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Forest Science and Technology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tfst20

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To cite this article: Citra Gilang Qur'ani, Bora Lee, Sigit D. Sasmito, Agus Muhamad Maulana, Mihyun Seol, Putu Angga Wiradana, Budi Leksono, Ni Luh Watiniasih & Himlal Baral (2024) Natural and anthropogenic impacts on mangrove carbon dynamics: a systematic review protocol, Forest Science and Technology, 20:1, 1-7, DOI: 10.1080/21580103.2023.2272705

To link to this article: https://doi.org/10.1080/21580103.2023.2272705

Published online: 15 Nov 2023.

FOREST SCIENCE AND TECHNOLOGY
E-ISSN 2158-0715, 2024, VOL. 20, NO. 1, 1–7
https://doi.org/10.1080/21580103.2023.2272705

RAPID COMMUNICATION

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Natural and anthropogenic impacts on mangrove carbon dynamics: a systematic review protocol

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ABSTRACT

The mangrove ecosystem serves as a vital habitat for coastal flora and fauna while playing a crucial role in storing and sequestering carbon as part of global carbon cycles. Therefore, it is imperative to evaluate the carbon dynamics, encompassing storage and sequestration, within mangrove ecosystems and their interconnectedness with natural climate fluctuations and anthropogenic influences, including land-use and land-cover changes (LULCC). Although there has been an increase in monitoring data and literature on mangrove carbon dynamics over the past two decades, there is still limited understanding regarding how climate variability, when combined with anthropogenic drivers, moderates the resilience of carbon storage and sequestration in mangroves. This study aims to build upon and enhance the previous systematic review conducted by Sasmito et al. (2019). Our specific objectives involve collating more recent literature published since 2018 and strengthening the analysis of carbon loss and recovery in tree biomass across different species, as well as its correlation with local and regional climate variations. Additionally, we will explore the impact of various types of land-use and land-cover changes on mangrove forests. Our systematic review will focus on field-based data collected from the Asia Pacific mangrove region, which represents the world's largest and most diverse mangrove ecosystem and has been extensively studied in comparison to other regions, as indicated by previous systematic reviews. To gather relevant literature, we will conduct comprehensive searches across various databases, including Scopus, Web of Science, and Google Scholar. The structure established by Sasmito et al. (2019) for literature search, screening, and data extraction will be adopted. Data analysis will involve comparing carbon storage and sequestration under locally and regionally varying climatic conditions and anthropogenic influences. Furthermore, we will employ geographical mapping techniques to visualize species distribution and diversity within the Asia Pacific region, while also estimating carbon storage and recovery capacities.

ARTICLE HISTORY
Received 20 July 2023
Revised 10 November 2023
Accepted 13 October 2023

KEYWORDS
Species distribution; species diversity; carbon dynamic; land-use change; land-cover change; blue carbon

1. Background

Mangrove ecosystems across the globe provide various ecological functions and services. These coastal wetlands are among the most efficient natural carbon (C) sinks on Earth and are as highly productive as tropical forests and coastal wetlands (Alongi 2014). Mangroves, along with seagrass meadow and tidal marshes, contribute to significant long-term carbon storage (Donato et al. 2011; McLeod et al. 2011). However, instead of being long-term carbon-stock storage, mangrove can become a significant source of C emissions if they are degraded with particularly due to land-use and land-cover change and subsequently add to global atmospheric greenhouse-gas concentrations. Assessing and quantifying the amount of C stored in mangrove ecosystems, and in blue-carbon (blue C) ecosystems in general, is therefore fundamental in the context of climate change and for developing sustainable mitigation plans.

Mangrove forests across the world have been decreasing in area, with total loss of 0.13% between 2000 and 2016, an average annual rate equal to 3363 km^2. In Southeast Asia alone, the vast majority (80%; 2068 km^2) lost between 2000 and 2016 was due to anthropogenic activities, particularly, conversion to

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aquaculture and agriculture (Goldberg et al. 2020). In Indonesia, mangrove cover declined by 430,000 ha between 1985 to 2019 (12,647 ha yr^{-1}) owing to conversion to oil-palm plantations, agriculture and aquaculture and development of oil and gas and urban areas (MoEF Indonesia 2019). Conversion through multi-purpose land-use/-cover change was reported as the main cause of mangrove deforestation in Asia (FAO 2007; Richards and Friess 2016), gradually decreasing the ecosystems' ecological functions and services (Sannigrahi et al. 2020), with specifically contributing to substantial carbon emissions.

Land-use and land-cover change (LULCC) in mangroves directly impacts on the stability of C dynamics, including stocks, emissions, and sequestrations (Sasmito et al. 2019). LULCC disrupts the national coastal C cycle regulation provided by mangrove in tropical and sub-tropical regions, transforming them from carbon sink to carbon sources. Carbon emissions from mangrove loss could reach 2,391 teragrams (Tg) $CO_{2\ eq}$ by 2100 under the highest emissions scenario predicted for Southeast and South Asia (West Coral Triangle, Sunda Shelf, and the Bay of Bengal) due to conversion to aquaculture or agriculture, followed by the Caribbean and north Brazil owing to clearing and erosion (Adame et al. 2021). LULCC of mangroves has substantially reduced carbon stocks in biomass (82%±35%) and soil (54%±13%), with relative loss dependent on LULCC types (Sasmito et al. 2019). In Indonesia, world's largest mangrove country, mangrove deforestation and conversion has led to significant annual C loss to the atmosphere, ranging 0.96 petagrams (Pg) $CO_2e\ yr^{-1}$ through to 0.19 Pg $CO_2e\ yr^{-1}$ (Arifanti et al. 2019), as well as decreased C sequestration.

The loss of mangrove areas significantly impacts regional and global coastal C budget, due to the decrease of C sequestration rates but increase in emissions. Global mangrove C sequestration is estimated to be 14.2 TgC yr^{-1} (Alongi 2018) and sediment C stock is 72–936 Mg ha^{-1}, with large variation between individual observations (Ouyang and Lee 2020). In tropical northeast monsoon mangroves, *Rhizopora* spp., one of the most dominant species, has higher C absorption ability than *Bruguiera* spp. of the same age (Dewiyanti and Agustina 2019). Other studies reported that *Rhizopora* spp. stored high C stocks owing to high C uptake ability in this species compared to *Osbornia octodonta, Sonneratia alba, Ceriops tagal* and *Avicennia marina* in tropical northwest monsoon areas (Putra and Dewi 2019). By contrast, *Kandelia obovata* had the highest C density (148.03 Mg ha^{-1}), followed by *Avicennia marina* (104.79 Mg ha^{-1}) and *Aegiceras corniculatum* (99.24 Mg ha^{-1}) in another tropical monsoon climate (Bin et al. 2022). Further understanding and assessment of mangroves species' ability to absorb and store C in different climate zones is essential for an effective approach to mangroves species-specific rehabilitation programmes and mitigation of further ecosystem loss, by applying suitable species.

Mangrove ecosystems, consisting of approximately 70 tree species from 20 families in tropical and subtropical regions (Polidoro et al. 2010), play a crucial role in climate change mitigation by sequestering large amounts of carbon in tropical and subtropical regions (Donato et al. 2011; Alongi 2012; 2014; Tomlinson 2016). The spatial range of coastal blue carbon is influenced by the distribution and diversity of mangrove species, which determine carbon stock distribution (Radabaugh et al. 2018; Eid et al. 2020). Numerous studies have investigated the relationship between species distribution and carbon stocks in various mangrove forests, such as in Indonesia (Kusumaningtyas et al. 2019; Analuddin et al. 2020; Pricillia et al. 2021). The existence of dominant species, such as *Rhizophora* spp. and *Avicennia* spp., in multispecies' systems has been shown to increase sequestration approximately 200 MgC ha^{-1} greater than monospecies' plantations (Purwanto et al. 2022; Wirabuana et al. 2021). Multispecies' systems generally provide greater variety and higher levels of environmental services, such as conserving biodiversity and storing C. An assessment, however, is still lacking of species' distribution and their capacity to sequester and store C in natural and restored mangrove ecosystems with interconnections to ecosystem services (ES). Detailed information through spatial mapping of distribution provides essential knowledge for supporting mangrove rehabilitation programmes.

Sasmito et al. (2019) systematically reviewed the impacts of LULCC on C stocks and soil greenhouse-gas (GHG) effluxes from mangroves on a global scale. This study was however using literature dataset published up to December 2018 and therefore outdates, while the number of studies reporting mangrove carbon monitoring and assessment have been increased over the past five years. This review aims to build upon and extend the findings of Sasmito et al. (2019) by updating and strengthening analysis of tree carbon loss and recovery. We will examine species, local and regional climate variability, and different types of land-use and land-cover change drivers, particularly within Asia Pacific region, where the largest area and most diverse mangrove ecosystems are located. Furthermore, we will assess the distribution and diversity of mangrove species in different climate zones to inform effective species-specific rehabilitation programs and mitigation strategies.

The current review will provide a concise synthesis for policy makers associated with land-use planning in the coastal wetland areas and strengthening the current understanding of the crucial roles of mangrove as the highest blue C reservoir in the Asia Pacific region. Indonesia and other Asian countries are premier sites of mangrove ecosystems and research. For example, Indonesia is currently being supported by developed countries including UEA, Republic of Korea, and Japan to maintain continuity of its contribution to conserving and restoring mangrove forests and increasing C sinks. Emission reduction will come from improved management of land use, land-use change and forestry, in which blue C ecosystems play important roles. By offering an update and more detained perspective on mangrove ecosystems, this review will contribute to the development of sustainable mitigation plans and informed decisions for the conservation and restoration of these vital ecosystems.

2. Objectives of the review

The aim of this review is to systematically investigate and synthesize existing knowledge on the interaction between local and regional climate characteristics and their impact on the carbon storage and uptake capacities of mangrove species in the Asia and Pacific regions. By aligning these findings with current knowledge on habitat degradation, species diversity, and carbon dynamics, the review seeks to offer a perspective on the functioning and future sustainability of mangrove ecosystems as the climate changes.

2.1. Primary and secondary questions

The primary question of the review is:

- How do local and regional climate characteristics affect mangrove species carbon storage and uptake that align closely with the concept of carbon sequestration?

The secondary questions of the review are:

- What are the available data and pattern on mangrove carbon dynamics, biophysical factors and parameters, biomass allometry, species diversity and climate characteristics between mangrove regions?
- How does climate influence the diversity, carbon dynamics, biomass allometry and biophysical characteristics of the species?
- How does habitat degradation following land-use change and restoration affect the diversity of mangrove species and the deliverables of carbon dynamics?
- To what extent can mangrove restoration programmes recover the diversity of mangrove species and carbon sequestration benefits?

3. Methods

3.1. Authorial workshops

The authorial team will conduct two 1-day workshops to discuss the review's scope, key questions and critical appraisal and data extraction methods. The workshop was held alongside a mangrove conference at Udayana University, Bali on March 27th 2023 to enable side meetings with experts and potential advisors of the review (Table 1).

3.2. Scope and search strategy

The scope and search strategy for the current review will be based on the previous review protocol on the similar topic by Sasmito et al. (2019), with some improvements will be carried out particularly we will focus on the literature published from 2019 onwards from within Asia pacific region. The literature search will aim to find relevant documentation of C dynamics of mangrove species, including C stocks, fluxes and sequestration, species diversity, biophysical parameters (e.g. forest structure, soil properties, habitat setting), climate parameters (e.g. air temperature, tide condition, precipitation), and types of land-use and land-cover change.

Our search strategy will combine assessment of (i) the C storage and sequestration in different climate zones of mangrove species; (ii) C stocks and fluxes in pristine, natural or low-impacted mangrove systems and LULCC impacted sites; and (iii) species diversity and distribution in natural and restoration systems. We will use global mangrove species distribution map by Polidoro et al. (2010) (see Figure 1) as guidelines for species distribution analyses in the current systematic review.

3.2.1. Languages

A scoping study will first identify where there is a significant number of published studies in languages other than English. Based on initial research, we will examine the following languages in the literature search.

- Primary: English.
- Secondary: Indonesian/Malaysian.

3.2.2. Search terms

3.3. Search sources

3.3.1. Bibliographic databases

We will search the following bibliographic databases.

- Web of Science.
- Scopus.
- Google scholar.

All search results (along with abstracts when possible) will be stored in an online Endnote library for screening (Table 2).

3.3.2. Internet searches

We will use the following Internet search engines to ensure studies are not missed. These searches will use an abbreviated search string from the table above. The first 100 found items will be included in the screening process.

- Google Scholar.
- Mendeley Library.
- ResearchGate.

Table 1. Summary of terminologies used in the study.

Variables	Description/Definition	Reference
Carbon dynamic	Describing the spatial and temporal becoming/behaviour of mangrove produced/derived carbon (through primary production), in its organic, inorganic, particulate, dissolved and gas forms.	(Bouillon et al., 2008)
Carbon stock/storage	Describing the spatial and temporal becoming/behaviour of mangrove produced/derived carbon (through primary production), in its organic, inorganic, particulate, dissolved and gas forms.	(Bouillon et al., 2008)
Carbon pools	Carbon reservoirs, such as: • Aboveground pools (tree biomass, dead downed wood, litter and understorey) • Belowground pools (root biomass, organic soil)	(IPCC, 2000; Kauffman & Donato, 2012)
Tree biomass	Mangrove trees, reliable assessment based on the standardized protocol	(Komiyama et al., 2008) (Kauffman & Donato, 2012)
Dead downed wood	All dead and felled biomass above forest floor	(IPCC, 2000; Kauffman & Donato, 2012)
Root biomass	Belowground roots, pneumatophores and prop roots	(Komiyama et al., 2008) (Kauffman & Donato, 2012)
Organic soil	Carbon stored in belowground organic matter	(Howard et al., 2014)
Carbon fluxes	Transfer/exchange of carbon between different pools: • Lateral flux (towards adjacent environments, towards the hydrosphere) • Vertical flux (towards the geosphere, the atmosphere)	(Bouillon et al., 2008)
Net Primary Production	Net organic matter production by plants in an ecosystem	(IPCC, 2000)
Litterfall	Litterfall as a proxy for net primary production (accounting for one third of total NPP), clear latitudinal zonation with higher rate between 0° and 10°	(Bouillon et al., 2008)
Carbon emission	CO_2 efflux from creek waters during release of dissolved CO_2 in oversaturated water	(Bouillon et al., 2008) (Borges et al., 2003)
Mineralization	CO_2 efflux from sediment during mineralization of mangrove-derived organic matter	(Bouillon et al., 2008) (Borges et al., 2003)
Carbon export	Tidal export, tidal pumping, subsurface groundwater discharge, outwelling theory, lateral exchange	(Lee, 1995)
Carbon burial	The actual amount of mangrove-derived carbon sequestered in the soil. Usually defined as organic carbon accretion rates per hectare per unit of time	(Twilley et al., 1992; Jennerjahn et al., 2004; Breithaupt et al., 2012)
Land use	The type of activity being carried out on a unit of land	(IPCC, 2003)
Land cover	The types of vegetation covering the Earth's surface	(IPCC, 2003)
Deforestation	The conversion of forested land to non-forested land by direct anthropogenic activities	(IPCC, 2003)
Degradation	The loss of forest values from forest-cover reduction owing anthropogenic activities	(IPCC, 2003)
Rehabilitation	Ecosystem recovery processes, which may involve non-native species	(Chazdon et al., 2016)
Restoration	Ecosystem recovery processes that involve native species' composition and historic ecological integrity	(Chazdon et al., 2016)
Biomass	Amount of living material contained in trees expressed in tonnes of dry weight per unit area	(Brown, 1984)
Carbon content/absorption ability	How much CO_2 a plant binds from the air	(IPCC, 2021)
Ecosystem service	Benefit that an ecosystem provides to humans	(MEA, 2005)
Species' distribution/dispersion	The manner in which a biological taxon is spatially arranged, caused by biotic or abiotic factors	(Turner, 2006)
Species' diversity	Variety, and relative abundance, of species present in an ecosystem	(Bitantos et al., 2017)
Aboveground biomass	defined as the dry weight of the live or dead woody component of aboveground vegetation	(Duncanson et al., 2021)

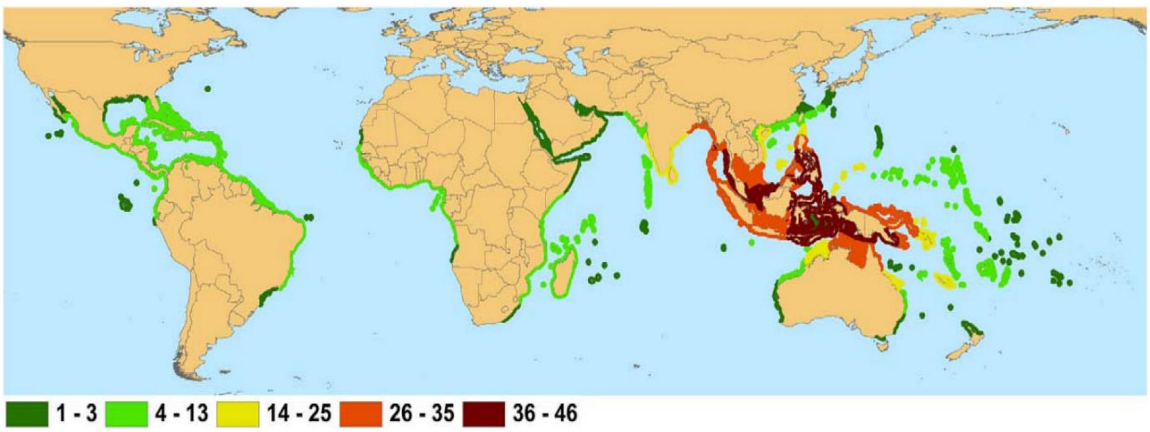

Figure 1. The native distribution of mangrove species richness across the globe. The introduced ranges are not shown in color: *Rhizophora stylosa* in French Polynesia, *Bruguiera sexangular, Conocarpus erectus*, and *Rhizophora mangle* in Hawaii, *Sonneratia apelata* in China, and *Nypa fruticans* in Cameroon and Nigeria (Source Polidoro et al. 2010).

Table 2. Search strings to be used with main bibliographic databases.

Category	Search term
Subject	mangrove* OR "coast* ecosystem*" OR Rhizophora OR Avicennia OR "coast* wetland*" OR "Intertidal wetland*" OR "tidal wetland*" OR "estuarine wetland"
Outcome	carbon OR biomass OR dynamic* OR flux* OR emission* OR stock* OR storage* OR NPP OR respiration OR litterfall OR NEP OR GPP OR efflux OR sequest* OR absorption
Geographical focus	tropic* OR subtropic* OR China OR Japan OR Mongolia OR NorthKorea OR SouthKorea OR Bangladesh OR Bhutan OR India OR Maldives OR Nepal OR Pakistan OR Sri Lanka OR Brunei OR Cambodia OR Indonesia OR Laos OR Malaysia OR Myanmar OR Philippines OR Singapore OR Thailand OR TimorLeste OR Vietnam OR Australia OR NewZealand OR Fiji OR PapuaNewGuinea OR Solomonisland OR Polynesia OR Micronesia OR Melanesia
Mangrove species	Species OR Rhizophora OR Rhizophora* OR R.* OR Avicennia OR A.* OR Bruguiera OR B.* OR Xylocarpus OR x.* OR Ceriops OR C.* OR Lumnitzera OR L.* OR Sonneratia OR S.* OR Nypa OR N.* OR Aegiceras OR Osbornia OR O.* OR Heritiera OR H.* OR Excoecaria OR E.*
Intervention	agricultur* OR aquacultur* OR "land use*" OR "oil palm" OR "shrimp farm*" OR "shrimp pond*" OR "rice cultivation" OR "rice farm*" OR "rice production" OR "rice field*" OR "rice area*" OR "fish farm*" OR "fish pond*" OR mining OR degrad* OR disturb* OR "land cover*" OR "urban development" OR deforest* OR conversion OR rehabilit* OR restor* OR pollut* OR erosion OR waste* OR sewage

Table 3. The populations, interventions, comparators, and outcomes.

Relevant populations	Intervention	Comparator	Outcome
Mangrove ecosystems in Asia Pacific regions; including species clusters such as mangrove palm (*Nypa fruticans*) and mangrove associates.	Any types of anthropogenic drives including land-use and land-cover changes and restoration impacting mangrove areas, such as: • Aquaculture • Oil palm • Agriculture • Urban development • Deforestation • Rehabilitation or restoration • Coastal disturbance (storm events, shoreline erosion, climate change impacts) • Organic and inorganic pollution	• Undisturbed or natural mangroves used as 'controlled' comparator plots that were established and analyzed at the same time, or before and after comparisons of the same areas or plots • Natural mangroves used as 'controlled' comparator plots with other types, such as degraded-drivers and restoration-approach that were established and analyzed at the same time, or before and after comparisons of the same areas or plots	• Any measured change in above- and belowground carbon stocks, fluxes, and biomass allometry of natural and impacted mangroves • Any measured carbon sequestration ability, fluxes, sequestration and stocks in different climate zones and habitat characteristics • Mapping of the distribution and diversity range of mangrove species to latitude, history, and topography shifts • Climatic variables between mangrove sites in Asia Pacific region

4. Study inclusion process and criteria

After duplicates are removed, all studies will undergo a three-stage screening process by title, abstract and full text by at least two reviewers. Study relevance will be determined using the inclusion criteria presented in Table 3. Studies will have to meet relevant subject, intervention, comparator, and outcome criteria. The title screening process will exclude obviously irrelevant studies not related to mangroves; the abstract and full text screening processes will apply the criteria and study designs as explained below. Before abstract screening, reviewers will use a Kappa test (McHugh 2012) to compare agreement in applying the inclusion criteria to the same 100 articles. A Kappa score of >0.6, denoting acceptable agreement, will have to be reached before screening continues. If reviewers disagree about an article's inclusion, further discussion will be held, with any necessary modifications to the inclusion criteria noted.

The types of study design that will be included in the review will focus on primary studies that examine quantitative changes of C dynamics in mangroves within Asia Pacific regions. Excluded study designs will include:

- Pot or greenhouse studies;
- Nutrient enrichment studies;
- Regional climatic set-up studies;
- Seedling or sapling studies;
- Modeling studies based on secondary data; and
- Qualitative studies that had no primary C measurements.

5. Critical appraisal of studies

All included articles after full text screening will be critically appraised for internal and external validity of their study designs. At least two reviewers will use questions to assess a timescale, replication, spatial variability, and the level of methodological detail of the study that is documented.

6. Data extraction strategy

Data will be extracted by at least two reviewers into Excel spreadsheets according to the below categories. Care will be taken to avoid replication. After all data is extracted, a third reviewer will randomly check 20% of studies to ensure consistent data recording. Literature metadata, all individual reported data and their standard deviation will be extracted following previous database developed by Sasmito et al. (2019), as follows:

- Bibliographic information: title, author, publisher, date of publication.
- Study and site(s) information: geographical location of the study (latitude, longitude, country), date of data collection/field work; climatic variables (annual

temperature and precipitation); site hydrogeomorphic settings and tidal range (fringe, transition, interior, oceanic, estuarine, riverine); mangroves species; size of plot/area studied.

- Methodology: study design, duration, type of measurements and analysis, number of replicates.
- Details of intervention: details of land-use and land-cover types; land-use shift, if any (date and activity); temporal and spatial scales; summary of the surrounding activities (aquaculture, fishing, agriculture, tourism, urban area etc) and their respective distance to mangroves.
- Confounding factors: soil/sediment variables (temperature, pH, salinity, organic soil depth, bulk density, carbon content (%C), organic carbon density (%OC), nitrogen content (%N), C/N ratio, redox, ^{13}C, ^{15}N); description of C pools (tree, dead downed wood, root, soil).
- Details of outcomes: forest structure (total surface, mean diameter, species' diversity, tree density, basal area, above- and belowground biomass and their allometry, root to shoot ratio), belowground soil C pool should capture different depths of soil C depending on groups of measurement. These subgroups include 0–15, 15–30, 30–50, 50–100; aboveground C pools; GHG efflux (CO_2, CH_4, N_2O); lateral particulate and dissolved flux/concentrations (POC, DOC, DIC); photosynthetic rates.
- Other relevant data that may be included: sediment accretion rates, litterfall, tree growth, fine root production, NPP.

7. Data synthesis and presentation

Our review study will use a quantitative synthesis to assess C storage and sequestration of mangrove species in various climate zones and habitat characteristics in association with the impacts of LULCC and restoration. We will combine the review of spatial and temporal effects of land-use changes since 1970 by Sasmito et al. (2019) with new dataset since 2019 generated by this current review.

Acknowledgements

This study is part of a research agreement between the Center for International Forestry Research and the Warm Temperate and Subtropical Forest Research Center, National Institute of Forest Science, Republic of Korea and is funded by the Korea Forest Service, Republic of Korea.

Authors' contribution

All authors conceived, designed the study, and approved the manuscript. CGQ, SS and HB drafted the manuscript and AMM produced the map.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study is part of a research agreement between the Center for International Forestry Research and the Warm Temperate and Subtropical Forest Research Center, National Institute of Forest Science, Republic of Korea and is funded by the Korea Forest Service, Republic of Korea.

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