uma perspectiva, seja esta global ou local, podemos encontrar ampla variabilidade dos estoques de carbono nos solos de manguezais. Esta variação é muitas vezes justificada por questões: 1) de produtividade primária e composição estrutural da vegetação; 2) de idade ou tempo de formação do ecossistema; 3) geomorfológicas; 4) biogeoquímicas; 5) ambientais; 6) edáficas e 7) quanto ao *status* de preservação ambiental (MARIANO NETO & SILVA, 2023; SANDERMAN et al., 2018; DONATO et al., 2011; NÓBREGA et al., 2019; ROVAI et al., 2022; SOARES et al., 2022; KAIRO, et al., 2021; ROVAI et al., 2018; SANDERS, et al., 2006; ALONGI, 2012; SINGH et al., 2022; BELOTO et al., 2023; ALONGI, 2020).

De acordo com as questões que predominantemente ditam os processos de sequestro, armazenamento e estocagem de carbono nos solos, podemos explicar que a produtividade primária das florestas e do fitoplâncton/fitobentos atuam sequestrando CO_2 atmosférico, e assim, a matéria orgânica oriunda deste processo (biomassa vegetal das árvores e das algas) entrará em decomposição em algum momento, iniciando assim, a passagem do carbono para os solos (ALONGI, 2002; ALONGI, 2014; LOO et al., 2024). Sendo assim, manguezais com árvores maiores, bem desenvolvidas e com espécies que capturam mais carbono e/ou com elevada densidade de algas, ou seja - maior produção de biomassa - tendem a ser ambientes de maior passagem do CO_2 atmosférico para seus solos (MARIANO NETO & SILVA, 2023; RAMOS et al., 2023; LUNSTRUM & CHEN, 2014).

Cabe mencionar que durante o processo da passagem de carbono a partir produtividade primária líquida podem ocorrer perdas para o sistema, e estudos indicam que para o manguezal, ~40% da produção primária sofrerá decomposição dentro do sistema, ~9.1% será consumida por herbívoros, ~29.5% será exportada, e ~10.4% pode ser armazenada no solo em forma de carbono, demonstrando assim a potencialidade do armazenamento de carbono nos solos proporcionalmente a produtividade primária do sistema (DUARTE & CEBRIAN, 1996; LOO et al., 2024)(Figura 5).

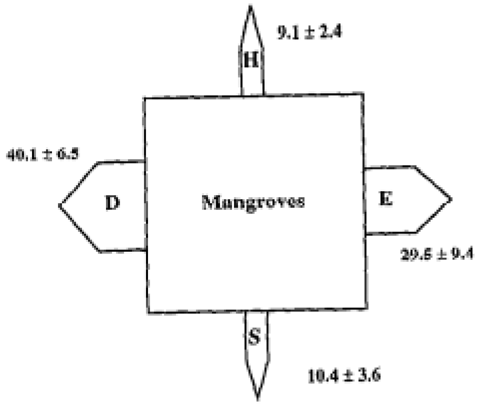


Figura 5 – Balanço da produção primária líquida em ambientes de manguezal. Fonte: DUARTE & CEBRIAN, 1996.

Outro aspecto abordado que se relaciona ao armazenamento e estocagem de carbono é a relação da idade e tempo de formação de ecossistemas. Alguns manguezais podem apresentar particularidades singulares com relação à estocagem de carbono, como é o caso da Península de Yucatán, no México, considerado o maior *hotspot* de carbono do mundo, apresenta valores de até 2792 Mg C ha^{-1} em seu solo. Nesse caso específico, o grande acúmulo de carbono ocorreu devido a um processo de deposição iniciado há 3220 anos, ou seja, a história de formação deste manguezal foi determinante para ditar o elevado conteúdo de carbono (38%) e estoque no solo (ADAME et al., 2021). Sabe-se que o aumento do conteúdo de carbono nos solos ao longo do tempo não é incomum, e pode também ser observado em florestas jovens, inclusive em áreas que estão passando por processos de florestamento (LUNSTRUM & CHEN, 2014).

Condições ambientais também podem exercer influência quanto à entrada (*input*) e saída (*output*) do carbono dos manguezais. Há constantemente *input* autóctone a partir da decomposição da matéria orgânica e alóctone oriundo de locais adjacentes, via rios e marés. Conquanto os rios e as marés podem carrear o carbono para longe, sendo também via de *output*. Desta maneira, o carbono armazenado no solo de manguezais se refere àqueles *inputs* autóctones e alóctones, corrigido pelos quantitativos de saída (*outputs*) (ALONGI, 2012; ALONGI, 2014; SOUZA et al., 2012).

Complementarmente, outra questão que pode ser relacionada ao aumento e redução do carbono no ambiente, é justamente a pressão antrópica exercida sob os manguezais. Intervenções humanas alteram facilmente os ciclos naturais, e no caso do carbono, efluentes urbanos podem introduzir uma quantidade significativa de carbono para o ambiente; além disso, o corte da vegetação, as queimadas, a instalação de tanques de aquicultura, a realização de atividade salineira são atividades que transformam manguezais em fontes de carbono para a atmosfera, tendo em vista que àquele carbono historicamente estocado passa a ser liberado com essas mudanças no uso do solo (SAINTILAN et al., 2013; DUARTE & CEBRIAN, 1996; SOUZA et al., 2012; DUARTE et al., 2013; ATWOOD et al., 2017; PENDLETON et al., 2012; GORDON et al., 2011;VALIELA et al., 2001; ALONGI, 2002).

Estima-se que no Brasil os impactos antrópicos já foram responsáveis pela emissão de uma quantidade significativas de CO_2, tendo ocorrido nas últimas décadas uma perda estimada em ~ 4% (>50.000 ha) das áreas originais de manguezais, em processos de degradação que não cessam, sendo agravantes para as mudanças climáticas, além de promoverem a escassez dos recursos pesqueiros (FERREIRA & LACERDA, 2016; NÓBREGA et al., 2019; MCLEOD et al., 2011; LACERDA et al., 2021; GOMES et al., 2021).

1.4 DECOMPOSIÇÃO DA MATÉRIA ORGÂNICA NOS SOLOS DE MANGUEZAIS (DMOS)

Os solos dos manguezais, geralmente, são compostos majoritariamente por areia, silte e argila, e em seu interior apresentam diversas raízes, rizomas e material vegetal morto (ALONGI, 2020). Suas condições bioquímicas podem ir de hiperácida a neutra (pH <3.5 – 6.5), e de anóxica a óxica (Eh <100 - >400 mV). Em uma mesma área os solos podem apresentar variabilidade quanto a sua composição e propriedades, sendo passível inclusive de oscilações sazonais de acordo com períodos de maior ou menor quantidade de chuva (RAMOS et al., 2023; QUEIROZ et al., 2021; HOSSAIN & NURUDDIN 2016).

Percentuais de matéria orgânica e carbono orgânico costumam ser altos nos solos, com quantitativos variáveis de acordo com o local e com suas condições de entrada e saída de material orgânico. A decomposição da matéria orgânica nos manguezais é um processo crucial para a passagem de nutrientes tais como o carbono para o solo do manguezal, por isso seu entendimento e caracterização são extremamente importantes. A DMOS pode ser influenciada por diversos fatores, tais como níveis e períodos de inundação, temperatura da água, disponibilidade de nutrientes, podendo por isso, ser suscetível a oscilações sazonais do ambiente (ALONGI, 2002; RAMOS et al., 2023; DEWIYANTI et al., 2021; KATHIRESAN & BINGHAM, 2001; HOSSAIN & NURUDDIN 2016; PARTAIN, 2019; ALSAFRAN, et al., 2017; TREVATHAN-TACKETT, et al., 2021; REZENDE et al., 2013; SEELEN et al., 2019).

Assim, observar a DMOS em locais com características diferentes é necessário, especialmente para verificar a funcionalidade de toda paisagem. Locais onde a DMOS ocorre extremamente rápido, por exemplo, podem ser àqueles menos favoráveis ao sequestro e armazenamento de carbono. Em contrapartida, locais onde as condições ambientais fazem com que a DMOS seja elevada e que esta ocorra lentamente são os mais propícios, e durante este processo é esperada uma relação entre o carbono orgânico do solo e a DMOS (ALONGI, 2014). Adicionalmente a DMOS é uma informação extremamente importante do ecossistema, por meio dessa é possível entender a dinâmica do ambiente, uma vez que seus resultados refletem a ciclagem de nutrientes em resposta às condições dos solos e da vegetação (SOARES, 2019).

1.5 PARA QUE COMPREENDER O CARBONO AZUL E A DMOS DO MANGUEZAL?

Existe uma ampla complexidade dos processos de DMOS e que influenciam o armazenamento e estocagem de COS, os quais ainda são pouco compreendidos, por outro lado sabe-se que as mudanças no uso de solo e os eventos extremos vêm promovendo a emissão de elevadas quantidades de CO_2 por manguezais (NÓBREGA et al., 2019; GOMES et al., 2021). E embora ainda sejam restritas as informações sobre quantitativos de carbono estocados em compartimentos dos manguezais da costa do Brasil (BELOTO et al., 2023; MARIANO NETO & SILVA, 2023; SOARES et al., 2022), é clara a necessidade de cessar com processos que estejam promovendo emissões de $CO_{2.}$ E para, além disso, é necessário compreender o funcionamento do ecossistema, considerando sua heterogeneidade e também oscilações ambientais. Uma melhor compreensão do ecossistema pode auxiliar na elaboração de informações que subsidiem e reforcem a necessidade do aumento da proteção legal das áreas de manguezal, podendo chamar atenção também quanto a prioritárias para conservação e restauração (BELOTO et al., 2023; SOARES et al., 2022), considerando para tal também sua potencialidade de mitigação climática.

2 OBJETIVOS

- O objetivo desta tese é avaliar os processos e fatores que podem favorecer o armazenamento e estocagem de carbono, e verificar a diferença entre em manguezais de regiões brasileiras e ao longo de um gradiente da paisagem por meio de um experimento *in situ* e um levantamento bibliográfico;
- O objetivo do Capítulo 1 é compreender o processo de decomposição da matéria orgânica nos solos de manguezais e sua relação com o ambiente, utilizando para tal um método internacional que estima a taxa de decomposição (k) e fator de estabilização (S);
- O objetivo do Capítulo 2 é realizar uma revisão sistemática para o entendimento da estocagem de carbono nos compartimentos (biomassa vegetal viva e morta – AGB e BGB, troncos caídos – DW e solos) dos manguezais brasileiros.

2.1 OBJETIVOS ESPECÍFICOS

- Os objetivos específicos do Capítulo 1 são: a) Promover uma análise experimental direta que avalie a taxa de decomposição (k) e o fator de estabilização (S) dos solos de dois manguezais brasileiros (Amazônico e Semiárido), de condições ambientais distintas; b) Avaliar a viabilidade da aplicação do método da decomposição da matéria orgânica pelo índice do saquinho de chá (TBI) em solos de manguezais, e seus possíveis vieses; c) Verificar se há diferença no processo de decomposição da matéria orgânica entre manguezal Amazônico e Semiárido, ao longo de um gradiente da paisagem com diferentes estágios sucessionais, relacionando com suas possíveis causas; d) Discutir ou propor possíveis adaptações metodológicas para áreas de manguezais na costa do Brasil; e) Compreender melhor como ocorre o processo de decomposição da matéria orgânica em manguezais;
- Os objetivos específicos do Capítulo 2 são: a) Verificar a variabilidade de estoques de carbono de acordo com características ambientais regionais da costa brasileira; b) Verificar se ocorrem diferenças entre estoques de carbono de locais impactados e não impactados dos manguezais brasileiros; c) Discutir variações espaciais de TECS, carbono orgânico em solos, em biomassa viva acima e abaixo do solo

(AGB e BGB respectivamente) e/ou biomassa morta (madeira derrubada - DW); e) Identificar questões de intersecção entre os trabalhos selecionados e; f) Apontar possíveis lacunas e viés metodológico sobre os valores dos estoques de carbono e propor recomendações para estudos futuros.

3 JUSTIFICATIVA

Ambientes de elevado potencial de sequestro, armazenamento e estocagem de carbono tais como manguezais, precisam ter seus processos mais bem compreendidos. A **decomposição da matéria orgânica** e os **quantitativos de carbono nos compartimentos dos manguezais** trazem informações relevantes para compreensão do ambiente. Por isso, o estudo aqui apresentado, se justifica pela constante necessidade de subsídios e informações que possam garantir a integridade de ambientes com elevada estocagem de carbono. Nesse sentido, a caracterização dos manguezais, observando e identificando suas potencialidades é essencial para que esses possam atuar junto às soluções para os grandes problemas globais. E finalmente, todo o conhecimento produzido por esta tese intenciona-se a reforçar a relevância dos manguezais para proteção da vida, atentando para que os processos que promovem o aumento das emissões atmosféricas em decorrência da degradação do manguezal possam ser cessados.

4 HIPÓTESES CIENTÍFICAS

4.1 CAPÍTULO 1

- Se condições ambientais promovem diferenças entre os processos de decomposição da matéria orgânica nos solos (DMOS) de manguezais, então é esperado que o experimento realizado possa demonstrar a variabilidade regional das taxas de decomposição (k) e fator de estabilização (S);
- Ambientes terrestres e aquáticos apresentam condições distintas quanto ao alagamento e outras questões, assim é possível que a aplicação de um método comumente utilizado em ambientes terrestres possa trazer vieses na aplicação para ambientes alagados, em caso positivo, espera-se identifica-los e propor alternativas a este;
- É possível que ocorra a variabilidade no processo de DMOS em escala regional, e também ao longo do gradiente da paisagem, em resposta a diferentes condições ambientais presentes, a serem indicadas, se for o caso;
- Se há estudos que apontam padrões definidos de decomposição da matéria orgânica, então, o experimento indicará de que forma isso se dá em um manguezal;

4.2 CAPÍTULO 2

- Seria possível detectar padrões de estoques de carbono de acordo com as regiões brasileiras e suas respectivas características?
- Sabe-se que manguezais impactados podem perder carbono, no entanto, seria possível verificar diferenças significativas entre os manguezais preservados e os impactados com relação aos estoques em seus compartimentos.
- Se há diferenças entre estoques de carbono em regiões brasileiras, então seria esperado também que estas pudessem ser observadas nos diversos compartimentos deste ecossistema (solos, AGB, BGB, DW, etc);
- Estudos sobre estoques de carbono na costa do Brasil podem apresentar algum ponto de intersecção entre si, quais seriam estas possíveis intersecções.

- É provável que os estudos acerca dos estoques de carbono dos manguezais brasileiros, ainda não estejam padronizados quanto aos seus métodos e objetivos, então quais seriam estes vieses comparativos;

5 REFERÊNCIAS

ADAME, M.F.; SANTINI, N.S.; TORRES-TALAMANTE, O.; ROGERS, K. (2021). Mangrove sinkholes (*cenotes*) of the Yucatan Peninsula, a global hotspot of carbon sequestration. **Biol. Lett.**, 17. https://doi.org/10.1098/rsbl.2021.0037.

ALONGI, D. M. (2002). Present state and future of the world's mangrove forests. **Environmental. Conserv.**, 29(03): 331 – 349. https://doi.org/10.1017/S0376892902000231.

ALONGI, D. M. (2012). Carbon sequestration in mangrove forests. **Carbon Management**, 3(3), 313–322. https://doi.org/10.4155/cmt.12.20.

ALONGI, D. M. (2014). Carbon Cycling and Storage in Mangrove Forests. **Annual Review of Marine Science**, 6(1), 195–219. https://doi.org/10.1146/annurev-marine-010213-135020.

ALONGI, D. M. (2020). Global Significance of Mangrove Blue Carbon in Climate Change **Mitigation. Sci**, 2(3), 67. https://doi.org/10.3390/sci2030067

ALSAFRAN, M.; SARNEEL, J.; ALATALO, J. (2017). Variation in plant litter decomposition rates across extreme dry environments in Qatar. **The Arab World Geographer,** 20(2-3): 252-260. http://hdl.handle.net/10576/15954

ATWOOD, T. B.; CONNOLLY, R. M.; ALMAHASHEER, H.; et al. (2017). Global patterns in mangrove soil carbon stocks and losses. **Nature Climate Change**, 7(7): 523–528. https://doi.org/10.1038/nclimate3326

BARBOSA, L. N.; LIMA, V. G. F.; FARIAS, J. F.; SILVA, E. V.(2016). Evolução espaço-temporal da vegetação de mangue no estuário do rio Pacoti/Ceará. **Revista Geonorte**, 7(Edição Especial 5):144-159.

BARTH, H. (1982). The biogeography of mangroves. In: Sen, D.N., Rajpurohit, K.S. (eds) Contributions to the ecology of halophytes. Tasks for vegetation science, vol 2. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-8037-2_4

BRASIL (2005). Decreto s/n° de 20 de maior de 2005. Dispõe sobre a criação da Reserva Extrativista Marinha de Caeté-Taperaçu, no Município de Bragança, no Estado do Pará. Disponível em: http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2005/dnn/dnn10531.htm Acesso em: 10/02/2024.

BELOTO, N.; COTOVICZ Jr., L.C.; RODRIGUES, J.V.M.; GMACH, M.R.; ZIMMER, M.; HELFER, V.; SOARES, M.O.S.; BEZERRA, L.E.A. (2023). Blue carbon stock heterogeneity in Brazilian mangrove forests: A systematic review. **Marine Pollution Bulletin,** 197 – 115694:1-10. https://doi.org/10.1016/j.marpolbul.2023.115694.

BELOTO, N.; NASCIMENTO, F. C. S.; BEZERRA, L. E. A. Inclusão da plataforma continental em inventários de carbono azul ao longo da costa brasileira. In: Livro de Resumo XXXIII Semana Nacional De Oceanografia - Da Lama ao Coral: Desafios Socioambientais dos Ecossistemas Tropicais. Anais...Recife(PE) UFPE, 2023. Disponível em:

https//www.even3.com.br/anais/xxxiii-semana-nacional-de-oceanografia/654271-INCLUSAO-DA-PLATAFORMA-CONTINENTAL-EM-INVENTARIOS-DE-CARBONO-AZUL-AO-LONGO-DA-COSTA-BRASILEIRA. Acesso em: 04/03/2024

CAVALCANTE, M.S. (2015). Transporte de carbono orgânico dissolvido no estuário do rio Jaguaribe sob clima semiárido. 83 f. Dissertação (Mestrado em Ciências Marinhas Tropicais) - Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza, 2015. http://www.repositorio.ufc.br/handle/riufc/17666

CEARÁ (2000). Decreto Nº 25.778, de 15 de Fevereiro de 2000. Denomina e cria a Área de Proteção Ambiental (APA) do rio Pacoti, situada entre os municípios de Fortaleza, Eusébio e Aquiraz, todos no Estado do Ceará, compreendendo o Rio Pacoti. Disponível em: https://www.legisweb.com.br/legislacao/?id=276897 Acesso em: 05/02/2024

DEWIYANTI, I.; DARMAWI, D.; MUCHLISIN, Z.A.; HELMI, T.Z.; IMELDA, I.; DEFIRA, C.N. (2021) Physical and chemical characteristics of soil in mangrove ecosystem based on differences habitat in Banda Aceh and Aceh Besar. **IOP Conference Series: Earth and Environmental Science**, 674 - 012092: 1-7. https://doi.org/10.1088/1755-1315/674/1/012092.

DONATO, D. C.; KAUFFMAN, J. B.; MURDIYARSO, D.: KURNIANTO, S.: STIDHAM, M.; KANNINEN, M. (2011). Mangroves among the most carbon-rich forests in the tropics. **Nature Geoscience**, 4(5), 293–297. https://doi.org/10.1038/ngeo1123.

DUARTE, C. M.; LOSADA, I. J.; HENDRIKS, I. E.; MAZARRASA, I.; MARBÀ, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. **Nature Climate Change**, 3(11), 961–968. https://doi.org/10.1038/nclimate1970

DUARTE, C.; CEBRIAN, J. (1996). The fate of marine autotrophic production. **Limnol. Oceanogr.**, 41(8): 1758-1766. https://doi.org/10.4319/lo.1996.41.8.1758

DUBREUIL, V.; FANTE, K.; PLANCHON, O.; LIMA NETO, J. (2018). Os tipos de climas anuais no Brasil : uma aplicação da classificação de Köppen de 1961 a 2015. **Revista franco-brasilera de geografia**, 37. https://doi.org/10.4000/confins.15738

DUKE, N. C.; BALL, M. C.; ELLISON, J. C. (1998). Factors Influencing Biodiversity and Distributional Gradients in Mangroves. **Global Ecology and Biogeography Letters**, 7(1), 27-47. https://doi.org/10.2307/2997695

FERNANDES, M.E.B. (2016) Os Manguezais da Costa Norte Brasileira Vol. III / organizador: Marcus Emanuel Barroncas Fernandes. Bragança: Laboratório de Ecologia de Manguezal, 2016. 175 p.: il. ISBN 978-85-89547-03-1

FERREIRA, A. C.; LACERDA, L. D. (2016). Degradation and conservation of Brazilian mangroves, status and perspectives. **Ocean & Coastal Management**, 125:38–46. https://doi.org/10.1016/j.ocecoaman.2016.03.011

FERREIRA, A.C.; FREIRE, F.A.M.; RODRIGUES, J.V.M.; BEZERRA, L.E.A. (2022). Mangrove Recovery in Semiarid Coast Shows Increase of Ecological Processes from Biotic and Abiotic Drivers in Response to Hydrological Restoration. **Wetlands**, 42(80): 1-19. https://doi.org/10.1007/s13157-022-01603-0.

FERREIRA, A.C.; LACERDA, L.D.; RODRIGUES, J.V.M.; BEZERRA, L.E.A. (2023). New contributions to mangrove rehabilitation/restoration. **Wetlands Ecol Manage**, 31:89-114. https://doi.org/10.1007/s11273-022-09903-2.

FIUZA, A. B.; LEHUGEUR, L.; QUEIROZ, B. (2010). Análise ambiental do estado de conservação do baixo curso do rio Pacoti – Ceará. **Arq. Ciên. Mar**, 43 (1): 18-29. https://repositorio.ufc.br/handle/riufc/4261

FOURQUREAN, J.W.; DUARTE, C.M.; KENNEDY, H.; et al. (2012). Seagrass ecosystems as a globally significant carbon stock. **Nature Geoscience**, 5: 505–509. https://doi.org/10.1038/ngeo1477

GADELHA, F.M. (2014). Solos de manguezais sob a influência do Semiárido cearense: Biogeoquímica de Fe, Mn, Cu, Ni e Cr. 59 f. Dissertação (Mestrado em Solos e Nutrição de Plantas) - Universidade Federal do Ceará, Fortaleza, 2014. http://www.repositorio.ufc.br/handle/riufc/36499

GOMES, L. E. D. O. et al., 2021. Ecosystem carbon losses following a climate-induced mangrove mortality in Brazil. Journal of Environmental Management, 297(113381).

GOMES, L.E.O.; SANDERS, C.J.; NOBREGA, G.N.; et al. (2021). Ecosystem carbon losses following a climate-induced mangrove mortality in Brazil. **J Environ Manage**, 1:297:113381. https://doi.org/10.1016/j.jenvman.2021.113381.

GORDON, D.; MURRAY, B.C.; PENDLETON, L.; VICTOR, B. (2011). Financing Options for Blue Carbon: Opportunities and Lessons from the REDD+ Experience, North Carolina: **Nicholas Institute for Environmental Policy Solutions Report** NI R 11-11. 20pp.

HOSSAIN, M.D.; NURUDDIN, A.A. (2016). Soil and Mangrove: A Review. Journal of **Environmental Science and Technology**, 9: 198-207. https://doi.org/10.3923/jest.2016.198.207.

HOWARD, J.; HOYT, S.; ISENSEE, K.; TELSZEWSKI, M.; PIDGEON, E. (eds.) (2014). **Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.** Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA. https://unesdoc.unesco.org/ark:/48223/pf0000372868.

ICMBio, 2018. **Atlas dos Manguezais Brasileiros. Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio)**, Brasília, ISBN 978-85-61842-75-8.

https://www.gov.br/icmbio/pt-br/centrais-de-conteudo/atlas-dos-manguezais-do-brasil-pdf (176 p.).

JIA, M; ZONGMING,W., MAO, D.; REN, C.; SONG,K.; ZHAO, Z.; WANG,C.; XIAO,X.; WANG, Y.(2023). Mapping global distribution of mangrove forests at 10-m resolution, **Science Bulletin**, 68(12):1306-1316. https://doi.org/10.1016/j.scib.2023.05.004.

KAIRO, J.; MBATHA, A.; MURITHI, M.M.; MUNGAI, F. (2021). Total Ecosystem Carbon Stocks of Mangroves in Lamu, Kenya; and Their Potential Contributions to the Climate Change Agenda in the Country. **Frontiers in Forests and Global Change**, 4, 7092227: 1-15. https://doi.org/10.3389/ffgc.2021.709227

KATHIRESAN, K.; BINGHAM, B.L. (2001). Biology of mangroves and mangrove Ecosystems. **Advances in Marine Biology**, 40:81-251.https://doi.org/10.1016/S0065-2881(01)40003-4

KRAUSE, G.; SCHORIES, D.; GLASER, M.; DIELE, K. (2001). Spatial patterns of mangrove ecosystems: The bragantinian mangroves of North Brazil (Bragança, Pará). **Ecotropica**, 7:93-107.

LACERDA, L. D.; MENEZES, M. O. T.; MOLISANI, M. M.(2007). Changes in mangrove extension at the Pacoti River estuary, CE, NE Brazil due to regional environmental changes between 1958 and 2004. **Biota Neotropica**, 7(3): 67–72. https://doi.org/10.1590/S1676-06032007000300007.

LACERDA, L. D.;WARD, R.D.; GODOY, M.D.; MEIRELES, A.J.A.; BORGES, R.; FERREIRA, A.C. (2021). 20-Years Cumulative Impact from Shrimp Farming on Mangroves of Northeast Brazil. **Frontiers in Forests and Global Change**, 4: 1-17. https://doi.org/10.3389/ffgc.2021.653096.

LACERDA, L.D.; CONDE, J.E.; KJERFVE, B.; ALVAREZ-LEÓN, R.; ALARCÓN,C.; POLANÍA,J. (2002). **American Mangroves**. In: LACERDA, L.D. Mangrove Ecosystem: Function and Management. Springer. ISBN978-3-642-07585-8. https://doi.org/10.1007/978-3-662-04713-2

LUNSTRUM, A.; CHEN, L. (2014). Soil carbon stocks and accumulation in young mangrove forests. **Soil Biology and Biochemistry**, 75, 223–232. doi:10.1016/j.soilbio.2014.04.008

MAGRIS, R. ; BARRETO, R. (2010). Mapping and assessment of protection of mangrove habitats in Brazil. PANAMJAS, **Pan-American Journal of Aquatic**, 5(4):546-556.

MAIA, R. C. (2016). **Manguezais do Ceará**. 1. ed. Recife: Imprima, 55 p.

MAPBIOMAS, 2021. Cobertura e transições bioma & estados (Coleção 7) - dados de área(ha) de cobertura e uso da terra por bioma e estado de 1985 a 2021. httpt://mapbiomas.org/estatisticas

MARIANO NETO, M.; SILVA, J. B. (2023). Estimativas dos estoque de carbono em ecossistema de manguezal no Brasil: Uma revisão. **Geoambiente On-line**, Goiânia, 45. Disponível em: https://revistas.ufj.edu.br/geoambiente/article/view/75044. Acesso em: 03/03/24.

MATNI, A.; MENEZES, M.; MEHLIG, U. (2006). Estrutura dos bosques de mangue da península de Bragança, Pará, Brasil. **Bol. Mus. Para. Emílio Goeldi, Ciências Naturais**, 1(3): 43-52. https://doi.org/10.46357/bcnaturais.v1i3.727.

MCCOY, E. D.; HECK, K. L. (1976). Biogeography of Corals, Seagrasses, and Mangroves: An Alternative to the Center of Origin Concept. **Systematic Zoology**, 25(3), 201–210. https://doi.org/10.2307/2412488

MCLEOD, E.; CHMURA, G. L.; BOUILLON, S.; et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. **Frontiers in Ecology and the Environment**, 9: 552–560. https://doi.org/10.1890/110004

MENEZES, M. P. M. D.; BERGER, U.; MEHLIG, U. (2008). Mangrove vegetation in Amazonia: a review of studies from the coast of Pará and Maranhão States, north Brazil. **Acta Amazonica**, 38(3): 403–420.

MURRAY, B.; PENDLETON, L.; JENKINS, W.; SIFLEET, S. (2011). Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats: **Nicholas Institute for Environmental Policy Solutions**, Report NI R 11-04. 38pp.

NÓBREGA, G.N.; FERREIRA, T.O.; SIQUEIRA NETO, M.; MENDONÇA, E. DE S.; ROMERO, R.E.; OTERO, X.L. (2019). The importance of blue carbon soil stocks in tropical semiarid mangroves: a case study in Northeastern Brazil. **Environ. Earth Sci.** 78 (12) https://doi.org/10.1007/s12665-019-8368-z.

OLIVEIRA, M.; RIBEIRO, T.; TEISSERENC, M. (2022). Ação Pública Socioambiental em Questão: desafios da cogestão de uma Resex Marinha na Amazônia Brasileira. **Caderno C R H**, 35:1-17. https://doi.org/10.9771/ccrh.v35i0.34542.

PARTAIN, M. (2019). Decomposition Rates in Black Mangrove (*Avicennia germinans*) Sediment Determined Using the Tea Bag Index (TBI) Method. Thesis for scope and quality of Texas A&M University-Corpus Christi. 27pp.

PENDLETON, L.; DONATO, D.C.; MURRAY, B.C.; CROOKS, S.; JENKINS, W.A.; SIFLEET, S.; BALDERA, A. (2012). Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. **PLoS One**, 7 (9), e43542. https://doi.org/10.1371/journal.pone.0043542.

QUEIROZ, H. M. (2021). Iron geochemistry in tropical estuarine soils affected by anthropic and natural disasters. 253p. Thesis (Doctor in Science) - USP / Escola Superior de Agricultura

"Luiz de Queiroz", Piracicaba, 2021. https://doi.org/10.11606/T.11.2021.tde-11102021-122952

REZENDE, R.S.; PINTO, M.O.; GONÇALVES JR., J.F.; PETRUCIO, M.M. (2013). The effects of abiotic variables on detritus decomposition in Brazilian subtropical mangroves. 25(2):158-168. http://dx.doi.org/10.1590/S2179-975X2013000200007.

RAMOS, M.A.V.; PÉREZ-ALBERTI, A.; NÓBREGA, G.N; OTERO, X.L. (2023). Spatiotemporal Variability in Soil Properties and Composition in Mangrove Forests in Baía de Todos os Santos (NE Brazil). **Land**, 12 (7),1392. https://doi.org/10.3390/land12071392.

ROVAI, A.S.; TWILLEY, R.R.; CASTAÑEDA-MOYA, E., RIUL, P.; CIFUENTES-JARA, M.; MANROWVILLALOBOS, M.; PAGLIOSA, P.R. (2018). Global controls on carbon storage in mangrove soils. **Nat. Clim. Chang.**, 8 (6): 534–538. https://doi.org/10.1038/s41558-018-0162-5.

ROVAI, A.S.; TWILLEY, R.R.; WORTHINGTON, T.A.; RIUL, P. (2022). Brazilian mangroves: blue carbon hotspots of national and global relevance to natural climate solutions. Front. **For. Glob. Change**, 4, 787533. https://doi.org/10.3389/ffgc.2021.787533.

SAINTILAN, N.; ROGERS, K.; MAZUMDER, D.; WOODROFFE, C. (2013). Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. **Estuarine, Coastal and Shelf Science** 128(10): 84–92. https://doi.org/10.1016/j.ecss.2013.05.010.

SANDERMANN, J.; HENGL, T.; FISKE, G.; et al. (2018). A global map of mangrove forest soil carbon at 30m spatial resolution. **Environmental Research Letters,** 13, 055002. DOI 10.1088/1748-9326/aabe1c

SANDERS, C. J.; MAHER, D. T.; TAIT, D. R.; WILLIAMS, D.; HOLLOWAY, C.; SIPPO, J. Z.; SANTOS, I. R. (2016). Are global mangrove carbon stocks driven by rainfall? **JGR Biogeosciences**, 121(10), 2600–2609. https://doi.org/10.1002/2016JG003510

SARAIVA, N.; ABDALA, G.; WESLEY, F.(2012). **Cartilha do Plano de Manejo da Reserva Extrativista Caeté-Taperaçu**. Brasília: ICMBio. 40 p.

SCHAEFFER-NOVELLI, Y.; CINTRÓN-MOLERO, G.; ADAIME, R.; CAMARGO, T. (1990). Variability of mangrove ecosystems along the Brazilian coast. **Estuaries**, 13: 204–218. https://doi.org/10.2307/1351590

SELEEN, L. M. S.; FLAIM, G.; KEUSKAMP, J. et al. (2019). An affordable and reliable assessment of aquatic decomposition. doi:10.1016/j.watres.2018.11.081

SEMACE, 2010. Área de Proteção Ambiental do Rio Pacoti. Disponível em: https://www.semace.ce.gov.br/2010/12/08/area-de-protecao-ambiental-do-rio-pacoti/. Acesso em: 11/02/2024.

SINGH, M. et al. (2022). Changes in Mangrove Carbon Stocks and Exposure to Sea Level Rise (SLR) under Future Climate Scenarios. Sustainability, 14(3873).

SINGH, M.; SCHWENDENMANN, L.; WANG, G.; ADAME, M.F.; MANDLATE, L.J.C. (2022). Changes in Mangrove Carbon Stocks and Exposure to Sea Level Rise (SLR) under Future Climate Scenarios. **Sustainability**, 14, 3873. https://doi.org/10.3390/su14073873.

SOARES, J.A.H. (2019). Funções ecossistêmicas de florestas ripárias: análise das taxas de decomposição foliar em um gradiente de fertilidade de solo. Dissertação de Mestrado, Universidade Federal de São Carlos, São Carlos. 46f.

SOARES, M.O., BEZERRA, L.E.A., COPERTINO, M., et al. (2022). Blue carbon ecosystems in Brazil: overview and an urgent call for conservation and restoration. **Front. Mar. Sci.** 9 (1–16). https://doi.org/10.3389/fmars.2022.797411.

SOUZA, M. F. L.; LONGHINI, C. M.; SILVA, A. M.; LENTINI, C. A. D. (2012). Ciclo do Carbono: Processos Biogeoquímicos, Físicos e Interações entre Compartimentos na Baía de Todos os Santos. **Rev. Virtual Quim.**, 4(5):566-582. DOI: 10.5935/1984-6835.20120044

SOUZA-FILHO, P.(2005). Costa de manguezais de macromaré da Amazônia: cenários morfológicos, mapeamento e quantificação de áreas usando dados de sensores remotos. **Revista Brasileira de Geofísica**, 23(4):427-437. https://doi.org/10.1590/S0102-261X2005000400006.

SPALDING, M.D , BLASCO, E.; FIELD, C.D. (Eds). (1997). **World Mangrove Atlas**. The International Society for Mangrove Ecosystems, Okinawa, Japan. 17 pp.

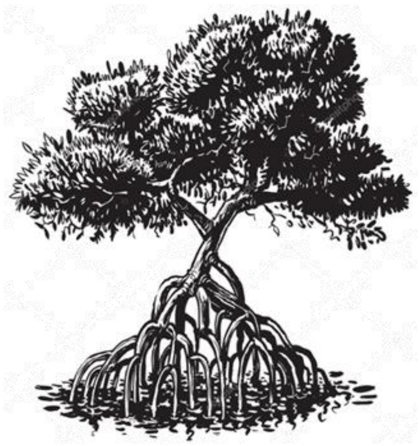
TREVATHAN-TACKETT, S.; KEPFER-ROJAS, S.; ENGELEN, A.; et al. (2021). Ecosystem type drives tea litter decomposition and associated prokaryotic microbiome communities in freshwater and coastal wetlands at a continental scale. **Science of the Total Environment**, (782) 146819. https://doi.org/10.1016/j.scitotenv.2021.146819

VALIELA; I.; BOWEN, J.L.; YORK, J.K.(2001). Mangrove Forests: One of the World's Threatened Major Tropical Environments: At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. **BioScience**, 51(10): 807–815. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2

VANDERKLIFT, M. A.; MARCOS-MARTINEZ, R.; BUTLER, J. R. A.; COLEMAN, M.; LAWRENCE, A.; PRISLAN, H.; THOMAS, S. (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. Marine Policy, 107, 103429. https://doi.org/10.1016/j.marpol.2019.02.001.

WORTHINGTON, T. A.; ZU ERMGASSEN, P. S. E.; FRIESS, D. A.; KRAUSS, K. W.; LOVELOCK, C. E.; THORLEY, J.; et al. (2020). A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. **Scientific Reports**, 10, 14652. doi:10.1038/s41598-020-71194-5.

CAPÍTULO I



Capítulo 1

1 ACESSANDO O CARBONO AZUL PELA DECOMPOSIÇÃO DA MATÉRIA ORGÂNICA DO ÍNDICE DO SAQUINHO DE CHÁ (TBI) EM MANGUEZAL AMAZÔNICO E SEMIÁRIDO

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Resumo

A elevada capacidade de armazenamento de carbono azul em solos de manguezais se relaciona a uma taxa relativamente baixa de decomposição de matéria orgânica (MO) em solos anóxicos e salinos. Portanto, os estudos sobre manguezais e a cinética de decomposição são relevantes para avaliar os fatores que podem acelerar ou reduzir o armazenamento de carbono, uma estratégia fundamental para a adaptação às mudanças climáticas. Assim, para realizar essa avaliação da decomposição de MO utilizamos o Tea Bag Index (TBI) - método de decomposição de saquinhos de chá - em manguezais brasileiros em duas regiões climáticas contrastantes (monção e semiárido). Nossos resultados indicaram que houve uma porcentagem maior de decomposição na região amazônica de monções, em comparação com uma região semiárida para o chá verde (~25 dias: Amazônia = 75%; semiárido = 60%; ~90 dias: Amazônia = 85%; semiárido = 70%) e chá de rooibos (~25 dias: Amazônia = 28%; semiárido = 20%; ~90 dias: Amazônia = 37%; semiárido = 30%). O padrão da taxa de decomposição (k) e do fator de estabilização (S) foi consistente com o que foi observado em ecossistemas alagados, com valores mais altos em ~25 dias, em comparação com o período seguinte (~90 dias) (kmean ~25-90dias: Amazônia = 0,03-0,01; semiárido = 0,02-0,01); (Smean ~25-90 dias: Amazônia = 0,10-0,13; semiárido = 0,28-0,16), indicando uma tendência à estabilização da decomposição da MO com o tempo. Além das diferenças climáticas, a concentração de MO, os valores de k e S nas regiões de monções tropicais e semiáridas podem estar vinculados a diferenças ambientais regionais, tais como espécie e tamanhos das árvores, composição do solo (mineralogia, teor de óxido de ferro e outros), entradas de rios e amplitude das marés. Portanto, tais diferenças regionais no processo de decomposição, juntamente com padrões climáticos distintos, provavelmente são um indicador consistente de que o ciclo do carbono pode variar substancialmente ao longo das costas tropicais e é suscetível a mudanças ambientais globais.

Palavras-chave: Mudanças climáticas; Amazônia; Semiárido; Decomposição; Mangue.

ASSESSING BLUE CARBON THROUGH THE DECOMPOSITION PROCESSES OF TEA BAG INDEX (TBI) IN TROPICAL MONSOON (AMAZON) AND SEMIARID MANGROVES

Abstract

The high capacity of blue carbon storage in mangroves soils is related to a relatively low rate of organic matter (OM) decomposition in anoxic and saline soils. Therefore, studies concerning mangroves and the decomposition kinetics are relevant to evaluate factors that could either accelerate or reduce carbon storage; a pivot strategy to climate change adaptation. In order to assess this, we conducted an evaluation of OM decomposition using Tea Bag Index (TBI) - litter bags decomposition method - in Brazilian mangroves within two contrasting climate regions (monsoon and semiarid). Our results indicated a greater percentage of decomposition in a monsoonal Amazon region compared with a semiarid region for green tea (~25-days: Amazon = 75%; semiarid = 60%; ~90-days: Amazon = 85%; semiarid = 70%), and rooibos tea (~25-days: Amazon = 28%; semiarid = 20%; ~90-days: Amazon = 37%; semiarid = 30%). The decomposition rate (*k*) and stabilisation factor (*S*) pattern was consistent with what has been observed in wetland ecosystems, with higher values in ~25-days, at the beginning of burial, compared to after (~90-days) (*k*mean ~25-90days: Amazon = 0.03-0.01; semiarid = 0.02-0.01); (Smean ~25-90 days: Amazon = 0.10-0.13; semiarid = 0.28-0.16), indicating a trend towards the stabilisation of OM decomposition. In addition to climate differences, the OM concentration, *k*, and S values in the tropical monsoon and semiarid regions can be linked to regional environmental differences, such as tree canopy species and size, soil composition (mineralogy, iron oxide content, and others), river inputs, and tidal range. Therefore, these regional differences in the decomposition process along with distinct climate patterns are likely to be a consistent indicator that the carbon cycle can vary substantially along the tropical coastlines and is susceptible to global environmental changes.

Keywords: Climate change; Amazon; Semiarid; Decomposition; Mangrove.

1.1 INTRODUCTION

Blue Carbon Ecosystems (BCEs), such as mangroves, have high potential to sequester and store carbon through their biomass and soils, more than terrestrial forest ecosystems. Indeed, their significant potential emphasises their capacity to mitigate climate change, acting as nature-based solution for reducing atmospheric CO_2 (MACREADIE et al., 2022; IPCC, 2021; SOARES et al., 2022). BCEs are well-recognized worldwide for their importance (DONATO et al., 2011; ADAME et al., 2021), and the coast of Brazil has been considered as a hotspot of carbon storages (ROVAI et al., 2022; BELOTO et al., 2023).

Mangroves are one of the most productive ecosystems in the world, and have a huge potential to absorb CO_2 as a consequence of forest primary production, superior even to tropical humid evergreen forests (ALONGI, 2012; 2014). Plant biomass is part of the organic matter (OM) input into this ecosystem, and during its decomposition process, part of this material can be stored as organic carbon in soils, and part is lost and exported (ALONGI, 2012). The passage of nutrients, such as carbon, to soil during the decomposition process can be favoured according to environmental factors, anoxic conditions facilitate OM burial as well as a slow decomposition (RAVEN et al., 2019). Additionally, OM decomposition also has the potential to emit CO_2, CH_4 and other gases, especially in faster decomposition process, with an accentuated increase of CO_2 gas with a progressive rise of anthropogenic impacts (KRISTENSEN et al., 2008b; BARROSO et al., 2022; COTOVICZ et al., 2024; NÓBREGA et al., 2016).

Generally, decomposition rates of OM in mangroves are challenging to comprehend, along with the factors influencing carbon storage. Factors such as climate, primary production, flood level, salinity, conservation status, geological settings, edaphic conditions, and availability of oxygen, are variables that can influence OM decomposition and consequently carbon storage (PARTAIN, 2019; SIMPSON, et al., 2023). Therefore, information on OM decomposition can provide a better understanding of the carbon cycle, including its inputs and outputs (PARTAIN, 2019; ALONGI, 2014).

In this context, the evaluation of OM decomposition rates often involves the use of litter bags, as they offer valuable insights into initial degradation processes. Using this approach, the most labile material (such as sugars, starches, and proteins) are initially degraded, while the more refractory materials (including cellulose, fats, waxes, tannins, and lignins) decompose at a slower rate and may eventually be stored in the soil (WIEDER & LANG, 1982; GESSNER et al., 1999). This method provides relevant information, including: 1) the remaining percentage of mass (or mass lost); 2) the mass loss over time or decomposition rate (*k*); and 3) the non-decomposed, stabilised material, (S) (WIEDER & LANG, 1982; GESSNER et al., 1999; SEELEN et al., 2019). However, while bags containing different material/leaves offer useful information about OM decomposition rates, they are not reliable indicators for comparing decomposition rates across different ecosystems (PARTAIN, 2019). In response to this limitation, a standardised method known as the “Tea Bag Index – (TBI)" has been developed to compare decomposition dynamics of OM in different sites using a standard OM material, e.g. green tea (*Camellia sinensis*) and rooibos tea (*Aspalathus linearis*) (KEUSKAMP et al., 2013).

This method allows comparison between sites and ecosystems, encompassing flooded and intertidal areas, to evaluate OM decomposition and the environmental conditions that could impact it (DJUKIC et al., 2018; ALSAFRAN et al., 2017; KEUSKAMP et al., 2013; SEELEN et al., 2019; MARLEY et al., 2019; TREVATHAN-TACKETT et al., 2021). Globally, TBI experiments have been carried out in mangroves (ALSAFRAN et al., 2017; DJUKIC et al., 2018; MUELLER et al., 2018), salt marshes (MARLEY et al., 2019) and lakes (SEELEN et al., 2019). Despite a growing interest in decomposition rates in flooded ecosystems, particularly in South America, there is no record of TBI method being applied in these neotropical mangrove forests. Therefore, this study is significant as it represents the first attempt to assess decomposition rates in Brazilian mangrove soils, considering environmental and regional differences, with the aim of enhancing our understanding of the role of carbon sequestration/storage in climate change mitigation.

1.2 METHODOLOGICAL PROCEDURES

1.2.1 SAMPLES SITES IN TROPICAL MONSOON (AMAZON) AND SEMIARID MANGROVES

Our experiment on organic matter decomposition followed the method outlined by KEUSKAMP et al., (2013) and teatime4science.org. The spreadsheet for non-woven bags was used to calculate S and *k* variables. A total of 72 tea bags were buried in the tropical monsoon mangroves (Amazon mangroves located in the state of Pará; lat.-0,9179; long.-46,6924) and 48 tea bags in semiarid mangroves (Semiarid mangroves located in the state of Ceará; lat. -3,8326; long. - 38,4209). We considered two distinct periods to recover the tea bags, each corresponding to areas with different vegetation cover (Figure 1).

The geomorphological and sedimentary characteristics of the mangroves of Pará are located in a deltaic environment, with a warm monsoon climate (Am) and macrotidal regime (>4m). Furthermore, they are located at the mouth of the Amazon River, representing river-dominated estuaries that receive large amounts of suspended sediment and fresh water (ICMBio, 2018; MENEZES et al., 2008). These characteristics, in conjunction with the local topography, wave and tidal current conditions, have facilitated expansion of mangroves in the region (WORTHINGTON et al., 2020; SOUZA-FILHO, 2005; DUBREUIL et al., 2018; DAVIES, 1964; HAYES, 1975). The sampled sites in the state of Pará state were located within a conservation unit, specifically the Resex Marinha Caeté-Taperaçu, known as one of the most pristine mangrove areas in Brazil, and the most studied mangrove in Pará state. The selected samples were situated in the area of Ajuruteua Peninsula, surrounded by the Caeté, Taperaçu and Maniteua Rivers (ICMBio, 2018; SARAIVA et al., 2012; MENEZES et al., 2008). The collected samples were divided and employed in six areas: *Avicennia* sp. (PA01); *Rhizophora mangle* (PA02); Field area - grass (unvegetated) (PA03); Mud (unvegetated) (PA04); Natural restoration (*Avicennia* sp.) (PA05); Dwarf trees (*Avicennia* sp.) (PA06) (Figure 2).

The coast of Ceará in the semiarid region features estuarine and open coast mangroves, characterised by a warm climate with distinct rainy winter (As) and a mesotidal regime (2-4 m) (WORTHINGTON et al., 2020; DUBREUIL et al., 2018; DAVIES, 1964; HAYES, 1975). The Intertropical Convergence Zone (ITCZ) serves as the primary force controlling rainfall, leading to a long period of water deficit and water hypersalinity during part of the year due to marked seasonality (CAVALCANTE, 2015; GADELHA, 2014). The extensive dry period of the semiarid climate, low tidal range, intermittent flow of exorheic rivers, and resulting high salinity are recognized stressors affecting the development and colonisation of mangrove trees in the region (SCHAEFFER-NOVELLI et al., 1990; MAIA, 2016). In the Ceará state sample site, the experiment was conducted in the Environmental Protection Area of Pacoti River (APA do Rio Pacoti). Despite facing various anthropogenic pressures, the region has recently experienced a gradual increase in vegetation cover to the deactivation of salt production, shrimp ponds, and restoration projects initiated since 2007 (LACERDA et al., 2007;

BARBOSA et al., 2016; FERREIRA et al., 2022a, 2023). For our experiment, samples were collected from four main areas, specifically: non-impacted (*Rhizophora mangle*) (CE01); impacted (salt extraction - unvegetated) (CE02); and areas under ecosystem restoration (restored 1 and restored 2 – *Avicennia* sp.; *Laguncularia racemosa*, respectively) (CE03 and CE04) (see Figure 1).

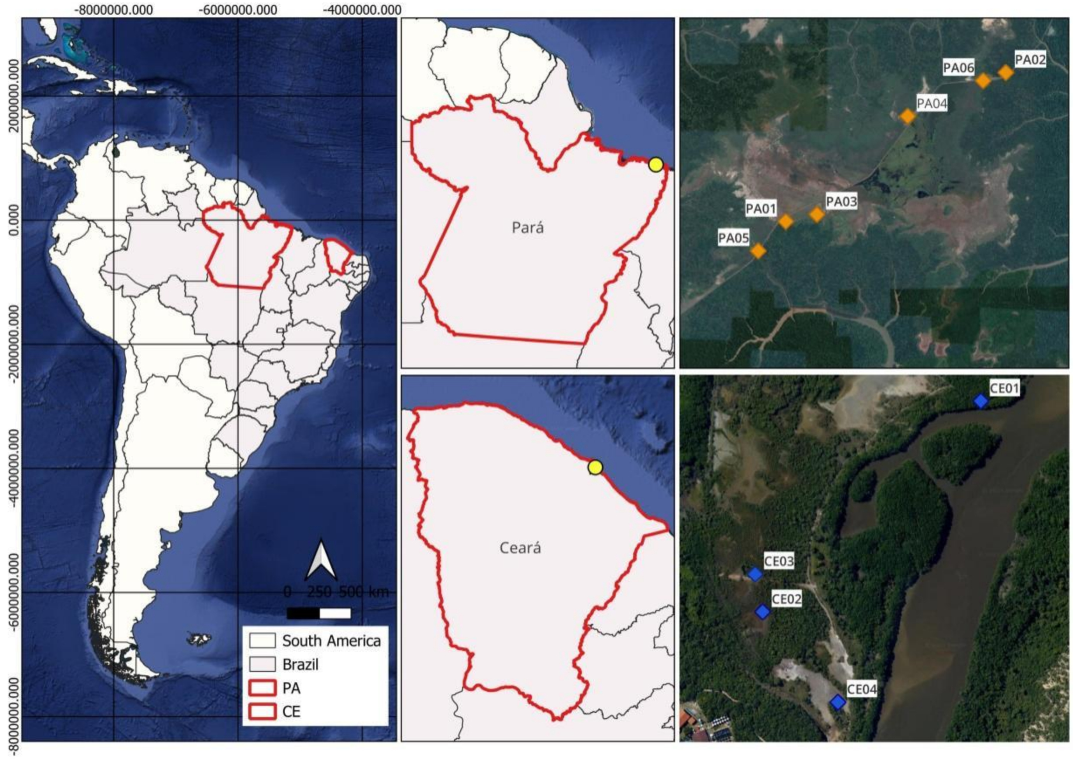
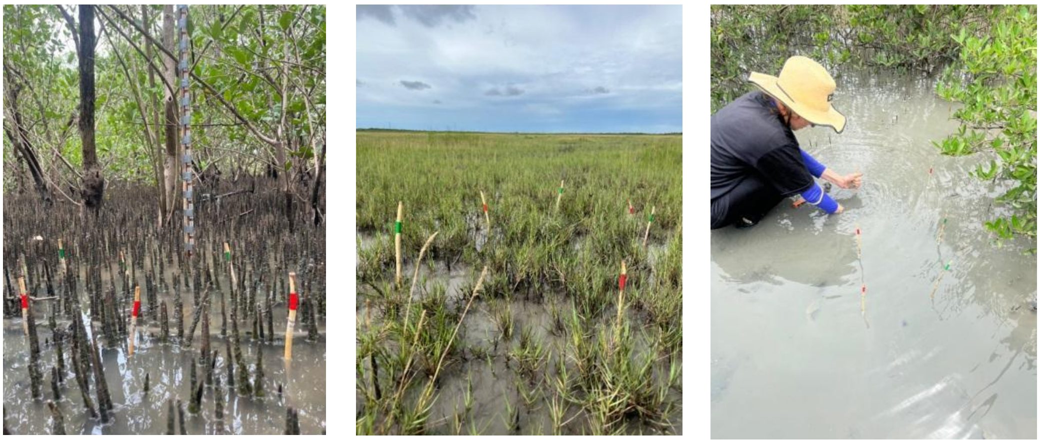


Figure 1- Map showing the locations of the sample sites for the Tea Bag Index (TBI) in the states of Pará (PA) and Ceará (CE) in Amazon and Semiarid region, indicating their distinct vegetative cover. *Avicennia* sp. (PA01); *Rhizophora mangle* (PA02); Field area - grass (unvegetated) (PA03); Mud (unvegetated) (PA04); Natural restoration (*Avicennia* sp.) (PA05); Dwarf trees (*Avicennia* sp.) (PA06); non-impacted (*Rhizophora mangle*) (CE01); impacted (salt extraction - unvegetated) (CE02); and restored areas (restored 1 and restored 2 – *Avicennia* sp.; *Laguncularia racemosa*, respectively) (CE03 and CE04). Map:WGS84 EPSG:4326.



(a) (b) (c)

(d) (e) (f)

Figure 2 - Sample areas at Resex Marinha Caeté-Taperaçu (Pará) and APA do rio Pacoti (Ceará). (a) *Avicennia* sp. area (P01); (b) Field area (P03); (c) Natural restoration area (P05); (d) non-impacted (*Rhizophora mangle*) (CE01); impacted (salt extraction - unvegetated) (CE02); and restored areas (restored 1 and restored 2 – *Avicennia* sp.; *Laguncularia racemosa*, respectively) (CE03 and CE04).

1.2.2 BURYING TEA BAG SAMPLES AND LABORATORY PROCEDURES

The first tea bag burial in Ceará was conducted on September 13th, 2022, during the dry season. On March 24th, 2023, the tea bags were buried in Pará, during the amazon winter, a period with the highest rainfall. Environmental characteristics such as salinity and flood level were measured occasionally (at bury and recover of tea bags) in the Amazon and Semiarid sites. Before burial, the tea bags were weighed and then recovered after approximately 25 and 90-days, with a retrieval percentage of around 70-80% of the total buried samples, accounting for some tea bags being preyed upon or not being found in the mud. To determine the stabilisation factor (*S*) and decomposition rate (*k*), samples were dried in an oven at 70°C for 24 hours, weighed, and then incinerated at 550°C for 2 hours. The ash content post-incineration served as the correction value (SOIL SURVEY STAF, 2004). The hydrolysable fraction for green and rooibos tea was defined following KEUSKAMP et al. (2013) (e.g., Hg=0.842; Hr=0.552, respectively), and the weight of some empty tea bags was measured to establish the bag value (green = 0.260g; rooibos = 0.255g).

Soil samples from the upper 10 cm were assessed for percentage organic matter (%OM), values were determined using loss on ignition (LOI) by incinerating the organic content of soils at 450ºC for 4 hours (HOWARD et al., 2014; RODRIGUES, 2022), and OM conversion into organic carbon (OC) was conducted using equation developed for a Brazilian Semiarid mangrove (%OC= 0.41*%LOI-0.36)

(RODRIGUES, 2022). Total soil carbon stock was calculated considering carbon density and content per sample, as described in the BC methods manual (HOWARD et al., 2014). Granulometry procedures, including washing, drying, weighing samples, and utilising a rotap shaker followed by sieve separation based on grain size. The data was then processed using the Granulometric Analysis System (SYSGRAN).

1.2.3 DATA ANALYSIS AND STATISTICS TESTS

- Excel, Datawrapper, Statistica Program and R software were used to conduct descriptive analysis, perform statistical tests, and generate graphs (R Core Team, 2021);
- The Shapiro-Wilk test was used to determine the normality or non-normality of the data;
- The Mann-Whitney U test was employed to assess differences between non-parametric distributed variables (e.g. lost mass % for ~25-days green) in Amazon and Semiarid and also to assess differences between non-normally distributed variable (OM% and total soil carbon stock) for both regions;
- ANOVA was used to test differences between parametric distributed variables (e.g. lost mass% for ~25-days rooibos; ~25-90-days green and rooibos) in the Amazon and Semiarid sites;
- A Kruskall-Wallis test was applied to compare multiple independent samples (groups) to check differences between mass loss and *k*-*S* variables of each region according to their respective sample area and to evaluate OM% difference in soil, according to vegetation coverage of Amazon and Semiarid regions;
- The Sysgran Program was used to calculate granulometric percentages.

1.3 RESULTS AND DISCUSSION

1.3.1 MASS LOST PERCENTAGE (%) OF GREEN AND ROOIBOS TEA

Amazon and Semiarid mangroves showed difference in mass loss (%), as determined by the Mann-U test for ~25-days green tea (Amazon/Semiarid: $p<0.05$), and ANOVA for ~25-90-days green and rooibos tea (Amazon/Semiarid: $p<0.05$). In all cases, the mass loss was consistently significantly greater in Amazon than in the Semiarid sites (Figure 3). When comparing only tea types, differences in mass loss between green and rooibos were observed over both periods ~25-90-days (green = 42-81% min-max; rooibos = 13-40% min-max; see Figure 3) ($p<0.05$), which was expected as the green tea presents more labile material and decomposes faster than rooibos tea (ALSAFRAN et al., 2017; KEUSKAMP et al., 2013; TREVATHAN-TACKETT et al., 2021; MACDONALD et al., 2018).

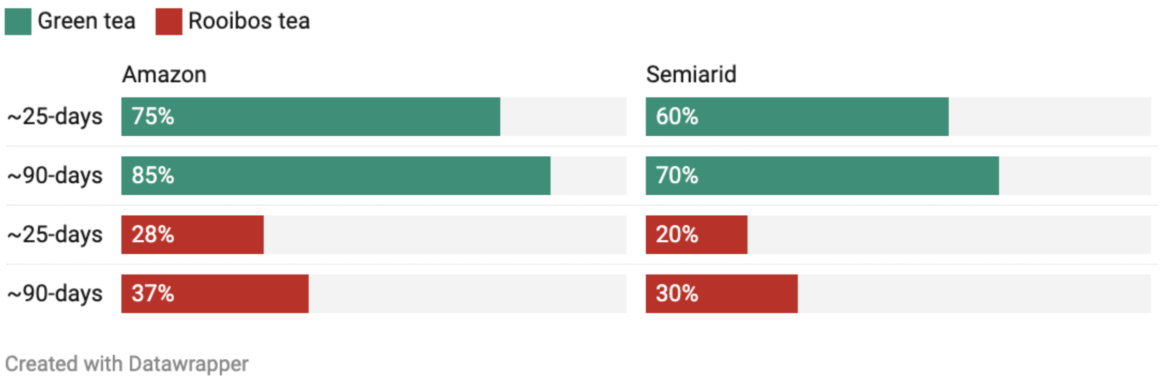


Figure 3 - Mass lost (%) in Amazon and Semiarid regions.

Additionally, specific findings regarding vegetative coverage conditions were observed in each region. The areas within Amazon mangrove (P01, P02, P03, P04, P05, P06) exhibited a difference in mass loss during the initial ~25-days period for green tea (KW-H=12.3; $p<0.05$). On the other hand, rooibos did not exhibit differences between sites during the same period (KW-H=6.5; $p>0.05$) (Figure 4). After around 90-days, some of the tea bags in the Amazon region either started to gain mass or completely lost it, exceeding the hydrolysable fraction of the samples. So we speculate the burial period over ~90-days was too long for this experiment in the Amazon, as this mangrove has high tidal variation (>4m), high organic matter content, significant river input, and the most intense rainfall, as the experiment was conducted during the Amazon winter. We therefore suggest monitoring the TBI experiment with continuous measurements of environmental characteristics using dataloggers or continuous measurement equipment. It is important to mention that samples exhibiting excessive mass gain or complete loss in ~90-days were excluded from the statistical analysis and graphs. Due to the limited data from this period, the Kruskall-Wallis test could not produce definitive results.

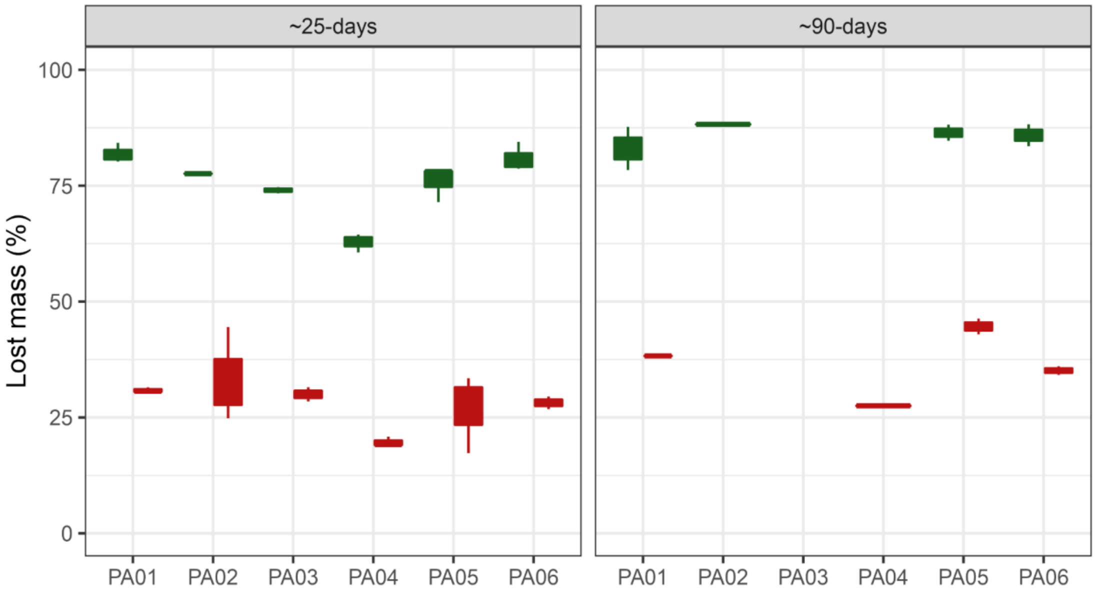


Figure 4 - Mass loss values (%) for green tea (green colour) and rooibos tea (red colour) during the experimental period (~25-90-days) varied according to vegetation coverage in Amazon region (P01 = *Avicennia* sp.; P02= *Rhizophora mangle* area; P03= Field area with grass; P04= Mud without vegetation; P05=Natural restoration area; P06= Dwarf trees of *Avicennia* sp.).

In Semiarid region sites, the analyses among areas (CE01, CE02, CE03, CE04) revealed differences in mass loss for rooibos tea during the first ~25-days (KW-H = 8.1; p<0.05) and for green tea at ~90-days (KW-H = 8.9; p<0.05; see Figure 5). However, no such differences were observed at ~25-days for green tea (KM-H = 5.1; p>0.05) and at ~90-days for rooibos tea (KM-H = 5.8; p>0.05). Notably, during the first ~25-days, the restored areas (CE02, CE03) lost as much mass as the non-impacted area (CE01) for both teas, however, after ~90-days, the non-impacted area (CE01) showed higher mass loss compared to the impacted and restored areas (CE02, CE03, CE04). It was observed that within the Semiarid areas, the impacted site (CE04) appeared to have the lowest litter decomposition, showing the lowest mass loss at both ~25 and ~90-days (Figure 5). Coincidentally, these impacted areas are in the process of restoration with reinstated hydrological connectivity and resultant improvement in soil quality and plant biomass coverage (FERREIRA et al., 2022a, 2023), showing that these areas have high potential for mangrove expansion. Differences in mass lost between areas suggest the presence of spatial heterogeneity in Semiarid mangroves, most likely as a result of different vegetation coverage, which is likely to impact the carbon storage potential of areas, also impacting carbon stocks in mangroves compartments (BELOTO et al., 2023).

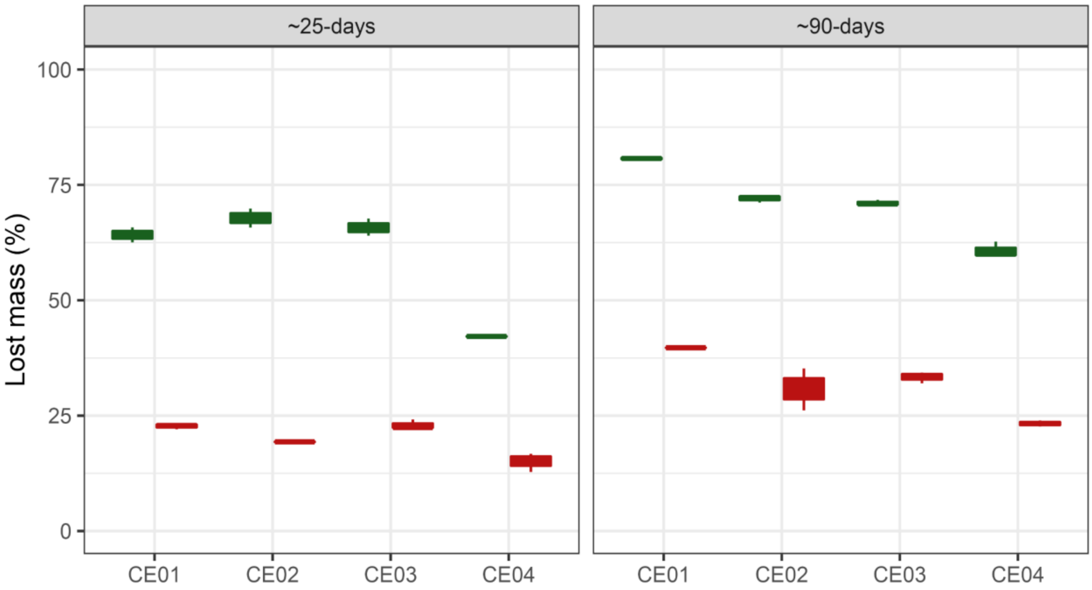


Figure 5 - Mass loss values (%) for green tea (green colour) and rooibos tea (red colour) during the experimental period (~25-90-days) varied according to vegetation coverage in Semiarid region (CE01=Non-impacted – R. mangle, CE02=Restored 1; CE03=Restored 2 – *Avicennia* sp. and *Laguncularia racemosa*; CE04=Impacted).

1.3.2 ORGANIC MATTER (%OM) AND TOTAL SOIL CARBON STOCK (MG HA^{-1}) IN SURFACE SOIL

Mangrove soil characteristics can exhibit differences regionally and globally, particularly concerning pH, salinity, bulk density, levels of nutrients, OM and carbon (FERREIRA et al., 2022b; BOMFIM et al., 2015; HOSSAIN & NURUDDIN, 2016; DEWIYANTI et al., 2021). Mangrove OM content can vary between 0.65 – 22.89% (HOSSAIN & NURUDDIN, 2016), and in our study, we found OM values ranging from 1.5 to 19.0% for the Amazon and Semiarid mangroves. Furthermore, our results revealed differences between both regions (U-test; $p<0.05$), with higher OM content in the Amazon than Semiarid (OM Amazon mean: 13% and Semiarid: 3%) (Figure 6), these regional trends were also observed for total soil carbon stocks (total soil carbon stock Amazon mean: 41 Mg C ha^{-1} and Semiarid: 10 Mg C ha^{-1}).

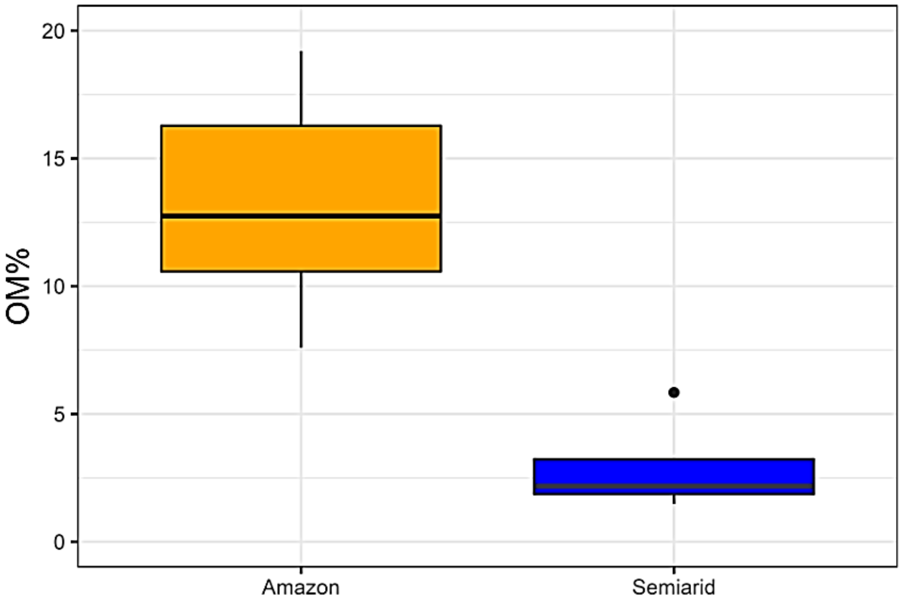


Figure 6 - OM% mean in Amazon: 13% and Semiarid: 3%.

Our observed OM% results as well as total soil carbon stock could possibly be explained by the OM inputs. The main OM input in mangroves are predominantly from autochthonous sources mixed within minor allochthonous sources (SAINTILAN et al. 2013), as a consequence of high rates of net primary productivity (NPP) (BOUILLON et al., 2008). Then the low decomposition pathways due to anoxic conditions in the mangroves (KRISTENSEN et al., 2008a) enhance OM preservation and storage in soils. The most known prominent source of autochthonous OM inputs can be the root tissues, plant litter and microphytobenthos, and the OM enrichment with these materials leads to an increase in microbiota, which has the potential to drive soil decomposition (PUPIN & NAHAS, 2014; CHYNEL et al., 2022; ALONGI, 2014; ALONGI, 2012; PRASAD, DITTMAR & RAMANATHAN, 2010; GESSNER et al., 1999). The natural anoxic conditions and the use of alternative electron acceptors in soils by microbiota, mainly from Fe oxyhydroxides and sulphates facilitate the long-term preservation of OM within the system, favouring carbon storage (KRISTENSEN et al., 2008a; NÓBREGA et al., 2013).

As we hypothesized, differences found in OM and total soil carbon stock between Amazon and Semiarid regions can be linked to OM input, as a consequence of NPP, as well as by other environmental factors. It is possible that the Amazon region mangroves exhibit higher NPP because of less stressed conditions (low salinity and wet season) than Semiarid region mangroves (high salinity and long dry season), and as a result, are capable to convert more plant biomass into OM in the long term, resulting in a higher total soil carbon stock, total ecosystem carbon stock (TEC), and aboveground biomass (AGB) than in the Semiarid region, as also observed in other studies (KAUFFMAN et al., 2018; KAUFFMAN et al., 2020; BELOTO et al., 2023). However, NPP alone may not entirely account for these differences, especially because OM deposition and total soil carbon stock depends on long-timescale formation, which includes others environmental factors. Some environmental factors such as mangrove preservation status (impacted, non-impacted), climate, edaphic conditions, quantity of biogenic inputs, and soil anoxic conditions, could also contribute to the higher levels of OM and total soil carbon stock in Amazon compared to Semiarid, as also cited in other studies (KAUFFMAN et al., 2018; BELOTO et al., 2023; FERREIRA et al., 2010; ANDRADE et al., 2018).

In general, the Semiarid mangroves of Brazil have low freshwater inputs, an extended dry season, and a low tidal range that increase salinity levels and hinder an optimal level of mangrove NPP (SCHAEFFER-NOVELLI et al., 1990; MAIA, 2016). Furthermore, the reduced influence of freshwater inhibits the influx of OM from upstream sources (COTOVICZ et al., 2024). For our experiment, the Semiarid study area included a restored and an impacted site with a dry and compact soil layer with recent or absent vegetation cover (CE02, CE03 and CE04). These specific areas received very low OM inputs over long periods, which have resulted in low soil OM percentages, as observed by the results. This highlights the importance of considering human impacts and environmental factors in studies evaluating total soil carbon stocks (RODRIGUES 2022).

1.3.3 DECOMPOSITION RATE (K) AND STABILISATION FACTOR (S) VALUES

In our study, the experiment successfully replicated the expected pattern for decomposition rate (*k*) and stabilisation factor (*S*), as described in other wetland ecosystems (MARLEY et al., 2019; DJUKIC et al., 2018). In most environments, decomposition rates are faster at ~25-days, after which the most refractory litter tends to reduce the velocity of decomposition rates and stabilise over time, as we observed (Figure 7) (KEUSKAMP et al., 2013; MARLEY et al., 2019; MACDONALD et al., 2018). In the initial stages of decomposition, it is expected that decomposers rapidly utilise the most labile compounds, such as sugars, amides and proteins, elucidating the rate of tea litter decomposition. Subsequently, a slower process ensures the decomposition of recalcitrant materials (WIEDER & LANG, 1982). In both the Amazon and Semiarid mangrove sites, we identified this process occurring; for example, the mean *k* value in the Amazon sites after ~25-days was 0.03, whereas after ~90-days it decreased to 0.01. The mean *S* value followed the same pattern with higher values after ~25-days (0.10), and lower values after ~90-days (-0.13). In the Semiarid sites, the mean *k* value in the first ~25-days was 0.02, and after ~90-days, it was 0.01. The mean *S* value followed the same pattern, with a value of 0.28 in the first ~25-days, followed by 0.16 after ~90-days. These results align with the trend of OM stabilisation over time for both regions (see Figure 7).

The Amazon mangrove sites had *k* notably higher after ~25-days compared to the Semiarid sites. This emphasises the possibility that the incubation period might be shorter for Amazon sites or that the experiment could be conducted during dry season, but as stated previously, it is interesting to check burial periods with long-term environmental variable measurements. The negative values for the stabilisation factor (*S*) also suggest the potential for reduced incubation period in Amazon, especially since, according to some authors, negative *S* values, as observed in the experiment, could indicate that the mass lost for the green tea exceeded its non-hydrolysable fraction (MUELLER et al., 2018). It was expected that the burial period for the tea bags might need adaptation for the experiment, considering that the original method was developed for boreal and temperate ecosystems, where the kinetics of OM degradation are slower than in tropical ecosystems (KEUSKAMP et al., 2013). Therefore, we strongly recommend a study in tropical forests using a longer time-series scale, e.g., 5 incubation periods, to find the best burial period adapted to the demands of these environments and capturing continuous environment information.

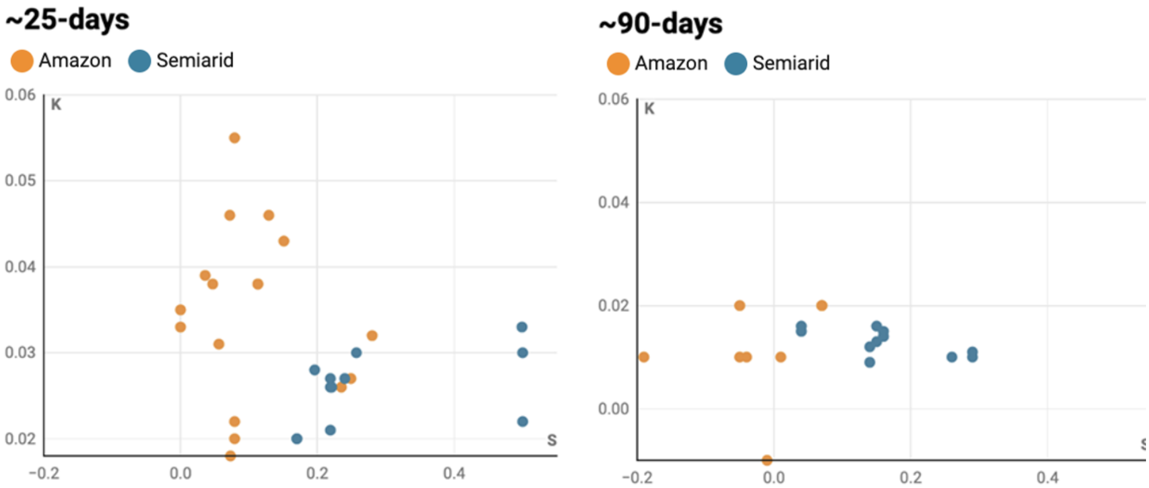


Figure 7 - Decomposition rate (k) vs. Stabilisation factor (S) in ~25-days (a) and ~90-days (b). Amazon (orange colour) and Semiarid (blue colour).

1.3.4 DECOMPOSITION RATE (K) AND ENVIRONMENTAL CHARACTERISTICS

There was no significant difference in the *k* value after~25-days between the Amazon sites (PA01, PA02, P03, PA04, PA05, PA06) (KW test= p>0.05). For the ~90-day period, due to issues with sample losses, the results could not be evaluated. In the Semiarid sites (CE01, CE02, CE03, CE04), no significant difference was recorded between the restored, non-impacted, and impacted areas after~25-days (KW test= p>0.05). However, after ~90-days a difference was observed (KW test= p<0.05), particularly in the non-impacted area (CE01) with higher k values compared to the restored and impacted areas (CE02, CE03, CE04). This is likely due to soil conditions, in non-impacted sites there is a high percentage of OM, high flood level and soil more silt+clay when compared to the restored and impacted areas (Figure 8, Figure 9, Table 1).

The absence of a *k* value pattern in a certain area is not uncommon and has also been observed by other authors in peatland areas and mangrove reforestation sites in comparison with natural sites (MACDONALD et al., 2018; ALSAFRAN et al., 2017). However, given the observed difference after ~90-days in decomposition rates according to vegetation cover in the Semiarid sites, it is evident that the decomposition process must be observed with caution, whilst considering site particularities.

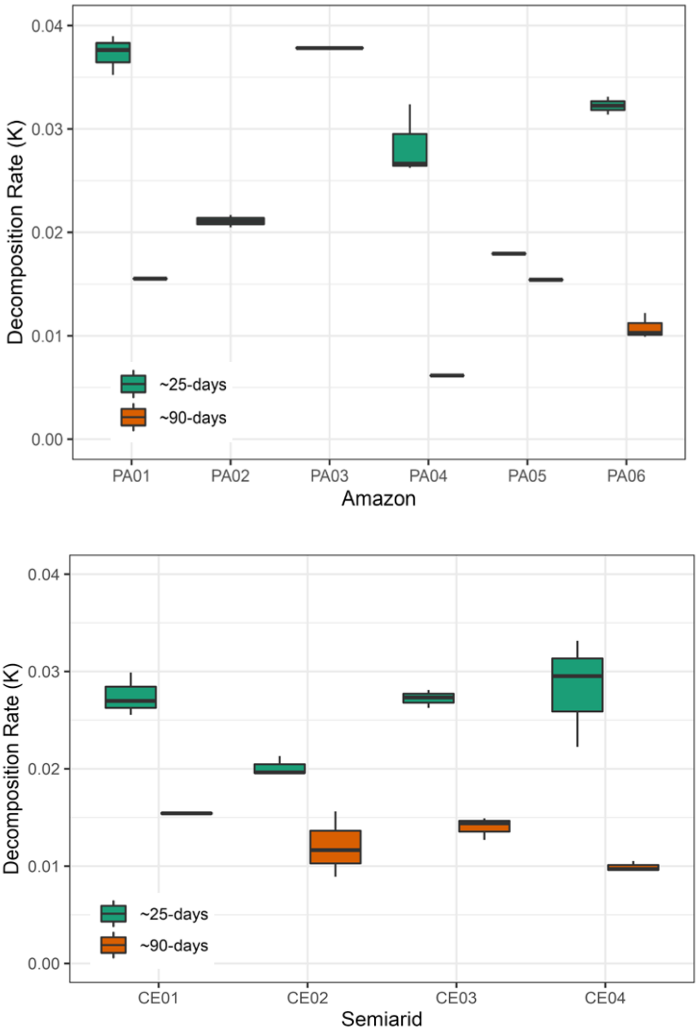


Figure 8 - Decomposition Rate (k) in Amazon (Avicennia sp. - PA01; Rhizophora mangle – PA02; field area – PA03; mud – PA04, restoration – PA05; dwarf trees – PA06) and Semiarid (non-impacted – CE01; restoration 1 – CE02; restoration 2 – CE03; impacted – CE04).

Our findings suggest that the regions could be categorised as a freshwater-influenced mangrove (Amazon sites) and a hypersaline mangrove (Semiarid sites). Freshwater discharge can influence the OM concentration in many ways (BREITHAUPT & STEINMULLER, 2022; COTOVICZ et al., 2024), for example i) with inputs of labile OM from upstream sources; ii) inputs of suspended sediments, iiii) by decreasing salinity and therefore changing the electron acceptors during OM degradation. The Amazon sites are located in a deltaic mangrove, tide and mud-dominated, whereas the Semiarid sites are more sediment-starved with sand grain prevalence (MUEHE, 2010; WARD et al., 2023) (Figure 9). Both hydrology (MUELLER et al., 2018) and granulometry are known for having an important role in the decomposition process, being good predictors of *k* and *S* (LIMA et al., 2022).

Table 1– Environmental characteristic, OM, total soil carbon stock, k and S values in Amazon and Semiarid mangroves.

	Area	**OM%**	**Total soil carbon stock (Mg C ha^{-1})**	***k*~25-days**	**S ~25-days**	**Salinity (min-max)**	**Flood level (cm) (min-max)***	**Tidal variation (m) (min-max)**
				Amazon				
PA01	*Avicennia* sp.	7.6	22.8	0.037	0.042	5	0 - 55	0.1 – 5.7
PA02	*R. mangle*	10.2	23.2	0.032	0.079	8	0 - 80	0.1 – 5.7
PA03	Field area	13.8	56.6	0.041	0.118	-	0 - 0	0.1 – 5.7
PA04	Mud	17.1	62.7	0.028	0.254	10	0 - 0	0.1 – 5.7
PA05	Restoration	11.7	33.5	0.036	0.099	5	1 - 45	0.1 – 5.7
PA06	Dwarf trees	19.2	46.8	0.032	0.056	0	5 - 40	0.1 – 5.7
	Mean±SD	**13.3±4.3**	**40.9±17**	**0.034**	**0.108**	**5.6±3.7**	**44±29.0**	
				Semiarid				
CE01	Non-impacted	5.8	21.3	0.027	0.231	25 - 40	0- >20	0.4 – 2.9
CE02	Restored 1	2.4	8.2	0.020	0.187	38	0 - 6	0.4 – 2.9
CE03	Restored 2	1.5	3.8	0.027	0.219	38 - 70	0 - 6	0.4 – 2.9
CE04	Impacted	2.0	7.1	0.028	0.499	35	0 - 6	0.4 – 2.9
	Mean±SD	**3±2**	**10±7.7**	**0.026**	**0.284**	**40.4±12.3**	**9.5±6.5**	

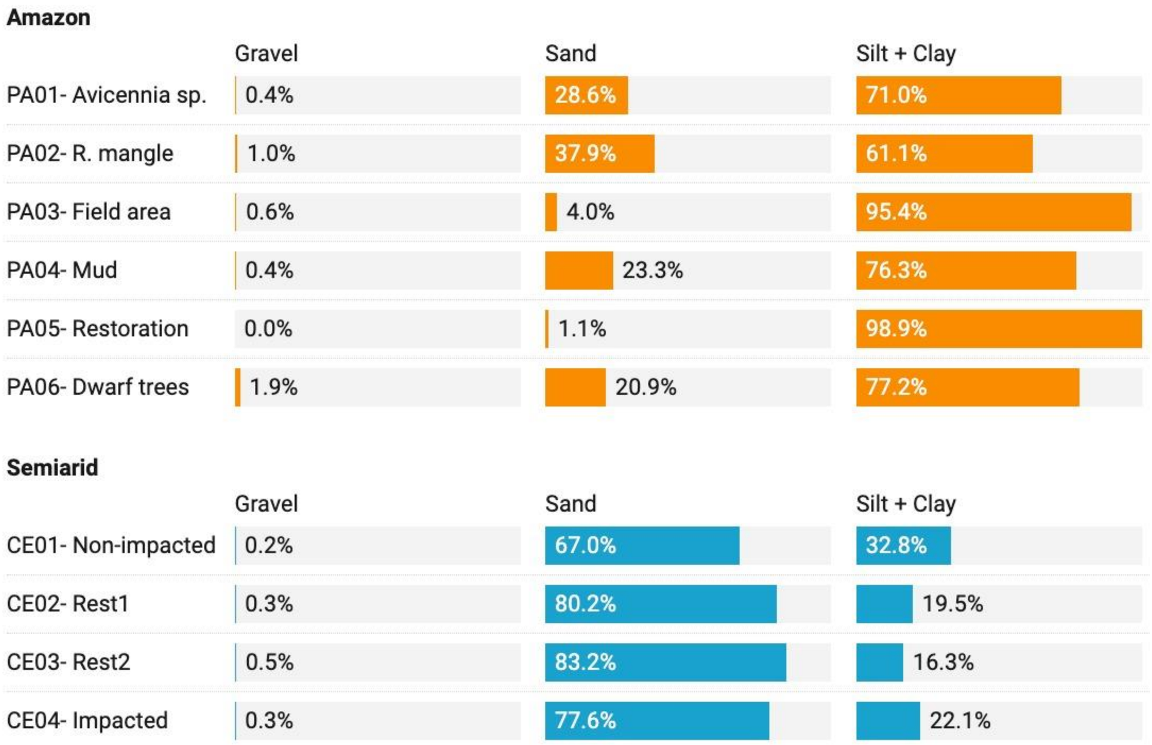


Figure 9 – Granulometry for Amazon (*Avicennia* sp.; *R. mangle*; field area; mud; restoration; dwarf trees) areas; and Semiarid sites (non-impacted, rest1, rest2, impacted) areas.

1.3.5 DECOMPOSITION RATE (K) AND STABILISATION FACTOR (S) WORLDWIDE

In an assessment of *k* and *S* values in different environments, involving only experiments > **60 days**, mangroves exhibited results similar to those of other environments (SEELEN et al., 2019). As shown in Figure 10, a semiarid desert demonstrated the highest stabilisation factor (*S* mean), while natural and planted mangroves in Qatar exhibited the highest decomposition rate (*k* mean) of all listed environments, followed by a saltmarsh in the same region (KEUSKAMP et al., 2013; ALSAFRAN et al., 2017). The results of the *k* mean suggest that elevated microbial activity in flooded environments can be efficient for the decomposition process, leading to higher decomposition rates compared to drier environments. Additionally, factors such as temperature, soil use, and vegetation type also influence the decomposition process globally (SEELEN et al., 2019; DJUKIC et al., 2018; MUELLER et al., 2018). In Brazil, the extensive territory and abundant biodiversity offer environmentally distinct conditions. Understanding decomposition processes in different soils could provide essential information concerning factors influencing carbon sequestration, as well as the influences on rates specific to each ecosystem and site. The findings of our study suggest that mangrove salinity, flood level, climate, tidal range, and edaphic characteristics may act as driving factors for OM content and decomposition, as well as for carbon sequestration and storage. Additionally, arid and dry conditions seem to be well suited for longer TBI experiments, whereas monsoon conditions with high inundation and precipitation rates call for shorter TBI experiment periods.

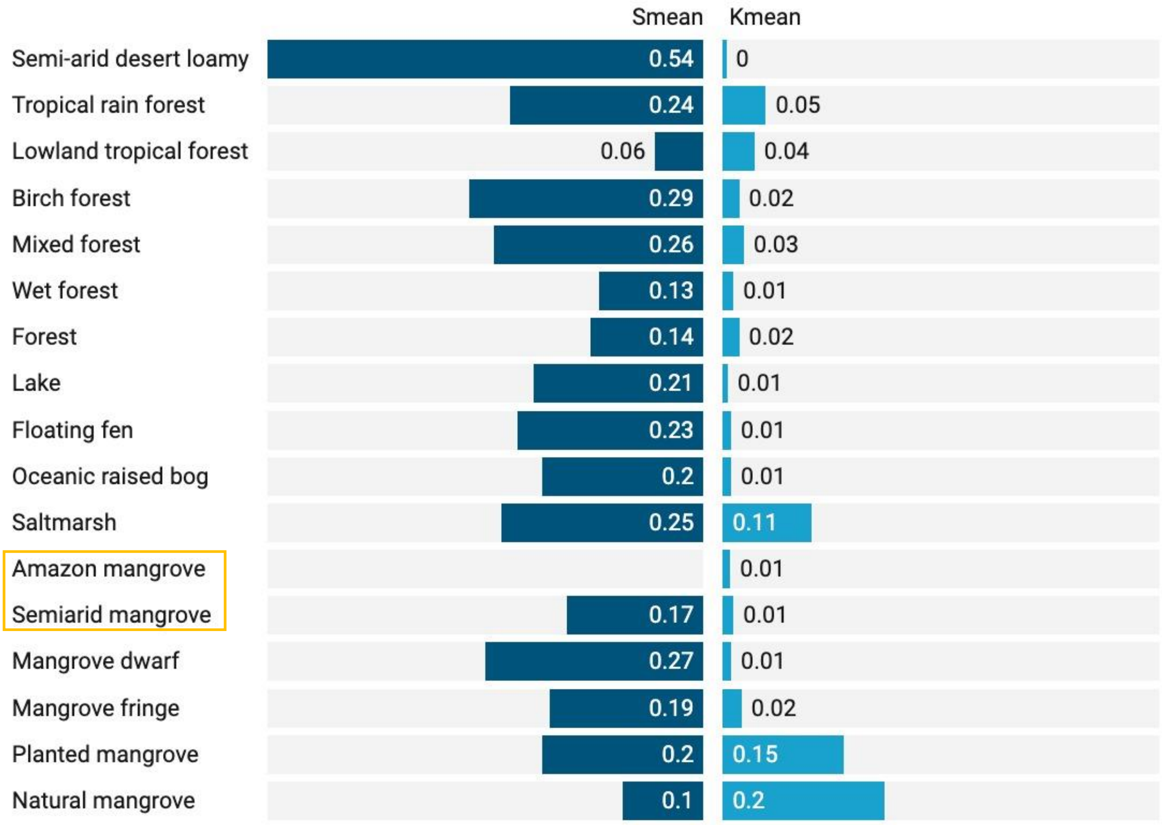


Figure 10 - *k* and *S* means from literature (this study, Keuskamp et al., 2013; Seelen et al., 2019; Eggleton et al., 2020; Alsafran et al., 2017).

1.4 CONCLUSIONS

The tea bag index is a valuable method that shows efficiency to be used in Brazilian mangroves, although with necessary adjustments to account for flood conditions. Our findings demonstrate heterogeneity in mangrove decomposition rate, thus affecting carbon cycling across different regions and sites. We noted the range of variables affecting decomposition process in mangroves, including: climate, conservation status, vegetation cover, hydrological characteristics (tidal range, flood level, and salinity) as well as the estuary type (river-dominated, deltaic, hypersaline, and others). Finally, our study underscores the intricacy of the carbon cycle in mangroves and emphasises the need for further research in Latin

American mangroves. Given the escalating climatic variability stemming from climate change, decomposition rates may undergo alterations influencing longer term carbon burial rates.

1.5 REFERENCES

ADAME, M.F.; SANTINI, N.S.; TORRES-TALAMANTE, O.; ROGERS, K. (2021). Mangrove sinkholes (*cenotes*) of the Yucatan Peninsula, a global hotspot of carbon sequestration. **Biol. Lett.**, 17. https://doi.org/10.1098/rsbl.2021.0037.

ALONGI, D. M. (2012). Carbon sequestration in mangrove forests. **Carbon Management**, 3(3), 313–322. https://doi.org/10.4155/cmt.12.20.

ALONGI, D. M. (2014). Carbon Cycling and Storage in Mangrove Forests. **Annual Review of Marine Science**, 6(1), 195–219. https://doi.org/10.1146/annurev-marine-010213-135020.

ALSAFRAN, M.; SARNEEL, J.; ALATALO, J. (2017). Variation in plant litter decomposition rates across extreme dry environments in Qatar. **The Arab World Geographer,** 20(2-3): 252-260. http://hdl.handle.net/10576/15954

ANDRADE, G.R.P.; CUADROS, J.; PARTITI, C.S.M.; COHEN, R.; VIDAL-TORRADO, P. (2018). Sequential mineral transformation from kaolinite to Fe-illite in two Brazilian mangrove soils. **Geoderma**, 309:84–99. http://dx.doi.org/10.1016/j.geoderma.2017.08.042.

BARBOSA, L. N.; LIMA, V. G. F.; FARIAS, J. F.; SILVA, E. V.(2016). Evolução espaço-temporal da vegetação de mangue no estuário do rio Pacoti/Ceará. **Revista Geonorte**, 7(Edição Especial 5):144-159.

BARROSO, G.C.; ABRIL, G.; MACHADO, W.; ABUCHACRA, R.C.; PEIXOTO, R.B.; BERNARDES, M.; MARQUES, G.S.; SANDERS, C.J.; OLIVEIRA, G.B.; OLIVEIRA FILHO, S.R.; AMORA-NOGUEIRA, L.; MAROTTA, H. (2022). Linking eutrophication to carbon dioxide and methane emissions from exposed mangrove soils along an urban gradient. **Science of The Total Environment**, 850: 157988. https://doi.org/10.1016/j.scitotenv.2022.157988.

BELOTO, N.; COTOVICZ Jr., L.C.; RODRIGUES, J.V.M.; GMACH, M.R.; ZIMMER, M.; HELFER, V.; SOARES, M.O.S.; BEZERRA, L.E.A. (2023). Blue carbon stock heterogeneity in Brazilian mangrove forests: A systematic review. **Marine Pollution Bulletin,** 197 – 115694:1-10. https://doi.org/10.1016/j.marpolbul.2023.115694.

BOMFIM, M.R.; SANTOS, J.A.G.; COSTA, O.V.; et al. (2015). Genesis, Characterization, and Classification of Mangrove Soils in the Subaé River Basin, Bahia, **Brazil. Rev. Bras. Ciênc. Solo**, 39 (5). https://doi.org/10.1590/01000683rbcs20140555

BOUILLON, S.; BORGES, A.V.; CASTAÑEDA-MOYA, E.; et al. (2008). Mangrove production and carbon sinks: A revision of global budget estimates. **Global Biogeochemical Cycles**, 22, GB2013. https://doi.org/10.1029/2007GB003052.

BREITHAUPT, J.L; STEINMULLER, H. E. (2022). Refining the Global Estimate of Mangrove Carbon Burial Rates Using Sedimentary and Geomorphic Settings. **Geophysical Research Letters**, 49(18). https://doi.org/10.1029/2022GL100177.

CAVALCANTE, M.S. (2015). Transporte de carbono orgânico dissolvido no estuário do rio Jaguaribe sob clima semiárido. 83 f. Dissertação (Mestrado em Ciências Marinhas Tropicais) - Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza, 2015. http://www.repositorio.ufc.br/handle/riufc/17666

CHYNEL, M.; ROCKOMANOVIC, S.; ABRIL, G.; BARROSO, G.; MAROTTA, H.; MACHADO, W.; SANDERS, C.J.; THINEY, N.; MEZIANE, T. (2022). Contrasting organic matter composition in pristine and eutrophicated mangroves revealed by fatty acids and stable isotopes (Rio de Janeiro, Brazil). **Estuarine Coastal and Shelf Science**, 277(1):108061. https://doi.org/10.1016/j.ecss.2022.108061

COTOVICZ, L. C.; ABRIL, G.; SANDERS, C.J.; TAIT, D.R.; MAHER, D.T.; SIPPO, J.Z.; HOLLOWAY, C.; YAU, Y.Y.; SANTOS, I.R. (2024). Methane oxidation minimizes emissions and offsets to carbon burial in mangroves. **Nature Climate Change**, 14:275-281. https://doi.org/10.1038/s41558-024-01927-1

DAVIES, J., 1964. A morphogenetic approach to world shorelines. Zeits fur Geomorph., Volume 2, p. 127–142.

DEWIYANTI, I.; DARMAWI, D.; MUCHLISIN, Z.A.; HELMI, T.Z.; IMELDA, I.; DEFIRA, C.N.(2021) Aceh Besar ecosystem based on differences habitat in Banda Aceh and Physical and chemical characteristics of soil in mangrove. **IOP Conf. Ser.: Earth Environ. Sci.**, 674 - 012092. https://doi.org/10.1088/1755-1315/674/1/012092.

DJUKIC, I.; KEPFER-ROJAS, S.; SCHIMIDT, I.; LARSEN, K.S.; BEIER, C.; BERG, B.; VERHEYEN,K. (2018). Early stage litter decomposition across biomes. **Science of the Total Environment**, 628–629:1369–1394. https://doi.org/10.1016/j.scitotenv.2018.01.012.

DONATO, D. C.; KAUFFMAN, J. B.; MURDIYARSO, D.: KURNIANTO, S.: STIDHAM, M.; KANNINEN, M. (2011). Mangroves among the most carbon-rich forests in the tropics. **Nature Geoscience**, 4(5), 293–297. https://doi.org/10.1038/ngeo1123.

DUBREUIL, V.; FANTE, K.; PLANCHON, O.; LIMA NETO, J. (2018). Os tipos de climas anuais no Brasil : uma aplicação da classificação de Köppen de 1961 a 2015. **Revista franco-brasilera de geografia**, 37. https://doi.org/10.4000/confins.15738

FERREIRA, A.C.; FREIRE, F.A.M.; RODRIGUES, J.V.M.; BEZERRA, L.E.A. (2022) a. Mangrove Recovery in Semiarid Coast Shows Increase of Ecological Processes from Biotic and Abiotic Drivers in Response to Hydrological Restoration. **Wetlands**, 42(80): 1-19. https://doi.org/10.1007/s13157-022-01603-0.

FERREIRA, A.C.; LACERDA, L.D.; RODRIGUES, J.V.M.; BEZERRA, L.E.A. (2023). New contributions to mangrove rehabilitation/restoration. **Wetlands Ecol Manage**, 31:89-114. https://doi.org/10.1007/s11273-022-09903-2.

FERREIRA, T.O.; OTERO, X.L.; SOUZA JUNIOR, V.S.; VIDAL-TORRADO, P.; MACÍAS, F.; FIRME, L.P.(2010). Spatial patterns of soil attributes and components in a mangrove system in Southeast Brazil (São Paulo). **J Soils Sediments**, 10:995–1006. https://doi.org/10.1007/s11368-010-0224-4.

FERREIRA, T.O.; QUEIROZ, H.M.; NÓBREGA, G.N.; et al. (2022) b. Litho-climatic characteristics and its control over mangrove soil geochemistry: A macro-scale approach. **Science of The Total Environment**, 811-152152. https://doi.org/10.1016/j.scitotenv.2021.152152.

GADELHA, F.M. (2014). Solos de manguezais sob a influência do Semiárido cearense: Biogeoquímica de Fe, Mn, Cu, Ni e Cr. 59 f. Dissertação (Mestrado em Solos e Nutrição de Plantas) - Universidade Federal do Ceará, Fortaleza, 2014. http://www.repositorio.ufc.br/handle/riufc/36499

GESSNER, M.; CHAUVET, E.; DOBSON, M. (1999). A Perspective on Leaf Litter Breakdown in Streams. **Oikos**, 85(2): 377-384. https://doi.org/10.2307/3546505.

HAYES, M., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. **Geology and Engineering**, p. 3–22. https://doi.org/10.1016/B978-0-12-197502-9.50006-X.

HOSSAIN, M.D.; NURUDDIN, A.A. (2016). Review Article Soil and Mangrove: A Review. **J. Environ. Sci. Technol.**, 9: 198-207. https://doi.org/10.3923/jest.2016.198.207

HOWARD, J.; HOYT, S.; ISENSEE, K.; TELSZEWSKI, M.; PIDGEON, E. (eds.) (2014). **Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.** Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA. https://unesdoc.unesco.org/ark:/48223/pf0000372868.

ICMBio, 2018. **Atlas dos Manguezais Brasileiros. Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio)**, Brasília, ISBN 978-85-61842-75-8. https://www.gov.br/icmbio/pt-br/centrais-de-conteudo/atlas-dos-manguezais-do-brasil-pdf (176 p.).

IPCC, 2021. Summary for Policymakers. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change V. P. Masson-Delmotte, A. Zhai, S. L. Pirani, C. Connors, S. Péan, N. Berger, et al. Cambridge University Press.

KAUFFMAN, J. B.; ADAME, M. F.; ARIFANTI, V. B.; SCHILE-BEERS, L. M.; BERNARDINO, A. F.; BHOMIA, R. K.; et al. (2020). Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. **Ecological Monographs**, 90(2). https://doi.org/10.1002/ecm.1405.

KAUFFMAN, J. B.; BERNARDINO, A.F.; FERREIRA, T.O.; GIOVANNONI, L.R.; GOMES, L.E.O.; ROMERO, D.J.; JIMENEZ, L.C.; RUIZ, F. (2018). Carbon Stocks of Mangroves and Salt Marshes of the Amazon Region, Brazil. **Biology Letters**, 14(9): 20180208. https://doi.org/10.1098/rsbl.2018.0208

KEUSKAMP, J.; DINGEMANS, B.; LEHTINEN, T.; SARNEEL, J.M.; HEFTING, M.M. (2013). Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems. **Methods in Ecology and Evolution**, 4(11): 1070-1075. https://doi.org/10.1111/2041-210X.12097.

KRISTENSEN, E.; BOUILLON, S.; DITTIMAR, T.; MARCHAND, C. (2008) a. Organic carbon dynamics in mangrove ecosystems: A review. **Aquatic Botany**, 89(2): 201–219. https://doi.org/10.1016/j.aquabot.2007.12.005.

KRISTENSEN, E.; FLINDT, M.R.; ULOMI, S.; BORGES, A.V. ABRIL, G.; BOUILLON, S. (2008) b. Emission of CO_2 and CH_4 to the atmosphere by sediments and open waters in two Tanzanian mangrove forests. **Marine Ecology Progress Series**, 370 (0):53-67. https://doi.org/10.3354/meps07642.

LACERDA, L. D.; MENEZES, M. O. T.; MOLISANI, M. M.(2007). Changes in mangrove extension at the Pacoti River estuary, CE, NE Brazil due to regional environmental changes between 1958 and 2004. **Biota Neotropica**, 7(3): 67–72. https://doi.org/10.1590/S1676-06032007000300007.

LIMA, M.A.C.; WARD, R. D.; JOYCE, C.B.; KAUER, K.; SEPP, K. (2022). Carbon stocks in southern England's intertidal seagrass meadows. **Estuarine, Coastal and Shelf Science**, 275-107947. https://doi.org/10.1016/j.ecss.2022.107947.

MACDONALD, E; BRUMMELL, M E; BIENIADA, A; ELLIOTT, J; ENGERING, A. et al. (2018). Using the Tea Bag Index to characterize decomposition rates in restored peatlands. **Boreal Environment Research; Helsinki**, 23(1-6): 221–235.

MACREADIE, P. I.; ROBERTSON, A.I.; SPINKS, B.; et al., (2022). Operationalizing marketable blue carbon. **One Earth**, 5: 485–492. https://doi.org/10.1016/j.oneear.2022.04.005.

MAIA, R. C. (2016). **Manguezais do Ceará**. 1. ed. Recife: Imprima, 55 p.

MARLEY, A. R. G.; SMEATON, C.; AUSTIN, W. E. N. (2019). An assessment of the tea bag index method as a proxy for organic matter decomposition in intertidal environments. **JRC Biogeosciences**, 124(10): 2991-3004. https://doi.org/10.1029/2018JG004957.

MENEZES, M. P. M. D.; BERGER, U.; MEHLIG, U. (2008). Mangrove vegetation in Amazonia: a review of studies from the coast of Pará and Maranhão States, north Brazil. **Acta Amazonica**, 38(3): 403–420. https://doi.org/10.1590/S0044-59672008000300004.

MUEHE, D. (2010). Brazilian coastal vulnerability to climate change. **Pan-American Journal of Aquatic Sciences**, 5(2): 173-183.

MUELLER, P.; SCHILE-BEERS, L.M.; MOZDZER, T. J.; et al., (2018). Global-change effects on early-stage decomposition processes in tidal wetlands – implications from a global survey using standardized litter. **Biogeosciences**, 15(10):3189–3202. https://doi.org/10.5194/bg-15-3189-2018.

NÓBREGA, G. N. (2013). Blue carbon em solos de manguezais do semiárido: importância, métodos de quantificação e emissão de gases C-CO2. Dissertação (Mestrado em Agronomia/Solos e Nutrição de Plantas) - Centro de Ciências Agrárias, Universidade Federal do Ceará, Fortaleza, 2013. 99ff.

NÓBREGA, G. N.; FERREIRA, T. O.; SIQUEIRA NETO, M.; QUEIROZ, H. M.; ARTUR, A. G.; MENDONÇA, E. D. S.; SILVA, E. de O.; OTERO, X. L. (2016). Edaphic factors controlling summer (rainy season) greenhouse gas emissions (CO_2 and CH_4) from semiarid mangrove soils (NE-Brazil). **Science of The Total Environment**, 542: 685–693. doi:10.1016/j.scitotenv.2015.10.108.

PARTAIN, M. (2019). Decomposition Rates in Black Mangrove (*Avicennia germinans*) Sediment Determined Using the Tea Bag Index (TBI) Method. Thesis for scope and quality of Texas A&M University-Corpus Christi. 27pp.

PRASAD, K.B.K.; DITTMAR, T.; RAMANATHAN, A.L. (2010). Organic Matter and Mangrove Productivity. In: Ramanathan, A.L., Bhattacharya, P., Dittmar, T., Prasad, M.B.K. and Neupane, B.R., Eds., Management and Sustainable Development of Coastal Zone Environments, Springer-Verlag, Berlin, 175-193. https://doi.org/10.1007/978-90-481-3068-9_12

PUPIN, B.; NAHAS, E. (2014). Microbial populations and activities of mangrove, restinga and Atlantic forest soils from Cardoso Island, Brazil. **Journal of Applied Microbiology**, 116(1): 851--864. https://doi.org/10.1111/jam.12413.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.: https://www.Rproject.org/.project.org/.

RAVEN, M. R.; FIKE, D. A.; GOMES, M. L.; WEBB, S. M. (2019). Chemical and Isotopic Evidence for Organic Matter Sulfurization in Redox Gradients Around Mangrove Roots. **Frontiers in Earth Science**, 7: 1-15. https://doi.org/10.3389/feart.2019.00098.

RODRIGUES, J.V.M. (2022). Carbono Azul no Semiárido Nordestino: estoque de carbono do solo de um manguezal em recuperação no estuário do Rio Pacoti, CE. Dissertação (Mestrado em Ciências Marinhas Tropicais) - Programa de Pós-Graduação em Ciências

Marinhas Tropicais, Instituto de Ciências do Mar - LABOMAR, Universidade Federal do Ceará, Fortaleza, 2022. 77f.

ROVAI, A.S.; TWILLEY, R.R.; WORTHINGTON, T.A.; RIUL, P. (2022). Brazilian mangroves: blue carbon hotspots of national and global relevance to natural climate solutions. Front. **For. Glob. Change**, 4, 787533. https://doi.org/10.3389/ffgc.2021.787533.

SAINTILAN, N.; ROGERS, K.; MAZUMDER, D.; WOODROFFE, C. (2013). Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. **Estuarine, Coastal and Shelf Science**, 128: 84–92. https://doi.org/10.1016/j.ecss.2013.05.010.

SARAIVA, N.; ABDALA, G.; WESLEY, F.(2012). **Cartilha do Plano de Manejo da Reserva Extrativista Caeté-Taperaçu**. Brasília: ICMBio. 40 p.

SCHAEFFER-NOVELLI, Y.; CINTRÓN-MOLERO, G.; ADAIME, R.; CAMARGO, T. (1990). Variability of mangrove ecosystems along the Brazilian coast. **Estuaries**, 13: 204–218. https://doi.org/10.2307/1351590

SEELEN, L.; FLAIM, G.; KEUSKAMP, J.; et al. (2019). An affordable and reliable assessment of aquatic decomposition: Tailoring the Tea Bag Index to surface waters. **Water Research**, 151:31-43. https://doi.org/10.1016/j.watres.2018.11.081.

SIMPSON, L.T.; CHAPMAN, S.K.; SIMPSON, L. M.; CHERRY, J.A. (2023). Do global change variables alter mangrove decomposition? A systematic review. **Global Ecol Biogeogr.**, 32(11):1874–1892. https://doi.org/10.1111/geb.13743.

SOARES, M.O., BEZERRA, L.E.A., COPERTINO, M., LOPES, B.D., BARROS, K.V.S., ROCHABARREIRA, C.A., MAIA, R.C., BELOTO, N., COTOVICZ, L.C. (2022). Blue carbon ecosystems in Brazil: overview and an urgent call for conservation and restoration. **Front. Mar. Sci.** 9 (1–16). https://doi.org/10.3389/fmars.2022.797411

SOIL SURVEY STAF, 2004. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Rep 42. Washington, DC, USA: USDA – NRCS.

SOUZA-FILHO, P. W. M.(2005). Costa de manguezais de macromaré da Amazônia: cenários morfológicos, mapeamento e quantificação de áreas usando dados de sensores remotos. **Revista Brasileira de Geofísica**, 23(4): 427-437. https://doi.org/10.1590/S0102-261X2005000400006.

TREVATHAN-TACKETT, S.; KEPFER-ROJAS, S.; ENGELEN, A.; et al. (2021). Ecosystem type drives tea litter decomposition and associated prokaryotic microbiome communities in freshwater and coastal wetlands at a continental scale. **Science of the Total Environment**, (782) 146819. https://doi.org/10.1016/j.scitotenv.2021.146819

WARD, R.; LACERDA, L.; CERQUEIRA, A.; GIARIZZO, T. (2023). Amazonian vegetated estuarine ecosystem as a global hotspot in carbon sequestration. **Research Square**. https://doi.org/10.21203/rs.3.rs-2513933/v1.

WIEDER, R.; LANG, G. (1982). A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology, 63(6):1636-1642. https://doi.org/10.2307/1940104.

WORTHINGTON, T. A.; ZU ERMGASSEN, P. S. E.; FRIESS, D. A.; KRAUSS, K. W.; LOVELOCK, C. E.; THORLEY, J.; et al. (2020). A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. **Scientific Reports**, 10, 14652. doi:10.1038/s41598-020-71194-5.

CAPÍTULO II

Capítulo 2

1 HETEROGENEIDADE DE CARBONO AZUL EM MANGUEZAS BRASILEIROS: UMA REVISÃO SISTEMÁTICA

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Resumo

Esta é a primeira revisão sistemática e meta-análise dos estoques de carbono azul nos manguezais brasileiros. Avaliamos o efeito das características ambientais e do status do local (impactado versus não impactado) sobre os estoques de carbono encontrados nos diversos compartimentos do Estoque Total de Carbono do Ecossistema (TECS) do manguezal. O TECS seguiu uma tendência inversa com a posição latitudinal: os valores mais altos foram encontrados no litoral norte (média de 511 Mg C ha^{-1}), seguido pelo nordeste e sudeste. Uma tendência latitudinal semelhante foi observada para os estoques de carbono do sedimento e da biomassa acima do solo. O status do local também afetou significativamente os estoques de carbono do sedimento e do TECS. A heterogeneidade observada nos estoques de carbono sugere que o regime de marés, a posição latitudinal, o clima e o status do local conduzem conjuntamente os processos relacionados ao sequestro e ao armazenamento. Os manguezais brasileiros armazenam ~ 0,44 PgC, representando 10-12% do TECS mundial. Isso destaca os manguezais brasileiros como um *hotspot* global de carbono azul e como uma solução eficiente baseada na natureza para a remoção de dióxido de carbono.

Palavras-chave: Mudanças climáticas; biomassa; sedimento; armazenamento de carbono; Brasil; remoção de dióxido de carbono

BLUE CARBON STOCK HETEROGENEITY IN BRAZILIAN MANGROVE FORESTS: A SYSTEMATIC REVIEW

Abstract

This is the first systematic review and meta-analysis of blue carbon stocks in Brazilian mangroves. We evaluated the effect of characteristics and site status (impacted *versus* non-impacted) on carbon stocks found in the various compartments on Total Ecosystem Carbon Stock (TECS). TECS followed an inverse trend with the latitudinal position: the highest values were found on the North coast (mean 511 Mg C ha^{-1}), followed by the Northeast and Southeast. A similar latitudinal trend was observed for sediment and above-ground biomass carbon stocks. Site status also significantly affected TECS and sediment carbon stocks. The heterogeneity observed in carbon stocks suggests that tidal regime, latitudinal position, climate, and site status jointly drive the processes related to sequestration and storage. Brazilian mangroves store ~ 0.44 PgC, representing 10-12% of the world TECS. This highlights Brazilian mangroves as a global blue carbon hotspot, and as an efficient nature-based solution for carbon dioxide removal.

Keywords: Climate Change; Biomass; Sediment; Carbon Storage; Brazil; Carbon dioxide removal

1.1 INTRODUCTION

Mangroves are coastal vegetated ecosystems providing numerous ecosystem goods and services. They support fishery resources, protect the shoreline against erosion and sea level rise, promote nutrient cycling, and are important nursery habitats for coastal and oceanic species (Barbier et al., 2011; Howard et al., 2014). Globally, mangrove forests comprise an area of ~13,760,000 ha distributed among 102 countries (Hamilton & Casey, 2016; Bunting et al., 2018). They are considered a promising nature-based solution for climate change mitigation and adaptation, due to their high carbon sequestration rates into their biomass, and long-term carbon storage in their biomass or particularly in their sediment on centennial to millennial time scales (Nelleman et al., 2009; Mcleod et al., 2011 Pendleton et al., 2012). Thus, mangrove forests - along with seagrass beds, kelp forests and salt marshes - are recognized as Blue Carbon Ecosystems (BCEs: Howard et al., 2014; Alongi, 2020; Thorhaug et al., 2020; Bertram et al., 2021; Soares et al., 2022).

Blue carbon stocks can widely vary among mangrove compartments (above- and below-ground living biomass, dead biomass - litter or downed wood - and sediments) and across distinct environmental conditions such as tidal range, climate, geomorphic and geochemical characteristics; the respective contribution of each compartment and the underlying factors determining those contributions are not fully understood (Ferreira et al., 2021; Kairo et al., 2021; Adame et al., 2021a; Nobrega et al., 2019; Rovai et al., 2018; Sanders et al., 2016). In terms of mangrove carbon storage capacity, the sediment is the main compartment (Nellemann et al., 2009; Donato et al., 2011; Alongi, 2014; Howard et al., 2009; 2014), with higher carbon content compared to living (above- and belowground biomass; AGB and BGB respectively) or dead biomass (litter and downed wood), accounting for 70% – 85% of the Total Ecosystem Carbon Stock (TECS) (Rovai et al., 2022; Kauffman et al., 2020).

Mangrove conservation and (re-)establishment projects (*sensu* Zimmer et al., 2022) have been rising as an effective nature-based solution to mitigate climate change, constituting an ocean-based solution for carbon dioxide removal (CDR) (Serrano et al., 2019; Macreadie et al., 2021). The selection of the best sites to implement projects to maximize CDR demands in-depth knowledge about the whole-ecosystem CO_2 sequestration and carbon storage capacity, and about the biotic and abiotic factors driving those processes (Turner et al., 2009; Herr et al. 2012; Wylie et al., 2016). Despite the recent advances in global assessment of mangrove carbon hotspots (Sandermann et al., 2018; Simard et al., 2019), our knowledge about the respective contribution of the distinct compartments to TECS is limited in many tropical regions, including the Southwestern Atlantic coast (Brazil).

Brazil has an extensive coastline with the second largest mangrove forest area in the world, just after Indonesia (Soares et al., 2022). Assessments of Brazilian mangrove forest extent resulted in an estimated area of ~1,011,160.27 ha (Hamilton & Casey, 2016; Diniz et al., 2019; Mapbiomas, 2021). Among the 16 Brazilian states hosting mangrove forests, Maranhao, Para and Amapa States (North Brazil), present the largest continuous area, representing ~78% of SW Atlantic mangrove forests (Magris & Barreto, 2010; ICMBio, 2018; Mapbiomas, 2021). Brazil has a great potential for implementing cost-effective mitigation of climate change through nature-based CDR strategies, by preserving and (re-)establishing mangrove forests, making use of the carbon credit mechanisms (Taillardat et al., 2020; Soares et al., 2022). However, land use changes, coastal erosion, climate extreme events, and pollution have been leading to continuous mangrove degradation in Brazil (Lacerda et al., 2021; Gomes et al., 2021).

Degradation processes were responsible for 4% of Brazilian mangrove forest loss (>50,000 ha) during the last decades (Ferreira & Lacerda, 2016). Shrimp farms are one of the most important drivers of mangrove forest degradation, mostly on the Brazilian northeastern coast. Conversion of mangrove forests to aquaculture ponds can result in the loss of 58%–82% of the TECS (Kauffman et al., 2018a). Indeed, mangrove forests impacted by shrimp farms effluents can experience increased microbial activity and organic matter degradation processes, thus reducing the amount of organic carbon in the sediment (Suarez-Abelenda et al., 2014). But in some instances, mangrove forest degradation represent decrease in biomass carbon stock, but does not necessarily result in decreased of carbon stocks in sediment (at least not as an immediate response). Indeed, Trujilo et al. (2020) showed that massive death of mangrove trees (e.g., *Rhizophora mangle*), can promote less reductive sediments and consequently store more carbon than non-degraded *Rhizophora mangle* forests. A general understanding of the effect of different types of anthropogenic impacts on carbon storage rates and/or stocks in a large latitudinal context at the Brazilian national level is missing.

Furthermore, studies focusing on blue carbon stocks, specifically in Brazilian mangroves, do not provide a clear picture of the respective contribution of the distinct compartments (living and dead biomass, and sediment) to TECS. While a recent review presented estimates of Brazilian mangrove carbon stocks (Rovai et al., 2022), a detailed understanding of the relationship between carbon stocks (in total or in the distinct compartments) and environmental conditions (e.g., regional environmental characteristics and site integrity status) is still missing, as highlighted by many recent publications (Da Motta-Portillo et al., 2016; Kauffman et al. 2018b; Rovai et al., 2021; 2022).

Here, we provide the first systematic review and meta-analysis of blue carbon stocks in the SW Atlantic mangrove forests along the Brazilian coast, aiming to: (i) provide a synthetic report about quantitative data related to TECS and carbon stocks from distinct mangrove compartments (above- and below-ground living biomass, downed wood and sediment) along the coast; (ii) evaluate the effect of regional environmental characteristics on carbon stocks; (iii) evaluate the effect of site status (impacted and non-impacted) on carbon stocks; (iv) point out possible gaps and methodological bias related to carbon stocks assessment in Brazilian mangrove ecosystems and propose recommendations for future studies.

1.2 MATERIAL AND METHODS

1.2.1 SYSTEMATIC REVIEW: INFORMATION SOURCES, STRATEGY AND SEARCH CRITERIA

We conducted a systematic review according to the pertinent literature (Galvão & Pereira, 2014; Mengist et al., 2020; Page et al., 2020) to provide a broad overview of mangrove blue carbon stocks in Brazil. We followed the PRISMA guidelines for the systematic review (Page et al., 2020; O'Leary, Bayliss and Haddaway, 2015) to ensure proper reporting.

Published scientific studies were searched from the three main bibliographic databases (ScienceDirect, Scopus, and Web of Science; accessed in April and May 2021). Surveys were performed to identify studies on blue carbon stocks in Brazilian mangroves and in the distinct mangrove compartments specifically (e.g., biomass and sediment). The terms applied were *"Blue Carbon", "Brazil", "stock", "mangrove"*, *"carbon stock", "biomass", and "sediment"*. No boolean operators were used and terms were retrieved from all article content. Original articles and review articles published between 1990 and 2021 were considered; books or book chapters, gray literature and non-peer reviewed articles were not considered.

1.2.2 ELIGIBILITY CRITERIA AND SCREENING STEPS

We used EndNote web for downloading the articles in RIS format. This tool is considered one of the most practical for duplicate detection and systematic review assessments (Yamakawa et al., 2014; Pereira & Galvão, 2014). After removal of duplicate articles, each single article (considering also supplementary materials) was evaluated, and several standardized inclusion and exclusion criteria were applied, following the PRISMA guidelines (Page et al., 2020) (Table 1).

We retained only studies that reported carbon stocks in terms of mean content per unit area (Mg C ha^{-1}), which would allow calculating carbon stocks per unit area in a national perspective. We also presented the median and standard deviation values for region and status in Supplementary Material (Tables S1 and S2). Some articles only presented carbon content; those values were not included in further analyses (but are available in Supplementary Material; Table S3).

Table 1- Inclusion and exclusion criteria used in this systematic review.

Inclusion Criteria
(a) Articles published and available in ScienceDirect, Scopus, and Web of Science
(b) Articles published from 1990 to 2021
(c) Articles that contained the terms "Blue Carbon", "Brazil", "stock", "mangrove", "carbon stock", "biomass", and "sediment"
Exclusion Criteria
(a) Articles that did not present quantities of carbon stocks (i.e., values per unit areas) in the sediment and/or in the plant biomass (living or dead) for Brazilian mangroves forests sites
(b) Articles that contained secondary data fully copied from other sources. Exceptions were given to those articles that integrated secondary data to compose Brazilian mean values
(c) Gray literature and not peer-reviewed studies
(d) Articles that did not present the method used for carbon stocks calculations

Carbon stocks information retrieved from the articles

We extracted all information related to carbon stocks per unit-area, including how values were computed, together with important characteristics related to mangrove compartment (and characteristics thereof). For example, some estimates of carbon stocks in plant biomass (AGB and/or BGB) used a conversion factor, and this conversion factor slightly differed among articles. These used values are presented in the Supplementary Material; Table S4. In addition, estimates of sediment carbon stocks were derived for different layers depending on the study (e.g., surface layers and down to 1 m depth, or higher depths (> 3m); detailed information about sample depth are presented in the Supplementary Material; Table S5). Some studies included carbon stocks in mangrove forests and also in non-vegetated areas (such as shrimp ponds or hypersaline tidal flats (HTFs)). These non-vegetated areas, although important for blue carbon stocks (Soares et al., 2022; Rodrigues, 2022), have distinct/different carbon patterns, especially because of microphytobenthos contribution; flood levels; sedimentary characteristics - as described by Brown et al. (2021) and Rodrigues (2022) – and because of its characteristics were not included in the systematic review.

Finally, recovered studies referred to carbon stocks in sediment using different terminologies: a) organic C; b) TOC - total organic carbon; c) SOC - soil organic carbon; d) SCS - soil C stock; and e) OC soil - organic carbon. Within this review, we chose to adopt the term "sediment carbon stock" as a standardized term, as this reflects more adequately the compartment, without considering pedogenic process, besides it is the most common term in scientific articles (Clark et al.,1998; Ferreira et al., 2007).

Regional environmental characteristics

To evaluate potential regional effects, we classified Brazilian mangrove forests in four Brazilian regions (according to Muehe, 2010, Soares et al., 2022), where the North region is rainy and wet with deltaic mangroves, Northeast the driest with seasonally hypersaline mangroves, Southeast with wave dominated mangroves and as in the South region with the colder climate and lowest tides. As no data was recovered for the South region, we will hereafter only refer to and describe more detailed the characteristics of the first three Brazilian regions.

The North region (5º N to 2,7º S), sheltering the most extensive mangrove forests along the SW Atlantic coast, refers to the Amazon coast, where the principal geomorphological features are macrotidal, river-dominated estuaries. The climatic regime in this low-latitude region is characterized by high rates of precipitation, referred to as tropical monsoon climate. The Northeast region, along which seasonally hypersaline estuaries and droughts are common features, encompasses a sediment-starved coast with a semi-arid climate and water deficit starting in Piauí state (latitude 2.8º S), and a more humid area, with mesotidal conditions, that reaches until Salvador-Bahia (latitude 13º S). The Southeast region (near 24º S) is characterized by the presence of wave-dominated deltas, remarkable seasonal behavior, double barrier-lagoons, and a typical rocky shore coast with microtidal conditions (< 2m) (Muehe, 2010; Alvares et al., 2013; Davies, 1964; Hayes, 1975).

These three regions match the geomorphological types defined by Muehe (2010) and tidal regimes for the Tropical Southwestern Atlantic coast, a classification that has been used in recent Brazilian blue carbon surveys (Soares et al., 2022). The tidal range of each study site was extracted from the Brazilian Navy platform information (https://www.marinha.mil.br/chm), and classified as Microtidal (0-2 m), Mesotidal (2–4 m), or Macrotidal (> 4m) according to Davies (1964) and Hayes (1975). The classification in North, Northeast and Southeast Brazilian regions coincides with the classification of macrotidal, mesotidal and microtidal regimes, respectively.

Sites status

Legally, the Brazilian Forest Code (2012) frames mangrove forests as Areas of Permanent Protection (APP), and most part of those (~87%) have been considered as marine protected areas (MPAs) by the National System of Conservation Units (ICMbio, 2018). Despite legal protection, mangroves have been losing areas and are in a constant degradation process in the whole national territory (Ferreira & Lacerda, 2016).

As comparing protected versus non-protected areas would not make sense according to the above, we rather evaluated the effect of site integrity, hereafter referred to as site status, and classified study sites as “impacted” or “no-impacted”, based on information describing the sampled site of each article. For instance, study sites described as integer, including all marine protected areas (MPAs) cited, were considered as non-impacted, while sites with human impact such as urbanization and/or sewage pollution, deforestation or shrimp farms were classified as impacted (see Supplementary Material; Table 6S). Articles with no site status information were not considered in analyses related to the effect of site status on carbon stocks.

1.3 DESCRIPTIVE AND META-ANALYSIS STATISTICS

Furthermore, there are potential issues related to differential sampling design and carbon analysis in the selected studies. There is growing effort in the scientific community to create practical tools and standardized guidance for proper quantification of carbon concentrations and stocks in coastal blue carbon ecosystems (e.g., Howard et al., 2018; IUCN, 2021; Fest et al., 2022). Despite this fact, some studies are still not properly standardized, making accurate comparisons challenging.

Data obtained from the articles were analyzed using parametric and non-parametric statistics due to the absence of normality in some cases ($p<0.05$ *Shapiro-Wilk*) and normality in others ($p>0.05$ *Shapiro-Wilk*). *One-way ANOVA* tests were applied to investigate differences between carbon stocks across regions (North, Northeast and Southeast) as well as *Kruskal-Wallis (KW)* for non-parametric data. In case of statistically-significant differences, a post-hoc (*Tukey HSD*) was used to evaluate which pairs differed significantly.

t-Test and *Mann-Whitney (MW)* tests were used to verify the difference between blue carbon stocks of impacted and non-impacted areas, for each compartment independently. All statistical analyses were conducted using the Statistica software (Version 14.0.0.15), and the figures were made using R (R Core Team, 2021).

1.4 RESULTS

1.4.1 DATA COLLECTION (ARTICLES)

A total of 326 articles were retrieved from our bibliographic surveys. After the removal of duplicates automatically (n=49) and manually (n=61), 216 articles were remaining. Finally, after applying the exclusion criteria (Table 1), 23 articles were considered eligible to compose the review (Figure 11).

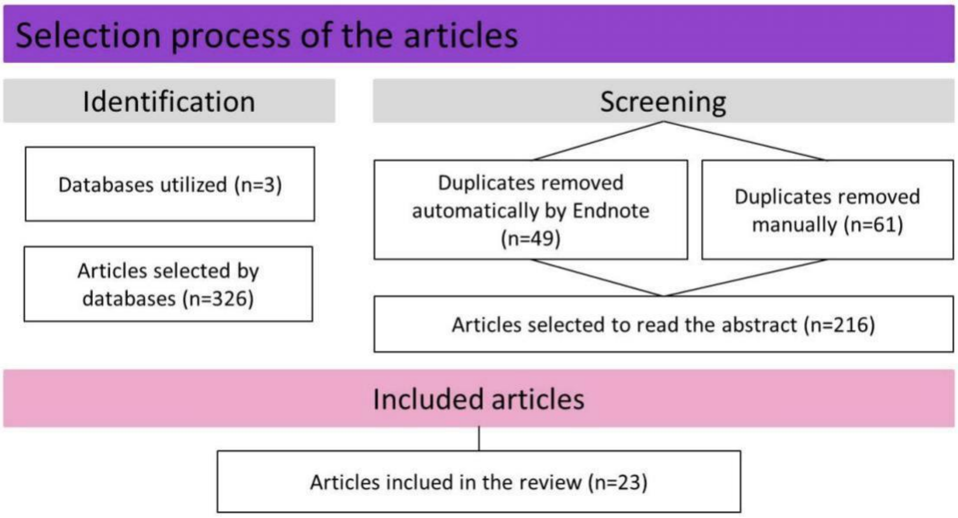
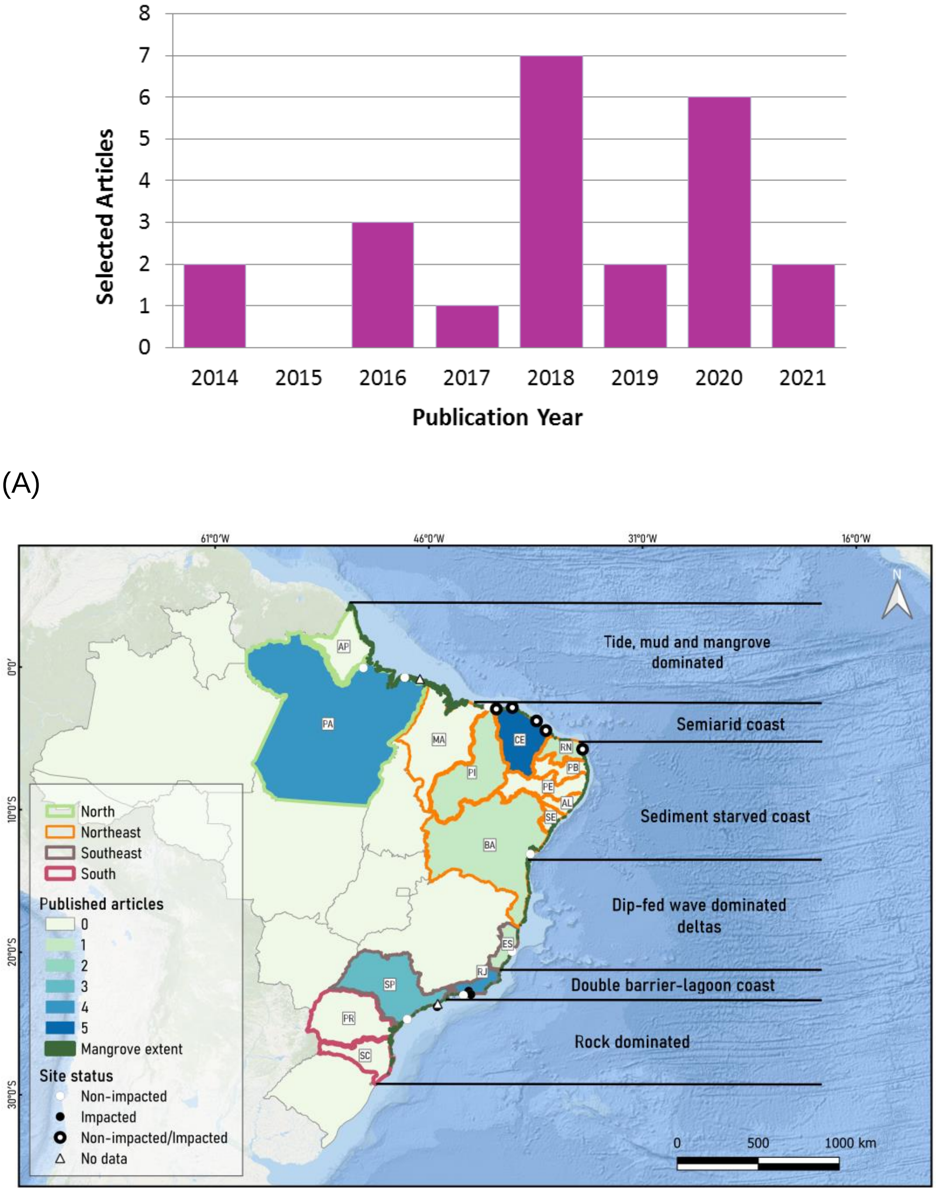


Figure 11- Flow diagram depicting the selection strategy used in this systematic review. Adapted from https://estech.shinyapps.io/prisma_flowdiagram.

1.4.2 TEMPORAL AND SPATIAL DISTRIBUTION OF STUDIES

Since the first studies on mangroves blue carbon published in 2014, there is a recurrent number of studies with two peaks in 2018 (n=7) and 2020 (n=6) (Figure 12A). Regarding the geographic distribution, some selected articles (n=3) did not refer to specific Brazilian regions, presenting only general values, and were therefore not included in the regional analyzes; they were only considered for computing the global values of TECS for Brazil. Other two studies just pointed to specific Brazilian states values; those studies were considered for the regional analysis, but not for the evaluation of impacted versus non-impacted sites. The remaining locals mentioned by articles (see Figure 12B) are presented according status classification, as either non-impacted (NI), impacted (I), impacted and non-impacted (NI/I; i. e. the location contained several sites that differed regarding their status) or no data (ND). Overall, the recovered studies are broadly distributed along the Brazilian coast, nonetheless, two of the Brazilian states with large mangrove areas (Amapa and Maranhao - Amazon Coast) were not included in the selected articles, and no publication were related to the northeastern states of Paraiba, Pernambuco, Alagoas or Sergipe. Beyond this, it is important to mention that some articles investigated the same sites (e.g., Nobrega et al., 2016 and Passos et al., 2016 both investigated Cocó, Timonha, and Jaguaribe estuaries).



(A)

(B)

Figure 12 – (A) Number of publications per year, reporting about carbon stock per unit area in Brazilian mangroves. Data derived from a bibliographic search in ScienceDirect, Scopus and Web of Science databases, accessed in April and May 2021. (B) Number of published articles for each Brazilian state (different colors) and sites of the selected articles according to their status (non-impacted, impacted, impacted/non-impacted or no data).

1.4.3 MANGROVE COMPARTMENTS COVERAGE

Mangrove carbon stock and also sequestration rates are different and important factors to analyze in the environment; here we decided to focus only in carbon stocks. But firstly, we can clarify both factors. Mangrove carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) in the biomass and sediments during a certain period of time (rate of carbon uptake per time), mostly related to the mangrove net primary production (Bouillon et al., 2008). The carbon stock, in turn, is defined by Howard et al. (2014) as "the amount of organic carbon (Corg) stored in a blue carbon ecosystem, typically reported as megagrams of organic carbon per hectare (Mg Corg/ha) over a specified soil depth". These stocks are determined by adding all relevant mangrove compartments within the investigated area.

Therefore, during the selection process of the articles we observe that the majority of them included carbon stock at AGB (n=16) or sediment (n=14), followed by BGB carbon stocks (n=11). Only three articles provided information about DW carbon stocks. Among the studies referring to TECS (n=8), four considered three compartments (AGB; BGB; sediment), only three considered all compartments (AGB; BGB; sediment; DW) and one considered only AGB and sediment (Figure 13).

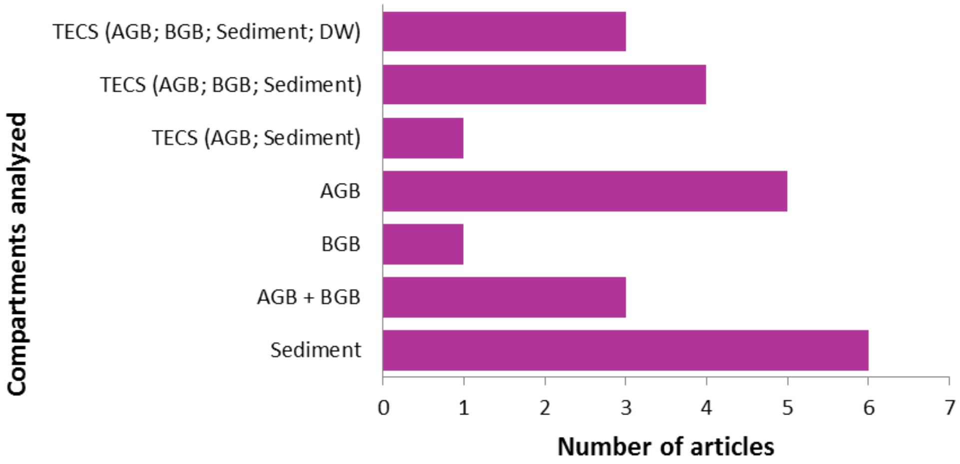


Figure 13 – Number of papers investigating carbon stocks in the distinct compartments of the Brazilian mangrove ecosystems. AGB=Above-ground biomass; BGB= Below-ground biomass; DW= Downed wood; TECS= Total ecosystem carbon stocks and Sediment= Sediment carbon stocks.

Because of this variation in TECS value, we tested the differences between values considering TECS (1): all means values found in the selected articles (irrespective of the compartments involved); TECS (2): summing up values of AGB, BGB and sediment (i.e.

ignoring the study reporting only about AGB and sediment and correcting the studies that had included also downed wood) and TECS (3): summing up values of AGB, BGB, DW and sediment. Then we decided to adopt TECS (1) as a mean value for this article and present all summary information and data about TECS (1)(2)(3) in Supplementary Material; Table 7S.

1.4.4 ENVIRONMENTAL CHARACTERISTICS AND BLUE CARBON STOCKS HETEROGENEITY IN BRAZILIAN MANGROVES

1.4.4.1 Regional environmental characteristics

We found a significant effect of the factor region on carbon stocks in mangrove sediments (*Kruskal-Wallis*, $p<0.05$), with a significant difference (*Tukey*, $p<0.05$) between mean values in the North (316±82 Mg C ha^{-1}) and Southeast (93±88 Mg C ha^{-1}) regions. Values in the Northeast region were intermediate (196±142 Mg C ha^{-1}) and did not significantly differ from the other two regions (Figure 14). A similar pattern, with larger values in the North, followed by intermediate value in the Northeast and lower values in the South, was also observed means values for TECS (511±63 Mg C ha^{-1} – North; 416±144 Mg C ha^{-1} – Northeast; 269±111 Mg C ha^{-1} – Southeast; Supplementary Material - Table S1) and AGB (103±54 Mg C ha^{-1} – North; 67±31 Mg C ha^{-1} – Northeast; 46±27 Mg C ha^{-1} – Southeast, but with no statistical significance (*Kruskal-Wallis*, $p>0.05$ in both cases). Carbon stocks in BGB did not significantly differ between regions (*Kruskal-Wallis*, $p>0.05$) and, interestingly, did not show the same pattern as the other compartments. For DW there were differences between regions (*Kruskal-Wallis*, $p<0.05$), but with no available data for the Southeast coast (Figure 14).

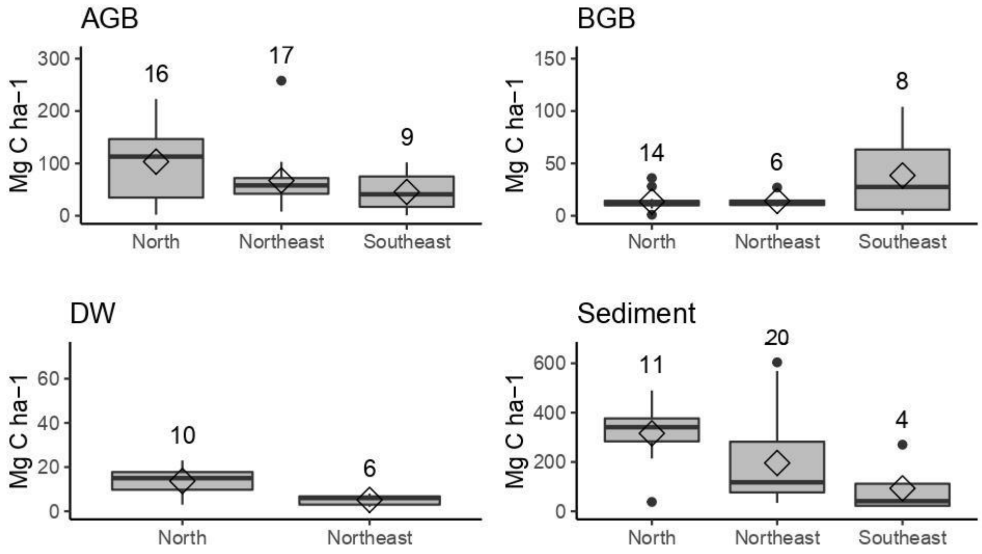


Figure 14– Box plot showing the carbon stocks in AGB, BGB, DW and sediment according to the region (North - macrotidal, Northeast - mesotidal, and Southeast - microtidal) along the Brazilian coast. Box plots represent the first quartile, mean, median and third quartile; whiskers represent the first and third quartile + 1.5 interquartile; circles are considered outliers. The diamond represents the mean value. The values above the boxes are the number of samples.

1.4.4.2 Site status (non-impacted *versus* impacted)

We found significant site status differences in blue carbon stocks between impacted and non-impacted forests (*T-test*, p<0.05), with higher carbon stocks in non-impacted sites (Figure 15). It happened for TECS (mean values of 515±90 and 226±42 Mg C ha^{-1} in non-impacted and impacted areas respectively; n=20; Supplementary Material - Figure S2) and sediment (*Mann-Whitney*, p<0.05) (mean values of 317±116 and 79±46 Mg C ha^{-1} in non-impacted and impacted areas; n=30). There was no difference for AGB (102±47 for non-impacted; 49±18 Mg C ha^{-1} for impacted areas; n=31), BGB (26±21 for non-impacted; 16±06 Mg C ha^{-1} for impacted areas; n=21) and DW (11±6.2 for non-impacted; 5±02 Mg C ha^{-1} for impacted areas; n=15) (Figure 15).

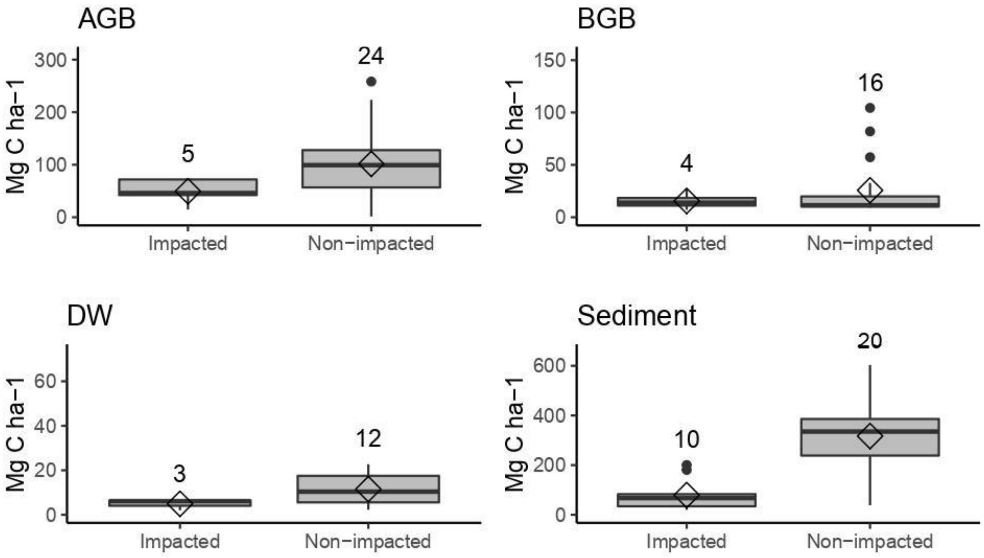


Figure 15- Box plot showing the carbon stocks in AGB, BGB, DW and sediment according to the site status (non-impacted or impacted) along the Brazilian coast. Box plots represent the first quartile, mean, median and third quartile; whiskers represent the first and third quartile + 1.5 interquartile; circles are considered outliers. The diamond represents the mean value. The values above the boxes are the number of samples.

1.5 DISCUSSION

1.5.1 LACK OF DATA, ARTICLES CONTENTS AND BIAS OF CARBON STOCKS MEASUREMENTS THROUGH THE EXTENSIVE SOUTHWESTERN ATLANTIC COAST (BRAZIL)

While the recovered studies covered a broad range of the Brazilian coastal zone, there are considerable gaps in the spatial distribution of carbon stocks data, highlighting the urgent need for additional research efforts to cover the extensive Brazilian coastal zone. Indeed, although 16 Brazilian states contain mangrove forests (Mapbiomas, 2021; ICMBio, 2018; Hamilton & Friess, 2018), we could recover scientific studies (primary data) about carbon stocks (per-area basis) in biomass and/or in sediment for only eight states. Surprisingly, there was no primary research data for Maranhao and Amapa states, which occupy, respectively, the first and third positions in terms of mangrove area in Brazil.

This is alarming since the low-latitude regions between 5°N and 5°S correspond to about 30% of the world’s mangrove area (Giri et al., 2011) and therefore potentially hold one of the largest global carbon stocks. Maranhao, Para (for which we recovered the highest number of publication for the North region; n=5), and Amapa, the three Amazon coast states, jointly harbor about 78% with 792,805.36 ha of the mangrove forests in Brazil (Mapbiomas, 2021), including the more pristine ones.

About 52% (n=12) of the selected articles were related to carbon stocks in the North and Northeast, and 43% (n=10) were from the Southeast region. Some articles reported some impacting activity over time in the Northeast region. Shrimp farms have been expanding since the 1990s and constitute the most significant anthropogenic impact in this region (Queiroz et al., 2013; Lacerda et al., 2021). Consequently, a great portion of the selected articles focusing on that region aimed at investigating the impact of shrimp farming on carbon stocks (e.g., Suarez-Abelenda et al. 2014; Passos et al., 2016; Nóbrega et al., 2016; Kauffman et al., 2018a). Kauffman et al. (2018a) notably showed that total carbon stocks can be reduced by more than half in mangrove forests impacted by shrimp farms in the Northeast region.

In the North region, the main research focus was to determine the carbon stocks in the distinct compartments, comparing several blue carbon environments (salt marshes and mangroves), vegetal biomass, and also comparing methodological procedures for biomass measurements (e.g., Kauffman et al., 2018b; Kauffman et al., 2020; Virgulino-Júnior et al., 2020; Matos et al., 2020; Salum et al., 2020). In contrast, in the Southeast region, most of the studies were dedicated to study impacted areas, and reported lower carbon stocks mainly due to deforestation (e.g., Pérez et al., 2018; Leite et al., 2021; Schaeffer-Novelli et al., 2018).

Regarding the site status, it has been shown that mangrove forest loss (due to conversion to aquaculture, agriculture, clearing or erosion) can potentially result in large emissions of CO_2 to the atmosphere, thereby turning mangrove forests into hotspot of CO_2 emissions if actual rates of mangrove loss stay unchanged (Adame et al., 2021). We indeed found that TECS, AGB and sediment organic carbon presented lower carbon stocks in impacted areas, possibly reflecting synergistic impacts of changes in land use (e.g., shrimp farms, urbanization, pollution, and deforestation) (LAL, 2005). Unfortunately, the few data available on completely restored (n=3) or under restoration (n=3) mangrove stands did not allow us to investigate how fast carbon stocks can be replenished.

Despite the increased attention mangrove ecosystems are receiving at the global scale in the context of carbon dioxide removal, we did not detect a clear increasing trend in published articles per year. Our understanding on carbon stocks and their drivers is still incipient and our gains in terms of enhanced knowledge are slow-moving.

Another important (but overlooked) issue for a better understanding of carbon stocks spatial distribution and their drivers is related to the depth of sediment sampling for sediment carbon stocks quantification. Estimates of mangrove sediment carbon stock in deep layers are almost absent in Brazil (and in many countries). The majority of global studies investigate upper layers as cited by Fest et al. (2020), and most Brazilian articles consider the surface layer up to 1 meter (Rovai et al., 2018; Table 5S). However, sediment depth in mangrove ecosystems can reach up to 3 m or more (Kauffman et al., 2020; Kida et al., 2021). In a recent study conducted in a mangrove forest in Thailand, Kida et al. (2021) estimated carbon stock in 3.5-m sediment cores and found four times higher sediment carbon stock values (nearly 1000 Mg C ha^{-1}) than the mean stocks considered for the whole Thai mangroves. This suggests that in spite of evaluating the first meter of sediment, it would be more informative to consider maximum sediment depth, determine the carbon stocks in distinct layers, as well as re-evaluate and standardize the carbon stock sediment method as suggested by Fest et al. (2022).

1.5.2 REGIONAL ENVIRONMENTAL CHARACTERISTICS AND SITE STATUS AS IMPORTANT CARBON STOCK DRIVERS

Our findings indicate that regional characteristics (e.g., geomorphology, tidal regime, climate) and the site status (impacted and non-impacted) of mangrove forests are important factors affecting carbon stocks in Brazilian mangrove forests.

Precipitation (Sanders et al. 2016) as well as geomorphology (Rovai et al., 2018) are known as important drivers of carbon stocks in sediments. Our regional analysis might indeed suggest that precipitation has a strong influence on sediment carbon stocks in mangroves along the Brazilian coast. For example, the highest sediment carbon stocks reported were related to Amazon mangroves (North of Brazil). This region corresponds to the rainiest region in the tropical SW Atlantic, with a monsoon tropical climate and a macrotidal regime (Alvares et al., 2013). But since our study focused on distinct regions that also differed in their tidal regime, we cannot exclude that changes in salinity, aeration and flood conditions promoted by tidal regime, also affected carbon accumulation rate and stocks.

The effect of water flow and rainfall on AGB carbon stocks is also well-documented. It is known that areas with low water flow and humidity exhibit low primary productivity and carbon stocks (Ferreira et al. 2019; Duke et al., 1998; Alongi, 2009; Atwood et al., 2017). Thus, the higher AGB carbon stocks at the Parnaiba River Delta might result from the climate conditions (such as rainfall). Indeed, the Parnaiba River Delta is established in a climatic transition zone (between the Amazon and the semiarid Brazilian coast) with a large annual rainfall. As it is also located in a large deltaic-estuarine environment that receives high amounts of carbon and nutrients from the main river channel, that is also well-conserved with low human impacts (Dubreuil et al. 2018; Worthington et al. 2020; ICMBio, 2018), other factors such as the geomorphological settings and the site status might also contribute to the high AGB carbon stocks observed.

In addition, a high variability of carbon stocks was observed within regions, both for the sediment and the AGB compartments. Heterogeneity of sediment carbon stocks can be discussed in light of four aspects discussed below.

(i) Organic matter fluxes (tides and runoff): Organic carbon in wetland sediments is resulting from incoming (input from the ocean via tides and waves or from the hinterland via surface runoff or riverine discharge) and outgoing (outwelling to the ocean or export to terrestrial habitat nearby) fluxes that can vary widely according to the local conditions (Neue et al., 1997; Dittmar et al., 2006). River and tides movement influence the rates of organic matter deposition and accumulation as they promote organic matter and nutrient exchange. For example, Northern mangroves (subject to a macrotidal regime) receive high amounts of both autochthonous (mangrove sources) and allochthonous (terrestrial and marine sources) organic matter, resulting in high carbon accumulation (Rovai et al., 2022).

(ii) Sediment aeration (tides): Sediment aeration affects microbial activity and element cycling processes (Rovai et al., 2018); carbon gets accumulated in tidally inundated suboxic and anoxic sediments and just a minor fraction returns to the atmosphere (Breithaupt et al., 2012). Therefore, sediment aeration as a consequence of tidal fluxes can greatly influence carbon accumulation rates. In forests that remain inundated, low oxygen availability prevents aerobic respiration of mangrove-derived organic matter; this also occurs under tidal regime of small amplitude, but to a lesser extent.

(iii) Climate conditions: warmer climate accelerates photosynthetic activity, root growth and decomposition processes, promoting higher carbon stocks (Alongi, 2012; Ferreira et al., 2019; Rovai et al., 2018; Nóbrega et al., 2019; Rovai et al., 2021).

(iv) Land-use changes (and other factors resulting in mangrove loss or degradation): this can result in low sediment carbon stocks (Kauffman et al., 2018a), as observed by our comparison of impacted mangrove forests with non-impacted mangrove forests along the Brazilian coast.

The heterogeneity of AGB carbon stock in Brazilian mangroves supposedly results from climatic conditions, as mentioned above. On a local scale, nutrient load and other environmental or human (e.g., land use change or wood harvesting) disturbances can also lead to spatial heterogeneity in AGB carbon stocks. For example, a restored eutrophic mangrove that receives sewage and is located in the middle of a urban site, contained lower AGB carbon stocks (41.4 Mg C ha^{-1}) than a non-impacted mangrove located in a same region, but without these urban impacts (101.9 Mg C ha^{-1}) (e.g., Leite et al., 2021; Rodrigues et al., 2014).

Meanwhile, considering the whole system (TECS), mangrove with a degradation process, as observed in our study, present twice less carbon than a non-impacted site (impacted 226 Mg C ha^{-1}; non-impacted 515 Mg C ha^{-1}). The carbon stock values reported highlight the high potential of mangrove ecosystems to sequester large amounts of atmospheric CO_2 in the long term (centennial to millennial) and therefore act as nature-based solution for climate change mitigation when conserved or (re-)established (e.g., Salum et al., 2020; Kauffman et al., 2018b; Zimmer et al. 2022).

All in all, spatial heterogeneity was observed at both the regional and local level. As the three distinct regions delineated in this study differed not solely by their climate, but also by their geomorphology, their tidal regime, and by site status, further research is needed to disentangle the respective contribution of those variables to carbon stock spatial distribution. As the Brazilian mangroves have a wide distribution, and thereby cover a wide range of latitudes and climatic conditions, geomorphological characteristics, tidal regime, and site status, that will all influence the distinct mangrove compartments and their carbon stocks, they represent an ideal system to support further research on Blue Carbon and its drivers, which is much needed.

1.5.3 BRAZILIAN MANGROVES AS BLUE CARBON HOTSPOT

Overall, considering a total national mangrove area of 1,011,160.26 ha (Mapbiomas, 2021), and TECS of 443 Mg C ha^{-1}, presented by mean values of the selected articles, Brazilian mangroves contain a total carbon stock (TECS) of about 0.44 PgC (the North, Northeast, and Southeast regions sheltering respectively, 78%, 15.4%, and 3.5% of those). This value is consistent with previous estimates, with some difference due to outdated information about total mangrove area ar/or to differences in the TECS values adopted (Rovai et al. (2022): 0.26 PgC - 767,500 ha/TECS 341 Mg C ha^{-1}; Alongi (2020): 0.42 PgC - 990,000 ha/TECS 432 Mg C ha^{-1}; Jakovac et al. (2020): 0,40 PgC - 767,500 ha/TECS 512.60 Mg C ha^{-1}). Our calculated total carbon stock of 0.44 PgC in Brazil represents ~10-12% of global mangrove carbon stocks considering recent global estimates of 3.78-4.19 PgC (Hamilton and Friess, 2018; Rovai et al., 2022).

Our calculated carbon stock (0.44 PgC) positions Brazil at the second place in terms of global carbon stock, just after Indonesia (1.27 PgC), and in front of Malaysia (0.25 PgC), Papua New Guinea (0.22 PgC), and Australia (0.15 PgC), completing the top-5 ranking (Hamilton & Friess, 2018). This reinforces the urgency about updating mangrove area information, following the most recent databases and also standardizing measurements of total ecosystem carbon stocks; we plead to always consider the AGB, BGB and sediment compartments. This result also highlights and confirms the position of Brazil as a hotspot of Blue Carbon and we hope that this will further raise awareness about the value of mangrove ecosystems for climate change mitigation and adaptation and plead for the sustainable management of those ecosystems.

1.6 CONCLUSIONS

Our systematic review and meta-analysis demonstrate that blue carbon stocks in mangrove forests along the extensive SW Atlantic Coast vary across Brazilian regions (North, Northeast, Southeast). These mangroves present distinct climate patterns, geomorphology and tidal regimes, and they are quite influenced by the status (impacted versus non-impacted) of the forests. Sediment, AGB and TECS of non-impacted mangrove areas exhibited higher values than impacted ecosystems. In addition, the size of blue carbon stocks varied greatly among regions, highlighting the need for further studies in under sampled low-latitude regions (e.g., Amazon coast) as well as methodological improvement and standardization of approaches for reliable blue carbon assessment and documentation across Brazil.

Our review highlights the immense capacity of mangrove forests along the Brazilian coast to store organic carbon, mainly in their above and belowground biomass and in their sediments, especially in the North and Northeast coastal regions characterized by warm tropical climate, with macro- and mesotidal regimes.

The observed high spatial heterogeneity in Brazilian mangrove carbon stocks highlights the need of considering mangrove specificities before adopting a reference value of carbon stocks from the literature when planning carbon mitigation projects, or before developing concepts of payments for ecosystem services, at the national or global levels. It also calls for caution when providing national values.

Coastal areas are under constant pressure due to various anthropogenic stressors and activities that threaten ecosystem integrity and thereby increase the vulnerability of carbon stocks. Projects aimed at preserving, re-establishing, or expanding mangrove forests, accompanied by efficient public policies and regulations could preserve and enhance carbon stocks in Brazil. Thereby, providing a promising nature-based (ocean-based) carbon dioxide removal solution for climate change mitigation and adaptation, and avoiding further greenhouse emissions due to land use changes. We hope that this study will foster similar meta-analyses of carbon stocks in other BCEs, but also in transitional habitats and interconnected ecosystems, such as mudflats and hypersaline tidal flats, to evaluate their respective potential for blue carbon, in national and global blue carbon inventories.

1.7 BIBLIOGRAPHY

ADAME, M.F. et al. (2021)**a**. Mangrove sinkholes (cenotes) of the Yucatan Peninsula, a global hotspot of carbon sequestration. **Biology Letters**. Vol. 17, May 5, 2021. https://doi.org/10.1098/rsbl.2021.0037.

ADAME, M.F., CONNOLLY, R.M., TURSCHWELL, M.P., LOVELOCK, C.E., FATOYINBO, T., LAGOMASINO, D., GOLDBERG, L.A., HOLDORF, J., FRIESS, D.A., SASMITO, S.D., SANDERMAN, J., SIEVERS, M., BUELOW, C., KAUFFMAN, J.B., BRYAN-BROWN, D.; BROWN, C.J. (2021)**b**. Future carbon emissions from global mangrove forest loss. **Glob Change Biol**, 27: 2856-2866. https://doi.org/10.1111/gcb.15571

ALONGI, D. M. (2012). Carbon sequestration in mangrove forests. **Carbon Management**, 3(3), 313–322. https://doi.org/10.4155/cmt.12.20

ALONGI, D. M. (2014). Carbon Cycling and Storage in Mangrove Forests. **Annual Review of Marine Science**, 6(1), 195–219. https://doi.org/10.1146/annurev-marine-010213-135020

ALONGI, D. M. (2020). Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. **Sci,** 2(3), 67. https://doi.org/10.3390/sci2030067

ALONGI, D. M. **The Energetics of Mangrove Forests**. 1st ed. Dordrecht: Springer Netherlands, 2009. Available in: https://link.springer.com/book/10.1007/978-1-4020-4271-3.

ALVARES, C.A.; STAPE, J.L.; SENTELHAS,P.C.; GONÇALVES, J.L.M; SPAROVEK, G. (2013). Koppen's climate classification map for Brazil. Meteorologische Zeitschrift, Vol. 22, No. 6, 711–728. https://doi.org/10.1127/0941-2948/2013/0507

ATWOOD, T. B., CONNOLLY, R. M., ALMAHASHEER, H., CARNELL, P. E., DUARTE, C. M., EWERS LEWIS, C. J., … LOVELOCK, C. E. (2017). Global patterns in mangrove soil carbon stocks and losses. **Nature Climate Change**, 7(7), 523–528. doi:10.1038/nclimate3326

BARBIER, E. B., HACKER, S. D., KENNEDY, C., KOCH, E. W., STIER, A. C., & SILLIMAN, B. R. (2011). The value of estuarine and coastal ecosystem services. **Ecological Monographs**, 81(2), 169–193. doi:10.1890/10-1510.1

BERTRAM, C., QUAAS, M., REUSCH, T.B.H. *et al.* (2021) The blue carbon wealth of nations. **Nat. Clim. Chang.** 11, 704–709. https://doi.org/10.1038/s41558-021-01089-4

BOUILLON, S., BORGES, A. V., CASTAÑEDA-MOYA, E., DIELE, K., DITTMAR, T., DUKE, N. C., … TWILLEY, R. R. (2008). Mangrove production and carbon sinks: A revision of global budget estimates. Global Biogeochemical Cycles, 22(2), n/a–n/a. doi:10.1029/2007gb003052

BREITHAUPT, J. L., SMOAK, J. M., SMITH, T. J., SANDERS, C. J., & HOARE, A. (2012). Organic carbon burial rates in mangrove sediments: Strengthening the global budget. Global Biogeochemical Cycles, 26(3). https://doi.org/10.1029/2012gb004375

BROWN, D. R.; MAROTTA, H.; PEIXOTO, R.B.; ENRICH-PRAST, A.; BARROSO, G.C.; SOARES, M.L., ... SANDERS,C.J.. (2021). Hypersaline tidal flats as important 'blue carbon' systems: A case study from three ecosystems." **Biogeosciences** 18 (8), 2527–38. https://doi.org/10.5194/bg-18-2527-2021.

BUNTING, P., ROSENQVIST, A., LUCAS, R., REBELO, L.-M., HILARIDES, L., THOMAS, N.; FINLAYSON, C. (2018). The Global Mangrove Watch - A New 2010 Global Baseline of Mangrove Extent. **Remote Sensing**, 10(10), 1669. https://doi.org/10.3390/rs10101669

CLARK, M.W.; MCCONCHIE, D.; LEWIS, D.W.; SAENGER, P. (1998). Redox stratification and heavy metal partitioning in Avicennia-dominated mangrove sediments: a geochemical model. **Chemical Geology**, 149: 147-171. https://doi.org/10.1016/S0009-2541(98)00034-5

DA MOTTA PORTILLO, J. T., LONDE, V., & MOREIRA, F. W. A. (2016). Aboveground biomass and carbon stock are related with soil humidity in a mangrove at the Piraquê-Açu

River, Southeastern Brazil. **Journal of Coastal Conservation**, 21(1), 139–144. https://doi.org/10.1007/s11852-016-0482-4

DAVIES, J. L. (1964). A morphogenetic approach to world shorelines. **Zeits fur Geomorph.,** 8: 127-142.

DINIZ, C., CORTINHAS, L., NERINO, G., RODRIGUES, J., SADECK, L., ADAMI, M., & SOUZA-FILHO, P. (2019). Brazilian Mangrove Status: Three Decades of Satellite Data Analysis. **Remote Sensing**, 11(7), 808. https://doi.org/10.3390/rs11070808

DITTMAR, T.; HERTKORN, N.; KATTNER, G.;LARA, R. J. (2006). Mangroves, a major source of dissolved organic carbon to the oceans. **Global Biogeochemical Cycles**, 20(1), n/a–n/a. https://doi.org/10.1029/2005gb002570

DONATO, D. C., KAUFFMAN, J. B., MURDIYARSO, D., KURNIANTO, S., STIDHAM, M., & KANNINEN, M. (2011). Mangroves among the most carbon-rich forests in the tropics. **Nature Geoscience**, 4(5), 293–297. https://doi.org/10.1038/ngeo1123

DUBREUIL, V., FANTE, K.P., PLANCHON, O. & LIMA NETO, J. (2018). Os tipos de climas anuais no Brasil: Uma aplicação da classificação de Köppen de 1961 a 2015. **Revista Franco-brasilera de Geografia**, 37, Confins. https://doi.org/10.4000/confins.15738

DUKE, N. C., BALL, M. C., & ELLISON, J. C. (1998). Factors Influencing Biodiversity and Distributional Gradients in Mangroves. **Global Ecology and Biogeography Letters**, 7(1), 27. https://doi.org/10.2307/2997695

FERREIRA, A. C., & LACERDA, L. D. (2016). Degradation and conservation of Brazilian mangroves, status and perspectives. **Ocean & Coastal Management**, 125, 38–46. doi:10.1016/j.ocecoaman.2016.03.011

FERREIRA, A. C., BEZERRA, L. E. A., & MATTHEWS-CASCON, H. (2019). Aboveground carbon stock in a restored neotropical mangrove: influence of management and brachyuran crab assemblage. **Wetlands Ecology and Management**. doi:10.1007/s11273-019-09654-7

FERREIRA, T.O.; QUEIROZ, H.M.; NÓBREGA, G.N.; SOUZA JÚNIOR, V.S.; BARCELLOS, D.; FERREIRA, A.D.; OTERO,X.L. (2022). Litho-climatic characteristics and its control over mangrove soil geochemistry: A macro-scale approach. **Science of The Total Environment**, 811:152152. https://doi.org/10.1016/j.scitotenv.2021.152152

FERREIRA, T.O.; VIDAL-TORRADO, P.; OTERO, X.L.; MACÍAS, F. (2007). Are mangrove forest substrates sediments or soils? A case of study in southeastern Brazil. **Catena**, 70: 79-91. https://doi.org/10.1016/j.catena.2006.07.006

FEST, B.J.; SWEARER, S.E.; ARNDT, S.K. (2022). A review of sediment carbon sampling methods in mangroves and their broader impacts on stock estimates for blue carbon ecosystems. Science of The Total Environment, 816(151618): 1-12. https://doi.org/10.1016/j.scitotenv.2021.151618

GALVÃO, T. F. & PEREIRA, M.G.. Revisões Sistemáticas Da Literatura: Passos Para Sua Elaboração. **Epidemiologia e Serviços de Saúde** 23, no. 1 (2014): 183–84. doi.org/10.5123/s1679-49742014000100018

GIRI C., OCHIENG E., TIESZEN L. L., ZHU Z., SINGH A., LOVELAND T., MASEK J. AND DUKE N. (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20, 154–159.

GOMES, L. E. DE O., SANDERS, C. J., NOBREGA, G. N., VESCOVI, L. C., QUEIROZ, H. M., KAUFFMAN, J. B., … BERNARDINO, A. F. (2021). Ecosystem carbon losses following a climate-induced mangrove mortality in Brazil. **Journal of Environmental Management**, 297, 113381. doi:10.1016/j.jenvman.2021.113381

HAMILTON, S. E., & CASEY, D. (2016). Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). **Global Ecology and Biogeography**, 25(6), 729–738. doi:10.1111/geb.12449

HAMILTON, S. E., & FRIESS, D. A. (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. **Nature Climate Change**, 8(3), 240–244. doi:10.1038/s41558-018-0090-4

HAYES, M. O. (1975). Morphology of sand accumulation in estuaries: An introduction to the symposium. **Geology and Engineering**, 3–22. doi:10.1016/b978-0-12-197502-9.50006-x

HERR, D.; PIDGEON, E.; LAFFOLEY, D. (2012). Blue Carbon Policy Framework: Based on the discussion of the International Blue Carbon Policy Working Group, IUCN, Gland, Switzerland and Arlington, USA, 2012. https://portals.iucn.org/library/node/10126.

HOWARD, J., HOYT, S., ISENSEE, K., TELSZEWSKI, M., PIDGEON, E. (eds.) (2014). **Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.** Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA. https://unesdoc.unesco.org/ark:/48223/pf0000372868.

ICMBio (2018). **Atlas dos Manguezais Brasileiros** - Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), Brasília, 176 p. ISBN 978-85-61842-75-8. https://www.gov.br/icmbio/pt-br/centrais-de-conteudo/atlas-dos-manguezais-do-brasil-pdf.

JAKOVAC, C. C., LATAWIEC, A. E., LACERDA, E., LEITE LUCAS, I., KORYS, K. A., IRIBARREM, A., … BAETA NEVES STRASSBURG, B. (2020). Costs and Carbon Benefits of Mangrove Conservation and Restoration: A Global Analysis. **Ecological Economics**, 176, 106758. doi:10.1016/j.ecolecon.2020.106758

KAIRO, J.; MBATHA, A.; MURITHI, M.M.; MUNGAI, F. (2021). Total Ecosystem Carbon Stocks of Mangroves in Lamu, Kenya; and Their Potential Contributions to the Climate Change Agenda in the Country. Frontiers in Forests and Global Change, 4, 7092227: 1-15. doi: 10.3389/ffgc.2021.709227

KAUFFMAN, J. B., ADAME, M. F., ARIFANTI, V. B., SCHILE-BEERS, L. M., BERNARDINO, A. F., BHOMIA, R. K., … HERNÁNDEZ TREJO, H. (2020). Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. **Ecological Monographs**, 90(2). doi:10.1002/ecm.1405

KAUFFMAN, J. B., BERNARDINO, A. F., FERREIRA, T. O., BOLTON, N. W., GOMES, L. E. DE O., & NOBREGA, G. N. (2018**a**). Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. **Ecology and Evolution**, 8(11), 5530–5540. doi:10.1002/ece3.4079

KAUFFMAN, J. B., BERNARDINO, A.F., FERREIRA, T.O., GIOVANNONI, L.R., GOMES, L.E.O., ROMERO, D.J., JIMENEZ, L.C. & RUIZ, F.. (2018**b**). Carbon Stocks of Mangroves and Salt Marshes of the Amazon Region, Brazil. **Biology Letters,** 14, no. 9 (2018): 20180208. https://doi.org/10.1098/rsbl.2018.0208

KIDA, M; WATANABE, I.; KINJO, K. et al. (2021). Organic carbon stock and composition in 3.5-m core mangrove soils (Trat, Thailand). Science of Total Environment 801:1-09.

LACERDA, L. D., WARD, R.D., GODOY, M.D., MEIRELES, A.J.A., BORGES, R. & FERREIRA, A.C.. (2021). 20-Years Cumulative Impact from Shrimp Farming on Mangroves of Northeast Brazil. **Frontiers in Forests and Global Change**, 4 (2021). https://doi.org/10.3389/ffgc.2021.653096.

LAL, R. (2005). Forest soils and carbon sequestration. **Forest Ecology and Management**, 220(1-3), 242–258. https://doi:10.1016/j.foreco.2005.08.015

LEITE, R. A., NÓBREGA, G. N., LEAL, L. R. Z. C., KIEFER, M. C., & SOARES-GOMES, A. (2021). The colonization of a coastal lagoon by a mangrove ecosystem: Benefit or threat to the lagoon? **Aquatic Botany**, 171, 103362. doi:10.1016/j.aquabot.2021.103362

MACREADIE, P.I. et al. (2021). Blue carbon as a natural climate solution. **Nature Reviews Earth & Environment**, 2, 826–839, 2021. https://doi.org/10.1038/s43017-021-00224-1

MAGRIS, R.A. & BARRETO, R. (2010). Mapping and assessment of protection of mangrove habitats in Brazil. **PANAMJAS**, Pan-American Journal of Aquatic Sciences. 5(4):546-556

MAPBIOMAS (2021). Cobertura e transições bioma & estados (Coleção 7) - dados de área (ha) de cobertura e uso da terra por bioma e estado de 1985 a 2021. https://mapbiomas.org/estatisticas.

MCLEOD, K. W., G. L. CHMURA, S. BOUILLON, R. SALM, M. BJORK, C. M. DUARTE, C. E. LOVELOCK, H. SCHLESINGER, AND B. R. SILLIMAN. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. **Frontiers in Ecology and the Environment**, 9:552–560.doi:10.1890/110004

MENGIST, W., SOROMESSA, T., & LEGESE, G. (2020). Method for conducting systematic literature review and meta-analysis for environmental science research. MethodsX, 7, 100777. doi:10.1016/j.mex.2019.100777

MUEHE, D. (2010). Brazilian coastal vulnerability to climate change**. Pan-American Journal of Aquatic Sciences.** 5(2): 173-183.

NELLEMANN, C., CORCORAN, E., DUARTE, C. M., VALDÉS, L., DE YOUNG, C., FONSECA, L., GRIMSDITCH, G. (Eds). (2009). **Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme**, GRID-Arendal, https://www.grida.no/publications/145.

NEUE, H.U.; GAUNT,J.L.; WANG, Z.P.;BECKER-HEIDMANN, P.; QUIJANO,C. (1997). Carbon in tropical wetlands. Geoderma 79: 163-185.

NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., MENDONÇA, E. DE S., ROMERO, R. E., & OTERO, X. L. (2019). The importance of blue carbon soil stocks in tropical semiarid mangroves: a case study in Northeastern Brazil. **Environmental Earth Sciences**, 78(12). doi:10.1007/s12665-019-8368-z

NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., QUEIROZ, H. M., ARTUR, A. G., MENDONÇA, E. D. S., … OTERO, X. L. (2016). Edaphic factors controlling summer (rainy season) greenhouse gas emissions (CO_2 and CH_4) from semiarid mangrove soils (NE-Brazil). **Science of The Total Environment**, 542, 685–693. doi:10.1016/j.scitotenv.2015.10.108

O'LEARY, B. C., BAYLISS, H. R., & HADDAWAY, N. R. (2015). Beyond PRISMA: Systematic reviews to inform marine science and policy. **Marine Policy**, 62, 261–263. doi:10.1016/j.marpol.2015.09.026

PAGE, M. J., MCKENZIE, J. E., BOSSUYT, P. M., BOUTRON, I., HOFFMANN, T. C., MULROW, C. D., … MOHER, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. **BMJ**, 71. doi:10.1136/bmj.n71

PASSOS, T. R. G., ARTUR, A. G., NÓBREGA, G. N., OTERO, X. L., & FERREIRA, T. O. (2016). Comparison of the quantitative determination of soil organic carbon in coastal wetlands containing reduced forms of Fe and S. **Geo-Marine Letters**, 36(3), 223–233. doi:10.1007/s00367-016-0437-7.

PENDLETON, L., DONATO, D. C., MURRAY, B. C., CROOKS, S., JENKINS, W. A., SIFLEET, S., … BALDERA, A. (2012). Estimating Global “Blue Carbon” Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. **PLOS ONE**, 7(9), e43542. doi:10.1371/journal.pone.0043542

PEREIRA, M. G., & GALVÃO, T.F..(2014). Etapas De Busca e Seleção De Artigos Em Revisões Sistemáticas Da Literatura. **Epidemiologia e Serviços de Saúde**, 23, (2): 369–71. https://doi.org/10.5123/s1679-49742014000200019

PÉREZ, A., MACHADO W. , GUTIÉRREZ D., BORGES A.C., PATCHINEELAM S.R. & SANDERS, C.J.. (2018). Carbon Accumulation and Storage Capacity in Mangrove Sediments Three Decades after Deforestation within a Eutrophic Bay.” **Marine Pollution Bulletin,** 126: 275–80. https://doi.org/10.1016/j.marpolbul.2017.11.018

QUEIROZ, L., ROSSI, S., MEIRELES, J., & COELHO, C. (2013). Shrimp aquaculture in the federal state of Ceará, 1970–2012: Trends after mangrove forest privatization in Brazil. **Ocean & Coastal Management**, 73, 54–62. doi:10.1016/j.ocecoaman.2012.11.009

RODRIGUES, D. P., HAMACHER, C., ESTRADA, G. C. D., & SOARES, M. L. G. (2014). Variability of carbon content in mangrove species: Effect of species, compartments and tidal frequency. **Aquatic Botany**, 120, 346–351. doi:10.1016/j.aquabot.2014.10.004

RODRIGUES, J. V. M. (2022). Carbono Azul no Semiárido Nordestino: estoque de carbono do solo de um manguezal em recuperação no estuário do Rio Pacoti, CE. 2022. 77 f. Dissertação (Mestrado em Ciências Marinhas Tropicais) - Programa de Pós-Graduação em Ciências Marinhas Tropicais, Instituto de Ciências do Mar - LABOMAR, Universidade Federal do Ceará, Fortaleza, 2022. http://www.repositorio.ufc.br/handle/riufc/66013.

ROVAI, A. S., COELHO-JR, C., DE ALMEIDA, R., CUNHA-LIGNON, M., MENGHINI, R. P., TWILLEY, R. R., … SCHAEFFER-NOVELLI, Y. (2021). Ecosystem-level carbon stocks and sequestration rates in mangroves in the Cananéia-Iguape lagoon estuarine system, southeastern Brazil. **Forest Ecology and Management**, 479, 118553. doi:10.1016/j.foreco.2020.118553

ROVAI, A. S., TWILLEY, R. R., CASTAÑEDA-MOYA, E., RIUL, P., CIFUENTES-JARA, M., MANROW-VILLALOBOS, M., … PAGLIOSA, P. R. (2018). Global controls on carbon storage in mangrove soils. **Nature Climate Change**, 8(6), 534–538. doi:10.1038/s41558-018-0162-5

ROVAI, A.S., TWILLEY, R.R., WORTHINGTON, T.A., RIUL, P. (2022) Brazilian Mangroves: Blue Carbon Hotspots of National and Global Relevance to Natural Climate Solutions. Frontiers in Forests and Global Change 4, 787533. 10.3389/ffgc.2021.787533

SALUM, R. B., SOUZA-FILHO, P. W. M., SIMARD, M., SILVA, C. A., FERNANDES, M. E. B., COUGO, M. F., … ROGERS, K. (2020). Improving mangrove above-ground biomass estimates using LiDAR. **Estuarine, Coastal and Shelf Science**, 106585. doi:10.1016/j.ecss.2020.106585

SANDERMANN, J., HENGL, T., FISKE, G., SOLVIK, K., ADAME, M.F., BENSON, L., BUKOSKI, J.J., CARNELL, P., CIFUENTES-JARA, M., DONATO, D (2018). A global map of mangrove forest soil carbon at 30m spatial resolution. Environmental Research Letters 13, 055002. 10.1088/1748-9326/aabe1c/meta

SANDERS, C. J., MAHER, D. T., TAIT, D. R., WILLIAMS, D., HOLLOWAY, C., SIPPO, J. Z., & SANTOS, I. R. (2016). Are global mangrove carbon stocks driven by rainfall? **Journal of Geophysical Research**: Biogeosciences, 121(10), 2600–2609. doi:10.1002/2016jg003510

SCHAEFFER-NOVELLI, Y., CINTRÓN-MOLERO, G., REIS-NETO, A. S., ABUCHAHLA, G. M. O., NETA, L. C. P., & LIRA-MEDEIROS, C. F. (2018). The mangroves of Araçá Bay through time: An interdisciplinary approach for conservation of spatial diversity at large scale. Ocean & Coastal Management. doi:10.1016/j.ocecoaman.2017.12.024

SERRANO, O., KELLEWAY, J. J., LOVELOCK, C., & LAVERY, P. S. (2019). Conservation of Blue Carbon Ecosystems for Climate Change Mitigation and Adaptation. Coastal Wetlands, 965–996. doi:10.1016/b978-0-444-63893-9.00028-9

SIMARD, M., FATOYINBO, L., SMETANKA, C., RIVERA-MONROY, V. H., CASTAÑEDA-MOYA, E., THOMAS, N., & VAN DER STOCKEN, T. (2019). Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. **Nature Geoscience**, 12(1), 40–45. doi:10.1038/s41561-018-0279-1

SOARES, M. O.; BEZERRA, L. E. A.; COPERTINO, M.; LOPES, B. D.; BARROS, K. V. S.; ROCHA-BARREIRA, C. A.; MAIA, R. C.; BELOTO, N.; COTOVICZ, L. C. (2022).

Blue Carbon Ecosystems in Brazil: Overview and an Urgent Call for Conservation and Restoration. **Frontiers in Marine Science**, 9: 1-16, 2022.

SUÁREZ-ABELENDA, M., FERREIRA, T. O., CAMPS-ARBESTAIN, M., RIVERA-MONROY, V. H., MACÍAS, F., NÓBREGA, G. N., & OTERO, X. L. (2014). The effect of nutrient-rich effluents from shrimp farming on mangrove soil carbon storage and geochemistry under semi-arid climate conditions in northern Brazil. **Geoderma**, 213, 551–559. doi:10.1016/j.geoderma.2013.08.007.

TAILLARDAT, P.; THOMPSON, B.S.; GARNEAU, M.; TROTTIER, K.; FRIESS, D. A. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus 10 (5): 1-12. doi: 10.1098/rsfs.2019.0129.

THORHAUG, A., GALLAGHER, J. B., KISWARA, W., PRATHEP, A., HUANG, X., YAP, T.-K., … BERLYN, G. (2020). Coastal and estuarine blue carbon stocks in the greater Southeast Asia region: Seagrasses and mangroves per nation and sum of total. **Marine Pollution Bulletin**, 160, 111168. doi:10.1016/j.marpolbul.2020.111168

TURNER, W. R., OPPENHEIMER, M., & WILCOVE, D. S. (2009). A force to fight global warming. **Nature**, 462(7271), 278–279. doi:10.1038/462278a

TRUJILLO, L. V. P., PINEDA, J. E. M., CALDERON, J. H. M., ZIMMER, M., & SCHNETTER, M.-L. (2020). Massive loss of aboveground biomass and its effect on sediment organic carbon concentration: Less mangrove, more carbon? Estuarine, Coastal and Shelf Science, 106888. doi:10.1016/j.ecss.2020.106888

WORTHINGTON, T. A., ZU ERMGASSEN, P. S. E., FRIESS, D. A., KRAUSS, K. W., LOVELOCK, C. E., THORLEY, J., … SPALDING, M. (2020). A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. Scientific Reports, 10(1). doi:10.1038/s41598-020-71194-5

WYLIE, L., SUTTON-GRIER, A. E., & MOORE, A. (2016). Keys to successful blue carbon projects: Lessons learned from global case studies. Marine Policy, 65, 76–84. doi:10.1016/j.marpol.2015.12.020

YAMAKAWA, E. K., KUBOTA, F. I., BEUREN, F. H., SCALVENZI, L., & MIGUEL, P. A. C. (2014). Comparativo dos softwares de gerenciamento de referências bibliográficas: Mendeley, EndNote e Zotero. Transinformação, 26(2), 167–176. doi:10.1590/0103-37862014000200006

ZIMMER M, AJONINA GN, AMIR AA, CRAGG S, CROOKS S, DAHDOUH-GUEBAS F, DUKE N, FRATINI S, FRIESS DA, HELFER V, HUXHAM M, KATHIRESAN K, KODIKARA KAS, KOEDAM N, LEE SY, MANGORA MM, PRIMAVERA J,

SATYANARAYANA B, YONG JWH, WODEHOUSE D. (2022). When nature needs a helping hand: different levels of human intervention for mangrove (re-)establishment. Frontiers in Forests and Global Change 5: 784322. doi.org/10.3389/ffgc.2022.784322.

CONSIDERAÇÕES FINAIS

Embora hajam múltiplos fatores que influenciam a dinâmica dos processos de captura e armazenamento de CO_2 em manguezais, a ciência caminha para compreensão de cada passo, e vêm apresentando informações importantes sobre esses. Assim, com a tese, trouxemos relevante conhecimento científico para a área de *análise e interpretação de ecossistemas de manguezais*, especificamente no que se refere ao potencial de armazenamento e estocagem de carbono. Os Capítulos 1 e 2 puderam atingir o objetivo quanto ao ineditismo de dados, o experimento TBI nunca havia sido aplicado em um manguezal da América Latina, e nenhum levantamento bibliográfico sobre os estoques de carbono em manguezais brasileiros havia sido realizado até então. O presente trabalho evidencia o esforço da ciência em compreender processos de alta complexidade, os quais envolvem a medição e interpretação de múltiplas variáveis, bem como suas interações. E embora os resultados tenham indicado tendências mais gerais, essas abrem espaço para discussões sobre a potencialidade dos manguezais brasileiros em sequestrar, armazenar e estocar carbono, reforçando a necessidade de preenchimento de informações acerca da ciência de base, como dados consistentes de toda a costa brasileira. Todas as informações contidas neste trabalho podem ser utilizadas para fortalecer e reforçar a necessidade de um uso ordenado dos manguezais, considerando que a mudança do uso de solos podem potencializar as emissões de CO_2, e que os manguezais são de relevante interesse para a manutenção da vida. Reforça-se ainda que os trajetos para construção desta tese estiveram entrelaçados também junto a outras atividades e ações, tais como uma ampla investigação do ambiente e todos seus aspectos, a realização e normalização de procedimentos laboratoriais, a comunicação e a divulgação científica junto à comunidade acadêmica e não acadêmica, ao esforço formativo junto a pesquisadores de vários níveis de conhecimento, a consolidação de grupos de pesquisa, a divulgação internacional do conhecimento e ao desenvolvimento pessoal e profissional de todos os envolvidos. Assim, esta pesquisa científica ascende aos limites deste documento e perpassa entre todos os que tiveram contato com o projeto. Além disto, a tese e conteúdo publicado manterá o conhecimento em circulação para ser utilizado em prol das pessoas e dos manguezais. Cabe mencionar que o presente conhecimento construído estará em constante transformação à medida que novos estudos forem surgindo, e que a utilização deste conhecimento para o desenvolvimento de pesquisas e experimentos para potencialização da absorção de CO_2 por manguezais serão bem quistos pela comunidade científica e gestores ambientais. E assim, almejando a aplicação do conhecimento e continuidade dos processos, encerro o documento.

SUPPLEMENTARY MATERIAL

1- Supplementary Material

I. Carbon stock mean, median and standard deviation for region and status

Table S1 – Carbon stock data according with region (North, Northeast, Southeast) (MgC ha^{-1}).

	TECS1	AGB	DW	BGB	Sediment
North/Macrotidal					
Mean	510.92	103.38	13.61	13.49	316.01
Median	515.85	113.25	14.65	11.40	341.00
SD	62.86	53.93	5.25	5.78	81.79
Northeast/Mesotidal					
Mean	415.98	67.46	5.12	14.27	195.80
Median	413	57.71	6	11.7	117.5
SD	144.02	31.42	1.98	4.76	141.78
Southeast/Microtidal					
Mean	268.68	45.65		38.55	93.08
Median	268.68	41.4		27.45	41.205
SD	111.32	27.42		32.01	88.46

Table S2 – Mean, Median and SD data according with status (Impacted and Non-impacted) (MgC ha^{-1}).

	TECS1	AGB	DW	BGB	Sediment
Impacted					
Mean	226.23	49.48	4.93	15.60	79.38
Median	232.7	46	6.1	13.95	67.4
SD	41.98	18.26	1.96	5.90	46.42
Non-impacted					
Mean	514.94	101.63	11.53	25.75	317.01
Median	521.75	99.2	10.4	11.45	335.15
SD	89.73	47.01	6.20	21.69	115.78

II. List of carbon stock in soil not listed in article

Data presented refers to carbon stock in a unit that does not consider area, and because of these their presentation are only in the supplementary material.

Table S3 - Carbon content in sediment samples.

Article	State	Area	Carbon Stock
Queiroz et al. 2018	Ceará	Rio Cocó Rio Jaguaribe Rio Timonha	Min-Max = 28.8 - 39.6 g/kg Jaguaribe = 39 g/kg Cocó = 39.5 g/kg Timonha= 29 g/kg
Garcia et al. 2020	Paraná	Sistema Estuarino de Paranaguá	Antonina = 59 g/kg Guaraqueçaba = 35 g/kg Paranaguá = 25 g/kg Laranjeiras =15 g/kg Pinheiros= 22 g/kg Área de mistura = 11g/kg
Hatje et al. 2016	Bahia	Bahia de Todos os Santos	Min-Max = 1.6 – 17.4 g/kg
Pereira et al. 2019	Ceará	Rio Pacoti Rio Jaguaribe	Pacoti = 14 g/kg Jaguaribe = 9 g/kg

Nóbrega et al. 2014	Ceará	Rio Cocó Rio Jaguaribe Rio Timonha	**AE** Min-Max = 14.77- 58.87g/kg AE Mean = 36.15 g/kg Jaguaribe = 45.2g/kg Cocó = 25.7 g/kg Timonha = 35.3 g/kg **Termograv**. Min-Max = 46.43 - 242.14 g/kg Termograv. Mean = 127.18 g/kg Jaguaribe = 51.42 g/kg Cocó = 24.73 g/kg Timonha = 29.20 g/kg
Rovai et al. 2018	Pará, Bahia, São Paulo, Paraná and Santa Catarina		Maracanã - PA 20.37 mg cm-3 S. Caetano de Odivelas - PA 17.20 mg cm-3 S. João das Pirabas - PA 16.64 mg cm-3 Cairu - BA 24.07; 37.01; 33.57 mg cm-3 Caravelas - BA 30.01; 19.42; 20.47 mg cm-3 Iguape-SP - 27.48; 23.26 mg cm-3 Cananéia - SP 28.99 mg cm-3 Guaratuba - PR 16.24 mg cm-3 Itapoá - SC 21.36 mg cm-3 Florianópolis - SC 20.27 mg cm-3
Queiroz et al. 2019	Ceará	Rio Jaguaribe	Area with shrimp wastewater= 20.5 g/kg Area without wastewater= 12.8 g/kg
Passos et al. 2021	Pernambuco	Sistema Estuarino de Suape	Min-Max = 3.7 – 51.1 g/kg
Queiroz et al. 2020	Ceará	Rio Jaguaribe	Impacted area = 21 g/kg Preserved area= 13 g/kg
Ferreira et al. 2010	São Paulo	Rio Crumahú	41 – 328 g/kg

III. Plant biomass conversion factor

Table S4 – Vegetation conversion factor used by selected articles.

Selected article reference	Conversion	Conversion factor	Reference basis
Da Motta Portillo et al. (2016)	Above-ground biomass (AGB) => Carbon	*0.5	No reference
Ferreira et al.(2019)	Above-ground vegetal biomass (AGB) - trees and downed woods=> Carbon	*0.44	Rodrigues et al. (2014)
Virgulino-Júnior et al. (2020)	Above-ground vegetal biomass (AGB) => Carbon	*0.419	Carneiro (2017)
	Below-ground vegetal biomass (BGB) => Carbon	*0.426	Rodrigues et al.(2014)
Hatje et al.(2020)	Above-ground vegetal biomass (AGB) – trees => Carbon	*0.46	Forqurean et al.(2014)
	Above-ground vegetal biomass (AGB) - downed woods and vegetal debris => Carbon	*0.5	Howard et al.(2014)
	Above-ground vegetal biomass (AGB) - litter => Carbon	*0.45	No reference
Kauffman et al. (2018)[b]	Above-ground vegetal biomass (AGB) - trees and downed woods => Carbon	*0.48	Kauffman & Donato (2012)
	Below-ground vegetal biomass (BGB) – roots => Carbon	*0.39	
Rovai et al.(2021)	Above-ground vegetal biomass (AGB)=> Below-ground vegetal biomass (BGB)	*1.14	Santos et al. (2017)
	Above-ground vegetal biomass (AGB) – trees => Carbon	*0.44	Rodrigues et al. (2014)
	Below-ground vegetal biomass (BGB) => Carbon	*0.42	
	Above-ground vegetal biomass (AGB) - litter => Carbon	*0.43	
Santos et al. (2017)	Below-ground vegetal biomass (BGB) => Carbon	*0.408	Khan et al. (2007)
	Above-ground vegetal biomass (AGB) => Carbon	*0.45	Twilley et al. (1992)
Hamilton & Friess (2018)	Above and below-ground vegetal biomass (AGB; BGB) => Carbon	*0.475	Sem referência

Salum et al. (2020)	Above-ground vegetal biomass (AGB)=> Carbon	*0.45	Howard et al.(2014)
Simard et al. (2019)	Above-ground vegetal biomass (AGB)=> Carbon	*0.451	IPCC (Hiraishi et al. 2013)
Kauffman et al. (2018)[a]	Above-ground vegetal biomass (AGB)=> Carbon	*0.48	Kauffman & Donato (2012)
	Below-ground vegetal biomass (BGB) => Carbon	*0.39	
Leite et al.(2021)	Above-ground vegetal biomass (AGB)=> Carbon	*0.48	Howard et al. (2014); Kauffman et al.(2018)
Schaeffer-Novelli et al. (2018)	Above-ground vegetal biomass (AGB)=> Carbon	*0.45	Twilley et al.(1992)
	Below-ground vegetal biomass (BGB) => Carbon	*0.39	Kauffman & Donato (2011); Fourqurean et al. (2014)
Kauffman et al.(2020)	Above-ground vegetal biomass (AGB)=> Carbon	*0.48	Kauffman & Donato (2012)
	Above-ground vegetal biomass (AGB) - downed woods and vegetal debris => Carbon	*0.5	
	Below-ground vegetal biomass (BGB) => Carbon	*0.39	
Portela et al. (2020)	Above and below-ground vegetal biomass (AGB; BGB) => Carbon	*0.5	IPCC (2007)

IV. Depths and interval range for sediment

Table S5- Samples depth and interval range for sediment sampling.

Selected article reference	Sample depth	Interval range
Hatje et al. (2020)	0-100 cm and 100 – 200 cm	
Pérez et al. (2018)	0-50 cm	
Matos et al. (2020)	0-35 cm	
Kauffman et al.(2018)[b]	0-100 cm and >1m (up to 3 m)	
Passos et al. (2016)	0-30 cm (coastal pounds) 0-40 cm (mangroves and hypersaline plain)	10 cm 10 cm
Rovai et al. (2021)	0-100 cm	
Nóbrega et al. (2016)	0-40 cm	10 cm
Simard et al. (2019)	0-100 cm	
Kauffman et al.(2018)[a]	0-100 cm and >1m (after 3m samples were pooled)	15 cm 20 cm 50 cm
Suarez-Abelenda et al. (2014)	0-40 cm	
Nóbrega et al. (2019)	0-40 cm	
Kauffman et al.(2020)	0-100 cm e >100cm (up to 3 m)	

V. Environmental characteristics of studies area

Table S6 – Environmental information of the sampled sites.

Authors	Local	State	Region	Geomorphological aspect	Tidal Range	Climate Koppen	Latitudinal band	U/S	D	S	R/R	NI/I	CU
Virgulino-Júnior et al.2020	Ajuruteua - Bragança	PA	North	Tide and mud dominated	Macrotidal	Am	0 5					ND	
Salum et al. 2020	Guarás Island	PA	North	Tide and mud dominated	Macrotidal	Am	0 5					NI	x
Matos et al. 2020	Marapenin Estuary	PA	North	Tide and mud dominated	Macrotidal	Am	0 5					NI	x
Kauffman et al. 2020		PA/CE	North/Northeast	Tide and mud dominated/Sediment starved coast	Macrotidal/Mesotidal	Am/As	0 5					ND	
Kauffman (a) et al. 2018	Jaguaribe e Acaraú	CE	North/Northeast	Tide and mud dominated/Sediment starved coast	Macrotidal/Mesotidal	Am/As	0 5			x		ND	
Kauffman (b) et al. 2018		PA/CE	North/Northeast	Tide and mud dominated/Sediment starved coast	Macrotidal/Mesotidal	Am/As	0 5					NI/I	
Nobrega et al. 2016	Cocó; Jaguaribe; Timonha	CE	Northeast	Sediment starved coast	Mesotidal	As	0 5	x	x	x		NI/I	
Passos et al. 2016	Cocó; Jaguaribe; Timonha	CE	Northeast	Sediment starved coast	Mesotidal	As	0 5	x	x	x		NI/I	

Suarez-Abelenda et al. 2014	Acaraú; Jaguaribe	CE	Northeast	Sediment starved coast	Mesotidal	As	0 5			x		NI/I	
Nobrega et al. 2019		CE	Northeast	Sediment starved coast	Mesotidal	As	0 5	x	x	x		NI/I	
Ferreira et al. 2019	Jaguaribe river	RN	Northeast	Sediment starved coast	Mesotidal	As	5 10	x	x	x	R/R	NI/I	
Portela et al. 2020	Parnaíba Delta	PI	Northeast	Sediment starved coast	Mesotidal	As	0 5					NI	x
Hatje et al. 2020	Jaguaripe river	BA	Northeast	Sediment starved coast	Mesotidal	Af	10 15					NI	
Da Motta Portillo et al. 2016	Piraquê-Açu - Santa Cruz	ES	Southeast	Dip-fed wave dominated deltas	Microtidal	Aw	15 20					NI	x
Santos et al. 2017	Guaratiba, Sepetiba Bay	RJ	Southeast	Double barrier-lagoon coast	Microtidal	Cfb	20 25					NI	x
Leite et al. 2021	Itaipu lagoon	RJ	Southeast	Double barrier-lagoon coast	Microtidal	Af	20 25	x	x		R/R	I	
Pérez et al. 2018	Guanabara Bay - Mauá mangrove	RJ	Southeast	Double barrier-lagoon coast	Microtidal	Af	20 25	x	x			I	
Rodrigues et al. 2014	Guaratiba	RJ	Southeast	Double barrier-lagoon coast	Microtidal	Cfb	20 25					NI	x
Rovai et	Cananéia-	SP	Southeast	Rock dominated	Microtidal	Cfb	20 25					NI	x

al. 2021	Iguape												
Pavani et al. 2018	Ubatuba, Caraguatatuba, São Sebastião e Ilha Bela	SP	Southeast	Rock dominated	Microtidal	Cfb	20 25					ND	
Schaeffer-Novelli et al.2018	Araçá Bay	SP	Southeast	Rock dominated	Microtidal	Cfb	20 25	x	x			I	
Hamilton e Friess 2018	Brazil - all states												
Simard et al. 2019	Brazil	SP/PA											
Kauffman et al. 2020	Brazil	CE/PA											

U/S = Urbanization and sewage
D = Deforestation
S = Shrimp farming
R/R = Restored/In restoration
NI/I = Non-Impacted/Impacted
CU = Conservation unit
ND= no data

VI. Total Ecosystem Carbon Stock (TECS)

The question about TECS is that some articles considered different compartments to compose their final value. Because of it we presented a table and figures about a possible difference between this approaches, considering region and status data.

Table S7 – TECS values and compartments

		Mean/Median values±DP	**Min-Max**
TECS (1)*	Sum of all the final TECS values found in the 23 articles	443/461±120	145-746
TECS (2)	Sum of the compartments AGB, BGB and sediment	442/475±123	126-729
TECS (3)	Sum of the compartments AGB, BGB, DW and sediment	476/506±121	128-746

*TECS (1) was the values chosen to compose the review article.

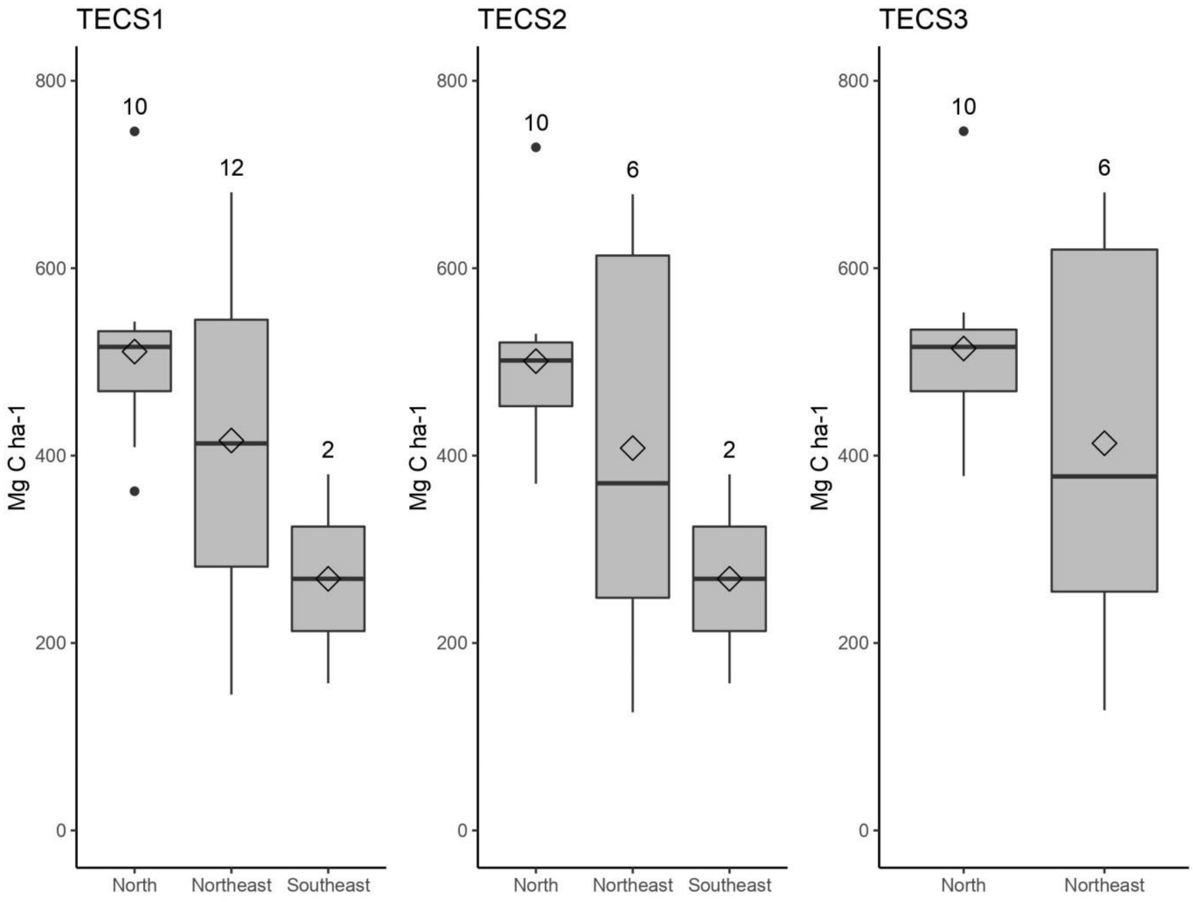


Figure S1 - **Box plot showing the carbon stocks TECS1, TECS2, TECS3 according to the region (North, Northeast, and Southeast) along the Brazilian coast. Box plots represent the first quartile, mean, median and third quartile; whiskers represent the first and third quartile + 1.5 interquartile; open circles are considered outliers. The diamond represent the mean value.**

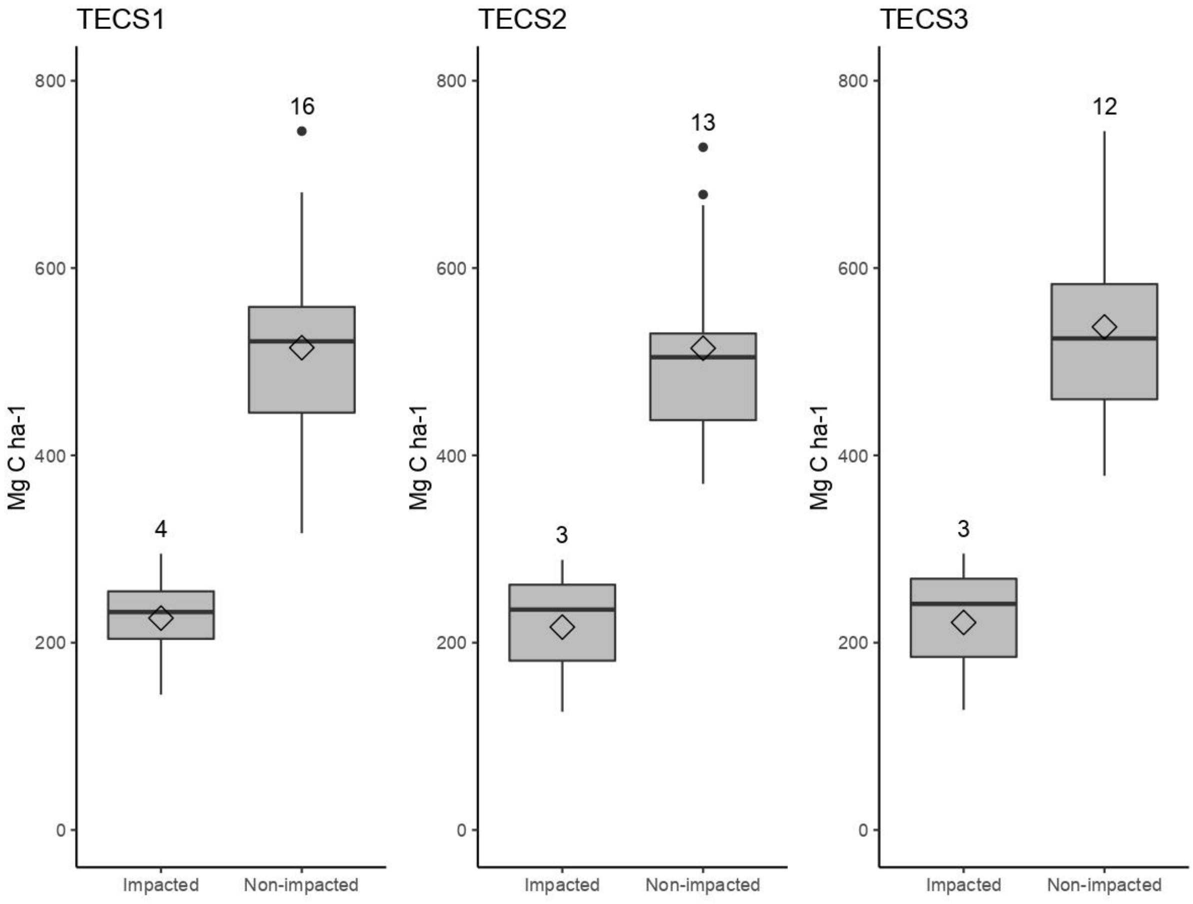


Figure S2 - Boxplot Box plot showing the carbon stocks TECS1, TECS2, TECS3 according to the status (Non-impacted and Impacted) along the Brazilian coast. Box plots represent the first quartile, mean, median and third quartile; whiskers represent the first and third quartile + 1.5 interquartile; open circles are considered outliers. The diamond represent the mean value.

VII. Raw data used in the meta-analysis

Table S8 – Raw data used in the meta-analysis, all carbon stock information (TECS1, TECS2, AGB, DW, BGB, sediment) are presented in MgC ha^{-1}.

	Local	Estado	TECS 1	TECS 2	TECS3	AGB	DW	BGB	Sediment
Virgulino-Júnior et al.2020	Península de Ajuruteua - Bragança C1 SAL>100ppt	PA				1.82		1.4	
Virgulino-Júnior et al.2020	Península de Ajuruteua - Bragança C2 SAL=54ppt	PA				7.45		6.8	
Virgulino-Júnior et al.2020	Península de Ajuruteua - Bragança C3 SAL=49ppt	PA				27.71		27.74	
Virgulino-Júnior et al.2020	Península de Ajuruteua - Bragança/Península total	PA				36.98		35.95	
Salum et al. 2020	Ilha Guarás - Florestas de mangue	PA				110.1			
Matos et al. 2020	Estuário do Rio Marapenin (PA)	PA							38.11
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Boca Grande	PA	522.8	510.8	529.2	155.4	18.4	10.5	344.9
Kauffman et al. 2020	Boca Grande	PA				18.4			
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Caetano	PA	746.2	729	746.2	223.4	17.2	15.6	490
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Caeté	PA	520.7	504.8	520.5	121.8	15.7	11.8	371.2

Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Furo do Chato	PA	361.6	369.5	378.2	145.7	8.7	10.3	213.5
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Furo Grande	PA	457.8	437.6	457.9	96.5	20.3	9.3	331.8
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Mangue Sul	PA	543	530.1	552.8	194.8	22.7	15.1	320.2
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Maruípe	PA	408.9	406.1	408.9	147.6	2.8	11.9	246.6
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Barreto	PA	501.1	496.6	501.2	104.8	4.6	9.6	382.2
Kauffman (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Salino	PA	536.1	524.1	536.2	116.4	12.1	11.1	396.6
Kauffman (b) et al. 2018	Manguezal Amazônico(PA)	PA	511	497.9	511.5	145.2	13.6	11.7	341
Kauffman (b) et al. 2018	Manguezal Caatinga (CE)	CE	413			72			
Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Acaraú - Boca	CE	673	667.1	673	88.9	5.9	9.2	569
Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Acaraú - Mangue Cauassu	CE	680.8	678.5	680.8	64.8	2.3	10.2	603.5
Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Acaraú - Mangue Quatro Bocas	CE	460.5	452.8	460.5	103.4	7.7	10.9	338.5

Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Jaguaribe - Manguinho	CE	295	288.4	295.1	72.6	6.7	15.4	200.4
Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Jaguaribe - Mangue Porto do Céu	CE	144.5	126.2	128.2	46	2	27.4	52.8
Kauffman (a)e (b) et al. 2018/Kauffman et al. 2020 (solo>1m)	Jaguaribe - Rego Escuro	CE	241.4	235.3	241.4	42.2	6.1	12.5	180.6
Kauffman (a) et al. 2018	Acaraú	CE	605			72			347
Kauffman (a) et al. 2018	Jaguaribe	CE	224			72			35
Kauffman (a) et al. 2018	Jaguaribe e Acaraú	CE	413						
Nobrega et al. 2016	Rio Timonha	CE							148
Nobrega et al. 2016	Rio Cocó	CE							83
Nobrega et al. 2016	Rio Jaguaribe	CE							83
Passos et al. 2016	Rio Cocó; Rio Jaguaribe; Rio Timonha (CE)	CE							111
Passos et al. 2016	Rio Cocó; Rio Jaguaribe; Rio Timonha (CE)	CE							77
Suarez-Abelenda et al. 2014	Ceará	CE							42.3
Suarez-Abelenda et al. 2014	Acaraú	CE							75
Suarez-Abelenda et al. 2014	Rio Jaguaribe	CE							33.9
Nobrega et al. 2019	Ceará	CE							82
Nobrega et al. 2019	Ceará	CE							124
Ferreira et al. 2019	Rio Jaguaribe (2011)	RN				26.59			
Ferreira et al. 2019	Rio Jaguaribe (2016)	RN				42.28			
Ferreira et al. 2019	Rio Jaguaribe	RN				8			
Ferreira et al. 2019	Rio Jaguaribe	RN				22.39			

Ferreira et al. 2019	Rio Jaguaribe	RN				43.68			
Portela et al. 2020	Delta do Rio Parnaíba	PI				258.34			
Hatje et al. 2020	Jaguaripe (1m)	BA	316.86			53.86			263
Hatje et al. 2020	Jaguaripe (2m)	BA	524.71			57.71			467
Rovai et al. 2021**	Sistema Estuarino Lagoa Cananéia-Iguape	SP	380	380		52.7		57.3	270
Rovai et al. 2021**	Sistema Estuarino Lagoa Cananéia-Iguape	SP				75.31		81.95	
Rovai et al. 2021**	Sistema Estuarino Lagoa Cananéia-Iguape	SP				30.17		32.83	
Pavani et al. 2018**	Ubatuba, Caraguatatuba, São Sebastião e Ilha Bela (SP)	SP	157.36	157.36		76.09		22.07	59.2
Schaeffer-Novelli et al.2018	Baía de Araçá	SP				14.6		7.1	
Santos et al. 2017	Rio Piracão, Reserva Biológica Estadual de Guaratiba, Baía de Sepetiba (RJ)	RJ						104.41	
Leite et al. 2021	Lagoa de Itaipu	RJ				41.4		1.6	
Leite et al. 2021	Lagoa de Itaipu	RJ				17.2		1.1	
Pérez et al. 2018	Baía da Guanabara - Mangue Mauá (RJ)	RJ							23.21
Pérez et al. 2018	Baía da Guanabara - Mangue Mauá (RJ)	RJ							19.89
Rodrigues et al. 2014	Guaratiba	RJ				101.9			
Da Motta Portillo et al. 2016	Rio Piraquê-Açu, Santa Cruz	ES				1.46			
Hamilton e Friess 2018**	Brasil (todos estados)		507.83	507.71		99.53		49.66	358.52
Simard et al. 2018	Brasil (PA e SP)		345	345.14		41.71		20.43	283

Kauffman et al. 2020	Brasil, todos os locais -PA e CE (solo até 1m ou solo<1m)	473			105.82	19.34		155

VII. Supplementary Material Bibliography

DA MOTTA PORTILLO, J. T.; LONDE, V.; MOREIRA, F. W. A. Aboveground biomass and carbon stock are related with soil humidity in a mangrove at the Piraquê-Açu River, Southeastern Brazil. **Journal of Coastal Conservation**, 21, n. 1, p. 139-144, 2017.

FERREIRA, A. C., BEZERRA, L. E. A., & MATTHEWS-CASCON, H. (2019). Aboveground carbon stock in a restored neotropical mangrove: influence of management and brachyuran crab assemblage. **Wetlands Ecology and Management**. doi:10.1007/s11273-019-09654-7

FERREIRA, T. O., OTERO, X. L., DE SOUZA JUNIOR, V. S., VIDAL-TORRADO, P., MACÍAS, F., & FIRME, L. P. (2010). Spatial patterns of soil attributes and components in a mangrove system in Southeast Brazil (São Paulo). **Journal of Soils and Sediments**, 10(6), 995–1006. doi:10.1007/s11368-010-0224-4

GARCIA, M. R., PHILP, R. P., & MARTINS, C. C. (2020). Biogenic and thermogenic terpenoid hydrocarbons as potential geochemical tools for the study of sedimentary organic matter in subtropical mangrove swamps. **Applied Geochemistry**, 104726. doi:10.1016/j.apgeochem.2020.104726

HAMILTON, S. E., & FRIESS, D. A. (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. **Nature Climate Change**, 8(3), 240–244. doi:10.1038/s41558-018-0090-4

HATJE, V., DE SOUZA, M. M., RIBEIRO, L. F., EÇA, G. F., & BARROS, F. (2016). Detection of environmental impacts of shrimp farming through multiple lines of evidence. **Environmental Pollution**, 219, 672–684. doi:10.1016/j.envpol.2016.06.056

HATJE, V., MASQUÉ, P., PATIRE, V. F., DÓREA, A., & BARROS, F. (2020). Blue carbon stocks, accumulation rates, and associated spatial variability in Brazilian mangroves. **Limnology and Oceanography**, 66(2), 321–334. doi:10.1002/lno.11607

KAUFFMAN, J. B., ADAME, M. F., ARIFANTI, V. B., SCHILE-BEERS, L. M., BERNARDINO, A. F., BHOMIA, R. K., … HERNÁNDEZ TREJO, H. (2020). Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. **Ecological Monographs**, 90(2). doi:10.1002/ecm.1405

KAUFFMAN, J. B., BERNARDINO, A. F., FERREIRA, T. O., BOLTON, N. W., GOMES, L. E. DE O., & NOBREGA, G. N. (2018a). Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. **Ecology and Evolution**, 8(11), 5530–5540. doi:10.1002/ece3.4079

KAUFFMAN, J. B., BERNARDINO, A.F., FERREIRA, T.O., GIOVANNONI, L.R., GOMES, L.E.O., ROMERO, D.J., JIMENEZ, L.C. & RUIZ, F.. (2018b). Carbon Stocks of Mangroves and Salt Marshes of the Amazon Region, Brazil. **Biology Letters**, 14, no. 9 (2018): 20180208. https://doi.org/10.1098/rsbl.2018.0208

LEITE, R. A., NÓBREGA, G. N., LEAL, L. R. Z. C., KIEFER, M. C., & SOARES-GOMES, A. (2021). The colonization of a coastal lagoon by a mangrove ecosystem: Benefit or threat to the lagoon? **Aquatic Botany**, 171, 103362. doi:10.1016/j.aquabot.2021.103362

MATOS, C. R. L., BERRÊDO, J. F., MACHADO, W., SANDERS, C. J., METZGER, E., & COHEN, M. C. L. (2020). Carbon and nutrients accumulation in tropical mangrove creeks, Amazon region. **Marine Geology**, 429, 2020. doi:10.1016/j.margeo.2020.106317

NÓBREGA, G. N., FERREIRA, T. O., ARTUR, A. G., DE MENDONÇA, E. S., DE O. LEÃO, R. A., TEIXEIRA, A. S., & OTERO, X. L. (2014). Evaluation of methods for quantifying organic carbon in mangrove soils from semi-arid region. **Journal of Soils and Sediments**, 15(2), 282–291. doi:10.1007/s11368-014-1019-9

NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., MENDONÇA, E. DE S., ROMERO, R. E., & OTERO, X. L. (2019). The importance of blue carbon soil stocks in tropical semiarid mangroves: a case study in Northeastern Brazil. **Environmental Earth Sciences**, 78(12). doi:10.1007/s12665-019-8368-z

NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., QUEIROZ, H. M., ARTUR, A. G., MENDONÇA, E. D. S., … OTERO, X. L. (2016). Edaphic factors controlling summer (rainy season) greenhouse gas emissions (CO2 and CH4) from semiarid mangrove soils (NE-Brazil). **Science of The Total Environment**, 542, 685–693. doi:10.1016/j.scitotenv.2015.10.108

PASSOS, T. R. G., ARTUR, A. G., NÓBREGA, G. N., OTERO, X. L., & FERREIRA, T. O. (2016). Comparison of the quantitative determination of soil organic carbon in coastal wetlands containing reduced forms of Fe and S. **Geo-Marine Letters**, 36(3), 223–233. doi:10.1007/s00367-016-0437-7.

PASSOS, T., PENNY, D., SANDERS, C., DE FRANÇA, E., OLIVEIRA, T., SANTOS, L., & BARCELLOS, R. (2021). Mangrove carbon and nutrient accumulation shifts driven by rapid development in a tropical estuarine system, northeast Brazil. **Marine Pollution Bulletin**, 166, doi:10.1016/j.marpolbul.2021.112219

PAVANI, B. F., SOUSA JÚNIOR, W. C., INOUYE, C. E. N., VIEIRA, S. A., & MELLO, A. Y. I. (2018). Estimating and valuing the carbon release in scenarios of land-use and climate changes in a Brazilian coastal area. **Journal of Environmental Management**, 226, 416–427. doi:10.1016/j.jenvman.2018.08.059

PEREIRA, T. M., NÓBREGA, G. N., FERREIRA, T. O., OGAWA, C. Y., DE CAMARGO, P. B., FEITOSA SILVA, J. R., & REZENDE, C. F. (2019). Does food partitioning vary in leaf-eating crabs in response to source quality? **Marine Environmental Research.** doi:10.1016/j.marenvres.2018.12.005

PÉREZ, A., MACHADO W. , GUTIÉRREZ D., BORGES A.C., PATCHINEELAM S.R. & SANDERS, C.J.. (2018). Carbon Accumulation and Storage Capacity in Mangrove Sediments Three Decades after Deforestation within a Eutrophic Bay.” **Marine Pollution Bulletin,** 126: 275–80. https://doi.org/10.1016/j.marpolbul.2017.11.018

PORTELA, M. G., ESPINDOLA G. M., VALLADARES G. S., AMORIM J.V. & FROTA, J.C.. (2020). Vegetation Biomass and Carbon Stocks in the Parnaíba River Delta, Ne Brazil. **Wetlands Ecology and Management**, 28 (4): 607–22. https://doi.org/10.1007/s11273-020-09735-y

QUEIROZ, H. M., ARTUR, A. G., KENJI TANIGUCHI, C. A., SOUZA DA SILVEIRA, M. R., COSTA DO NASCIMENTO, J., NÓBREGA, G. N., … FERREIRA, T. O. (2019). Hidden contribution of shrimp farming effluents to greenhouse gas emissions from mangrove soils. **Estuarine, Coastal and Shelf Science**. doi:10.1016/j.ecss.2019.03.011

QUEIROZ, H. M., FERREIRA, T. O., TANIGUCHI, C. A. K., BARCELLOS, D., DO NASCIMENTO, J. C., NÓBREGA, G. N., … ARTUR, A. G. (2020). Nitrogen mineralization and eutrophication risks in mangroves receiving shrimp farming effluents. **Environmental Science and Pollution Research**. doi:10.1007/s11356-020-09720-1

QUEIROZ, H. M., NÓBREGA, G.N., OTERO, X.L. & FERREIRA, T.O..(2018). Are Acid Volatile Sulfides (AVS) Important Trace Metals Sinks in Semi-Arid Mangroves? **Marine Pollution Bulletin,** 126: 318–22. https://doi.org/10.1016/j.marpolbul.2017.11.020

RODRIGUES, D. P., HAMACHER, C., ESTRADA, G. C. D., & SOARES, M. L. G. (2014). Variability of carbon content in mangrove species: Effect of species, compartments and tidal frequency. **Aquatic Botany**, 120, 346–351. doi:10.1016/j.aquabot.2014.10.004

ROVAI, A. S., COELHO-JR, C., DE ALMEIDA, R., CUNHA-LIGNON, M., MENGHINI, R. P., TWILLEY, R. R., … SCHAEFFER-NOVELLI, Y. (2021). Ecosystem-level carbon stocks and sequestration rates in mangroves in the Cananéia-Iguape lagoon estuarine system, southeastern Brazil. **Forest Ecology and Management**, 479, 118553. doi:10.1016/j.foreco.2020.118553

ROVAI, A. S., TWILLEY, R. R., CASTAÑEDA-MOYA, E., RIUL, P., CIFUENTES-JARA, M., MANROW-VILLALOBOS, M., … PAGLIOSA, P. R. (2018). Global controls on carbon storage in mangrove soils. **Nature Climate Change**, 8(6), 534–538. doi:10.1038/s41558-018-0162-5

SALUM, R. B., SOUZA-FILHO, P. W. M., SIMARD, M., SILVA, C. A., FERNANDES, M. E. B., COUGO, M. F., … ROGERS, K. (2020). Improving mangrove above-ground biomass estimates using LiDAR. **Estuarine, Coastal and Shelf Science**, 106585. doi:10.1016/j.ecss.2020.106585

SANTOS, D. M. C., ESTRADA, G. C. D., FERNANDEZ, V., ESTEVAM, M. R. M., SOUZA, B. T. D., & SOARES, M. L. G. (2017). First Assessment of Carbon Stock in the

Belowground Biomass of Brazilian Mangroves. **Anais Da Academia Brasileira de Ciências**, 89(3), 1579–1589. doi:10.1590/0001-3765201720160496

SCHAEFFER-NOVELLI, Y., CINTRÓN-MOLERO, G., REIS-NETO, A. S., ABUCHAHLA, G. M. O., NETA, L. C. P., & LIRA-MEDEIROS, C. F. (2018). The mangroves of Araçá Bay through time: An interdisciplinary approach for conservation of spatial diversity at large scale. Ocean & Coastal Management. doi:10.1016/j.ocecoaman.2017.12.024

SIMARD, M., FATOYINBO, L., SMETANKA, C., RIVERA-MONROY, V. H., CASTAÑEDA-MOYA, E., THOMAS, N., & VAN DER STOCKEN, T. (2019). Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. **Nature Geoscience**, 12(1), 40–45. doi:10.1038/s41561-018-0279-1

SUÁREZ-ABELENDA, M., FERREIRA, T. O., CAMPS-ARBESTAIN, M., RIVERA-MONROY, V. H., MACÍAS, F., NÓBREGA, G. N., & OTERO, X. L. (2014). The effect of nutrient-rich effluents from shrimp farming on mangrove soil carbon storage and geochemistry under semi-arid climate conditions in northern Brazil. **Geoderma**, 213, 551–559. doi:10.1016/j.geoderma.2013.08.007.

VIRGULINO-JÚNIOR, P. C. C., CARNEIRO, D. N., NASCIMENTO, W. R., COUGO, M. F., & FERNANDES, M. E. B. (2020). Biomass and carbon estimation for scrub mangrove forests and examination of their allometric associated uncertainties. **PLOS ONE**, 15(3), e0230008. doi:10.1371/journal.pone.0230008