WORKING PAPER 211

This review is associated with the Evidence-Based Forestry initiative, a collaboration between CIFOR and partner institutions supporting systematic reviews of evidence to enable better-informed decisions about forests and landscapes.

Carbon stocks and fluxes associated with land-use and land-cover change in mangrove ecosystems

A systematic review protocol

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CIFOR

Working Paper 211

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The authors declare that they have no competing of interests.

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1 Background

Across tropical to temperate biomes, mangrove ecosystems play a critical role in the global carbon (C) cycle. They are among the most efficient natural carbon sinks on earth, combining benefits from rapid forest biomass productivity and organic matter sediment deposition (Alongi 2014). Mangroves serve two functions in regulating the coastal C cycle: as a forest, they assimilate and fix carbon in above- and below-ground biomass, and as an intertidal wetland, they sequester atmospheric carbon and store it in waterlogged, organic-rich soil. On average, mangrove forests store about 956 Mg C ha^{-1} within their biomass and sediment, which is 3–5 times higher than any other terrestrial forest, and comparable – but still higher – than other similar intertidal ecosystems (Donato et al. 2011; McLeod et al. 2011). The term "blue carbon" has been used to bring together all types of vegetated intertidal ecosystems that act as natural storage for significant amounts of carbon over a long period, which includes mangroves, sea grass and salt marshes (Nellemann et al. 2009; McLeod et al. 2011; Pendleton et al. 2012; Alongi 2014). Assessing and quantifying the amount of carbon stored in mangrove ecosystems – and in blue carbon ecosystems in general – is therefore fundamental in the context of climate change and the development of sustainable mitigation plans.

Across the world, mangrove forests and their total surface of 13.1 million ha (Hamilton and Casey 2016) face rapid decline due to deforestation and conversion to other land uses (Duke et al. 2007). In Southeast Asia alone, over 114,000 ha of mangroves were converted to aquaculture, rice and oil palm agriculture between 2000 and 2012 (Richards and Friess 2016). South Asia saw similar losses of 11,673 ha mangroves during the same time period (Giri et al. 2015). From a longer perspective, these surface coverage changes are significant; over the past 200 years, land-use changes have caused the disappearance of nearly 1 million ha of mangroves in Indonesia (Ilman et al. 2016), home to the world's largest mangrove area (Spalding 2010; Giri et al. 2011; Hamilton and Casey 2016). In addition to deforestation, climate change adds further risks to coastal ecosystems as mangroves are vulnerable to accelerated sea-level rise (Lovelock et al. 2015; Sasmito et al. 2016) and other climate change stressors (Ward et al. 2016).

Anthropogenic disturbances affect the overall environment and carbon cycle of mangrove ecosystems both physically and chemically. Reduction of mangrove surface areas followed by land-use conversion directly impacts mangrove carbon stocks and crucially exposes the mangrove's organic carbon-rich soil surfaces to the atmosphere (Kauffman et al. 2014; Bhomia et al. 2016a). These cleared and degraded lands emit sequestered carbon back to the atmosphere and over time, this effect has global significance (Pendleton et al. 2012). Although mangroves only represent 0.7% of tropical forests, 10% of the global CO_2 release from tropical deforestation is attributable to losses from mangroves as they are cleared (Donato et al. 2011; Pendleton et al. 2012). Disrupting mangrove ecosystems through land-use change can turn stored, long-term carbon into significant sources of carbon emissions and add to global atmospheric greenhouse gas (GHG) concentrations (McLeod et al. 2011; Pendleton et al. 2012; Siikamaki et al. 2012; Alongi and Mukhopadhyay 2015). We understand very little about the fate of carbon after conversion from mangrove to alternate habitat types (Kauffman et al. 2014; Kauffman et al. 2015; Bhomia et al. 2016a).

While many studies note the increasing risks land-use change poses to mangrove ecosystems and climate change goals, there is still no consensus on the magnitude of impact that land-use and land-cover changes (LULCC) have on mangroves and carbon dynamics. A previous study by Pendleton et al. (2012) estimated global mangrove carbon emissions from LULCC at 0.09–0.45 petagrams (Pg) [1] CO_2 yr^{-1} (billion metric tons of carbon dioxide per year). Still, this assessment remains preliminary with a high degree of uncertainty partly because the model uses global averages for mangrove

1 1 petagram (Pg) = 10^{12} kg

conversion rates (0.7–3.0% yr^{-1}) and global averages for cleared mangrove carbon emission rates (373–1492 megagrams (Mg)[2] CO_2 ha^{-1}). Important influencing factors such as: mangrove biomass, sediment heterogeneity, geographical variation, local hydro-geomorphic conditions and specific types of land-use conversion rates, were not included in the data analysis.

Over the last five years there has been a marked increase in the number of publications on mangrove carbon stock and emission assessments (Donato et al. 2011; Kauffman et al. 2011; Donato et al. 2012; Adame et al. 2013; Jones et al. 2014; Murdiyarso et al. 2015; Phang et al. 2015; Stringer et al. 2015; Bhomia et al. 2016a; Bhomia et al. 2016b; McFadden et al. 2016; Nam et al. 2016). This increase is due to two reasons. First, Donato et al. (2011) showed significant C storage of Indo-Pacific mangroves, which sparked further interest in quantifying mangrove carbon stocks. Second, Kauffman and Donato (2012) followed by Howard et al. (2014) developed a standardized protocol for carbon stock assessment in mangrove and blue carbon ecosystems, respectively. This collaborative carbon framework facilitated the development of local assessment surveys, which gave sound scientific data sets for mangrove areas all over the world. Thus, the combination of site diversity and consistent methods has led to better understanding of carbon dynamics and LULCC at local and regional scales. However, despite the growing interest in mangrove carbon stock assessments, case studies and broader climate change mitigation research, there is yet to be a synthesis that gathers the best available evidence on global mangrove C dynamics and LULCC.

Research aiming to assess mangrove deforestation and its impacts on carbon stocks has also increased within the last half-decade. For example, a recent study highlighted that ongoing agricultural expansion was responsible for significant mangrove cover losses in Southeast Asia (Richards and Friess 2016). Different types of land-use conversions to expand areas for pasture, agriculture, aquaculture and urban development led to a range of different carbon emission rates, but which were all higher when compared to pristine mangrove land. In fact, land-use conversions can emit up to 90% of the mangrove sequestered C (Kauffman et al. 2014; Kauffman et al. 2015; Murdiyarso et al. 2015; Andreetta et al. 2016; Bhomia et al. 2016a). It is clear that global analysis of mangrove C dynamics and associated LULCC is timely, urgent and critically important for global climate change mitigation strategies.

As a part of global climate change mitigation efforts, mangrove restoration and rehabilitation projects have developed to support blue carbon storage and sequestration initiatives as well as carbon credit benefits for local communities (Wylie et al. 2016). Although there are limited studies on evaluating how mangrove restoration projects affect C storage and sequestration capacity, a recent case study by Nam et al. (2016) provides potential insight into C storage and sequestration recovery of impacted mangroves in the Mekong Delta. This study examined mangroves affected by large-scale herbicide pollution and after a 30-year restoration project; it found that carbon stock recovery was similar to that of natural forests. Thus, in addition to LULCC factors, restoration and rehabilitation efforts should also include net C sequestration rates, as they are important for understanding global analyses of C dynamics (Osland et al. 2012; DelVecchia et al. 2014).

Carbon dynamics associated with LULCC may be accounted using carbon stock-based and process-based approaches (IPCC 2007). A stock-based approach requires sequence assessment of ecosystem carbon stocks (above- and below-ground carbon pools) prior to and after LULCC activities. A process-based approach requires annual carbon gain (e.g. net primary production, sediment carbon sequestration) and carbon loss (e.g. deforestation, GHG fluxes, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and particulate organic carbon (POC) exchanges) measurements for certain land-use types. Both approaches have been used recently to calculate emission rates generated from mangrove deforestation associated with LULCC (Pendleton et al. 2012; Sidik and Lovelock 2013; Kauffman et al. 2014; Murdiyarso et al. 2015; Andreetta et al. 2016). Detailed calculation processes of both approaches are described in Figure 1 (adapted from Wertz-Kanounnikoff et al. 2008).

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2 1 megagram (Mg) = 10^3 kg

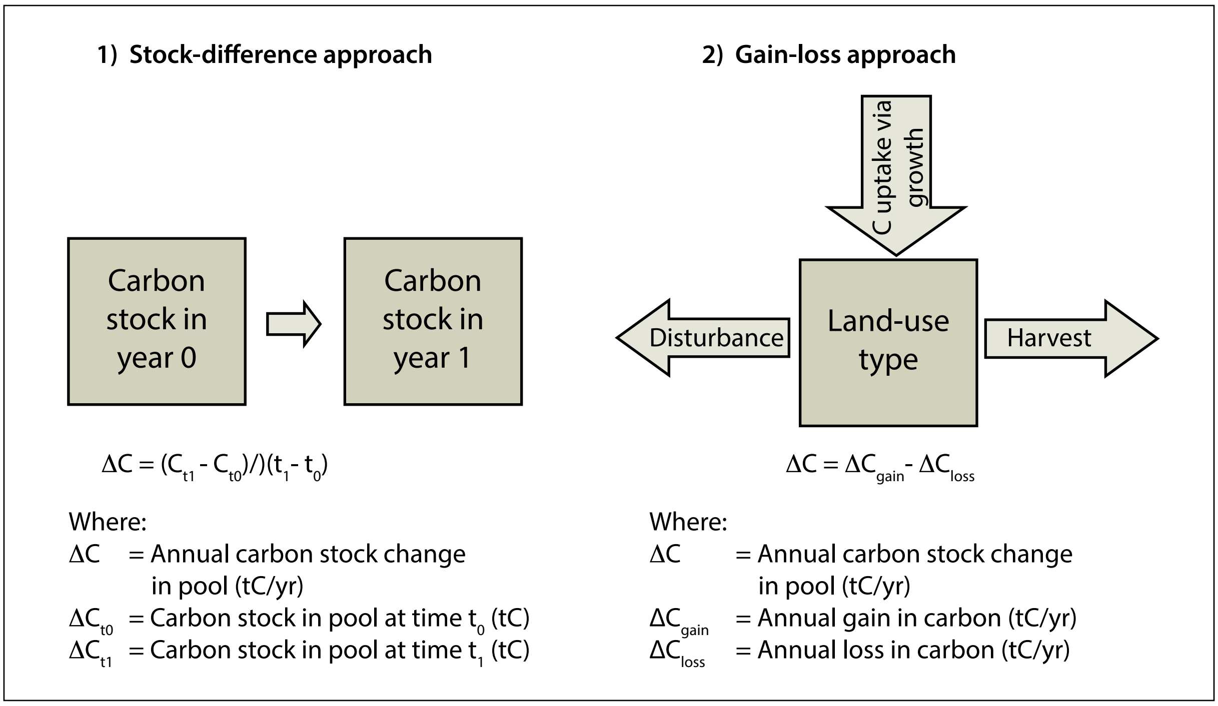

Figure 1. Approaches to estimate carbon exchanges in the biosphere. Estimation of emission factors using (1) a stock-based or stock-change approach, and (2) a process-based, or flux-change or gain-loss approach.

Source: Adapted from Wertz-Kanounnikoff et al. 2008

The objective of this systematic review is to provide a comprehensive synthesis of scientific evidence on the impacts LULCC has on the global mangrove C cycle and examine the research gaps that remain. Moreover, this review will lend further support to policy makers working in climate change, forests and coastal wetland ecosystems by presenting a concise analysis of the crucial significance mangroves have as the highest blue carbon reservoirs. Furthermore, a study on mangrove carbon is timely considering that the United Nations Framework Convention on Climate Change (UNFCCC) requirements for reporting national GHG inventories from wetland ecosystems (IPCC 2014) ask countries to provide carbon emissions and long-term biomass stocks. To show their support, Indonesia and other Southeast Asian countries have made recent pledges to significantly reduce GHG emissions. For example, Indonesia's Intended Nationally Determined Contribution (INDC) submitted to the 2015 Conference of Parties (COP) 21 in Paris aimed for a 29% reduction in emissions below business-as-usual rates and a conditional 41% reduction by 2030, if they receive sufficient international support (GoI 2015). Emission reduction targets will come from improved management of land-use, land-use change and forestry (LULUCF) efforts, of which 'blue carbon' ecosystems play important roles. Although current studies provide critical information on C stocks of coastal mangroves, they lack evidence on reference emission factors and activity data, which are often associated with land-use change practices and ecosystem restoration efforts.

2 Objective of the review

2.1 Primary and secondary questions

The primary question of the review is:
- How does land-use and land-cover changes (LULCC) affect carbon stocks and fluxes of mangrove ecosystems?

The secondary questions of the review are:
- How do different LULCC impact mangrove carbon stocks and fluxes?
- What is the magnitude of mangrove carbon stocks and flux changes in relation to types of LULCC identified?
- What are the implications of LULCC and restoration activities to mangrove ecosystems carbon loss and gain respectively?

Table 1. Summary of terminologies used in the context of mangrove ecosystems in this study.

Variable	Description/Definition	Reference
Carbon dynamics	The spatial and temporal change in fluxes and storages of carbon. This describes the spatial and temporal behavior of carbon produced and derived from mangroves (through primary production) under its organic, inorganic, particulate, dissolved and gas forms.	(Bouillon et al. 2008)
Coastal blue carbon	The carbon stored in tidal wetlands, which includes tidally influenced forests, mangroves, tidal marshes and sea grass meadows, within sediment, living biomass and nonliving biomass carbon pools. Coastal blue carbon is a subset of blue carbon that includes *oceanic blue carbon,* which represents carbon stored in open ocean carbon pools.	(McLeod et al. 2011)
Carbon stock/ storage	Total amount of organic carbon stored in ecosystem carbon pools (measured in megagrams of carbon per hectare (MgC ha^{-1})	(IPCC 2000)
Carbon pools	Carbon reservoirs, such as: • Aboveground pools (tree biomass, dead downed wood, litter and understory) • Belowground pools (root biomass, organic soil)	(IPCC 2000; Kauffman and Donato 2012)
Tree biomass	Live mangrove trees including stem, branch, twig and leaf	(Komiyama et al. 2008; Kauffman and Donato 2012)
Dead downed wood	All dead and felled biomass above the forest floor	(IPCC 2000; Kauffman and Donato 2012)
Root biomass	Below-ground roots, pneumatophores and prop roots	(Komiyama et al. 2008; Kauffman and Donato 2012)
Organic soil	Carbon that is stored as below-ground organic matter (OM)	(Howard et al. 2014)
Carbon fluxes	Transfer/exchange of carbon between different pools: • lateral flux (towards adjacent environments and towards the hydrosphere) • vertical flux (towards the geosphere and atmosphere)	(Bouillon et al. 2008)

continued on next page

Table 1. Continued

Variable	Description/Definition	Reference
Net primary production	Net OM production by plants in an ecosystem	(IPCC 2000)
Litter fall	Litter fall is a proxy for net primary production (accounts for one third of the total NPP), clear latitudinal zonation with higher rates between 0° and 10°	(Bouillon et al. 2008)
Carbon emission	CO_2 efflux from creek waters during released of dissolved CO_2 in its oversaturated water	(Borges et al. 2003; Bouillon et al. 2008)
Mineralization	CO_2 efflux from sediment during mineralization of the mangrove-derived OM	(Borges et al. 2003; Bouillon et al. 2008)
Carbon export	Tidal export, tidal pumping, subsurface groundwater discharge (SGD), outwelling theory, lateral exchange	(Lee 1995)
Carbon burial	The actual amount of mangrove derived carbon being sequestered in the soil. It is usually defined as organic carbon accretion rates per hectare per unit of time	(Twilley et al. 1992; Jennerjahn and Ittekkot 2004; Breithaupt et al. 2012)
Land use	The type of activity being carried out on a unit of land	(IPCC 2003)
Land cover	The type of vegetation covering the earth's surface	(IPCC 2003)
Deforestation	The conversion of forested land to non-forested land caused by anthropogenic activities	(IPCC 2003)
Degradation	The deterioration and loss of forest cover due to human driven activities	(IPCC 2003)
Rehabilitation	Ecosystem recovery processes that may involve non-native species	(Chazdon et al. 2016)
Restoration	Ecosystem recovery processes that involve native species to improve composition and historic ecological integrity	(Chazdon et al. 2016)

3 Methods

3.1 Author workshops

The systematic review author team had two one-day workshops to discuss the review's scope, key questions, critical appraisal and data extraction methods. Both workshops were organized alongside mangrove conferences in Darwin, Australia (May 2016) and St. Augustine, Florida (July 2016) to enable side meetings with experts and engage potential advisors of the review. The first workshop focused on developing and finalizing the review's scope and key questions, while the second workshop practiced the methods for critical appraisal and data extraction and the team reviewed a final draft of the research protocol.

3.2 Scope and search strategy

The review will include all peer-reviewed and gray literature (including unpublished studies) published or otherwise available since 1970. The literature search will aim to find any research that documents the influence of land use and cover change on above- and below-ground mangrove carbon stocks, mangrove productivity and their associated fluxes towards the atmosphere through its gaseous form (i.e. CO_2 and CH_4) and towards the coastal environment in particulate and dissolved forms (i.e. C burial, POC, DIC, DOC).

Our search strategy will combine the assessment of: (i) carbon stocks and fluxes in pristine, natural or low-impacted mangroves; and (ii) carbon stocks and fluxes in impacted mangroves. Different temporal scales will provide the amounts of carbon that are released and sequestered by ecosystem degradation and restoration, respectively. Figure 2 demonstrates how the review aims to evaluate and link the impact of land-use practices and associated land degradation influences (e.g. deforestation, fragmentation, pollution) upon mangrove carbon cycling at a global scale.

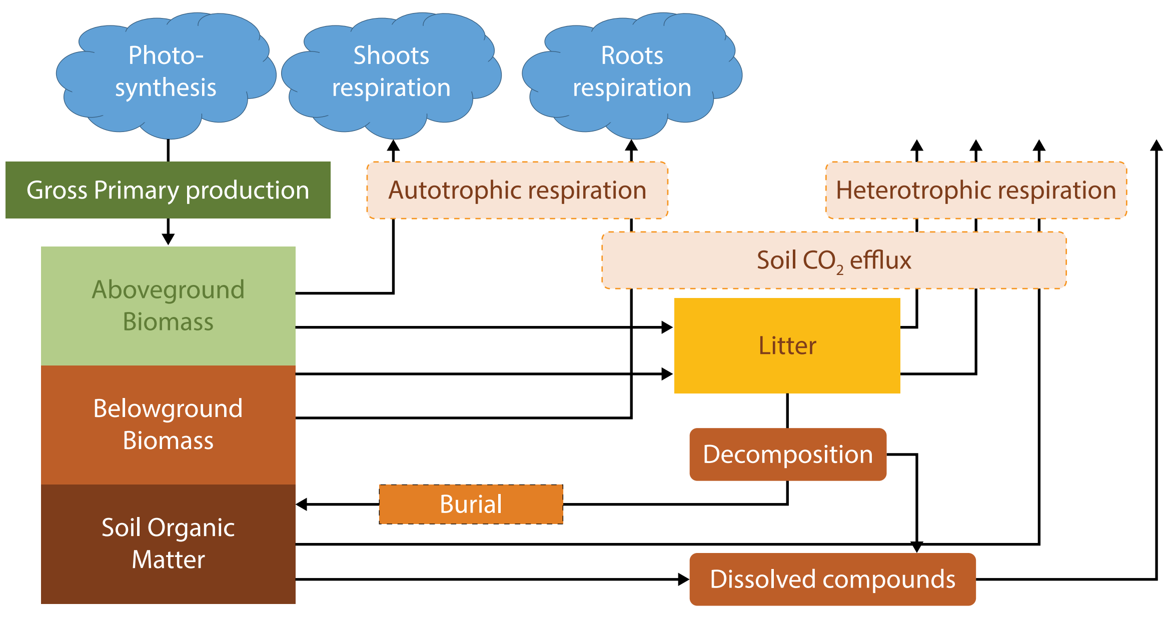

Figure 2. Mangrove carbon stocks and flux categories subject to land-use and land-cover change.

3.2.1 Primary search terms

The authors developed the search string by generating a list of keywords from the review's main questions. These keywords were organized under the headings of: population, intervention, comparator and outcome, a common approach for systematic reviews (CEE 2013) (Table 2). These keywords were formed into search strings using the Boolean operators 'OR' between similar terms and the Boolean operator 'AND' between each major heading (i.e. population, intervention, comparator and outcome). These terms and search strings were then trialed in two main bibliographic databases (i.e. Web of Science and Scopus) and selected based on an iterative process of screening search results. As the review aimed to include any global mangrove ecosystem impacted by LULCC, we excluded geographical terms (i.e. name of mangrove site, country and region) from the search string.

After the search strings were trialed, the search results were compared with a test library to assess search comprehensiveness. The test library contains 33 relevant studies selected by the review team for gauging the accuracy of the search results. The final search string selected (as shown in Table 2) resulted in 2317 and 2290 articles from Scopus and Web of Science (WoS), respectively (as of 12 August 2016). Out of the 33 studies from the test library, 31 studies were found in Scopus and 26 were found in WoS. Two studies (e.g. Deborde et al. 2015; Duncan et al. 2016) were not listed in either Scopus or WoS, but were found in the CAB Direct database. We therefore concluded that our search string was both sensitive and manageable in returning a relevant number of results.

Table 2. Final search string to be used in bibliographic databases.

Category	Search terms
Populations	mangrove* OR "coast* ecosystem*" OR "coast* wetland*" OR "intertidal wetland*" OR "tidal wetland*" OR "estuarine wetland"
Interventions	effect OR derived OR metal* OR source* OR nutrient OR clear* OR pristine OR intact OR plantation OR abandoned OR anthrop* OR impact* OR landform* OR 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 OR spatial OR temporal OR sulfate
Comparators	ecosystem OR sediment OR biomass OR dynamic* OR flux* OR emission* OR stock* OR storage* OR respiration OR efflux OR sequest* OR exchange OR export OR soil OR variability OR transfer OR concentration
Outcomes	carbon OR methane OR geochem*

3.2.2 Languages and secondary search terms

While trialing search strings, we did a preliminary scoping study to determine other languages apart from English that can reveal a significant amount of additional mangrove research. Based on our knowledge to date, we have identified a number of languages and guidelines for the literature search.

- All searches will be conducted in English.
- Secondary searches will potentially include Mandarin Chinese, Bahasa Indonesia/Malay and French.
- If resources and time allow, Portuguese and Spanish languages will also be used.

These secondary searches will use a simplified search string, drawing on keywords shown in Table 3. Google Scholar and Internet specialist websites will be among main search engines used for secondary searches. In the case of Google Scholar, the first 100 papers will be screened for each respective language. Each search string used will be saved and recorded for the full review.

Table 3. Suggested keywords to be used for secondary searches in additional languages.

Category	Search terms – English	Search terms – French	Search terms – Bahasa
Populations	mangrove	*mangrove*	*mangrove*
			bakau
Interventions	intact	*intact*	alami
	anthrop*	*anthropique/anthropogénique*	antrop*
	impact*	impact	dampak
	agricultur*	agriculture	pertani*
	aquacultur*	aquaculture	akuakultur*
	"land use*"	"utilisation du territoire"	tata guna lahan
	"shrimp farm*"	crevetticulture/"culture de crevettes"	tambak
	disturb*	perturbation	*ganggu*
	"land cover*"	"occupation du territoire"	tutupan lahan
	rehabilit*	réhabilitation	rehabilitasi
	restor*	restoration	restorasi
	pollut*	pollution/polluant	pulusi
Comparator	ecosystem	*écosystéme*	*ekosistem*
	sediment	*sédiment*	*sedimen*
	biomass	*biomasse*	*biomassa*
	dynamic*	*dynamique*	*dinamika*
	flux*	*flux*	*fluks*
	emission*	*emission*	*emisi*
	stock*	*stock*	*stok*
	storage*	*stock*	*stok*
	efflux	*efflux/flux*	*fluks*
	sequest*	*sequestration*	*sekuestrasi*
	exchange	*échange*	*pertukaran*
	export	*export*	*ekspor*
	soil	*sol*	*tanah*
	transfer	*transfert*	*transfer*
	concentration	*concentration*	*konsentrasi*
Outcomes	carbon	*carbone*	*karbon*
	methane	*methane*	*metana*

3.3 Search sources

3.3.1 Bibliographic databases

We will search the following bibliographic databases:
- Web of Science (https://apps.webofknowledge.com)
- Scopus (https://www.scopus.com/)
- CAB Direct (https://www.cabdirect.org/)

All search results (along with abstracts when possible) will be saved and stored in an online EndNote library for the screening process.

3.3.2 Internet searches

We will use the following Internet search engines to ensure that relevant studies are not missed.
- Google Scholar (https://scholar.google.com)
- Mendeley library (https://www.mendeley.com/research-papers/)

3.3.3 Specialist searches

In addition to publication databases, the following international research organizations, universities, government departments and private sector industries will be contacted for relevant studies (Table 4). Similarly, an abbreviated search string from Table 3 will be used in the websites and noted for the full review.

Table 4. A list of international research organizations, universities, government departments and private sector organizations that conduct relevant studies on mangroves and carbon dynamics.

Institution name	Official website address
International organizations	
Center for International Forestry Research (CIFOR)	http://www.cifor.org/swamp/
AsiaFlux network	http://www.asiaflux.net/
IPCC Technical Support Unit (TSU)/Emission Factor Database (EFDB)	http://www.ipcc-nggip.iges.or.jp/EFDB/main.php
Institut de Recherche pour le Developpement (IRD)	https://en.ird.fr/
Institute of Pacific Islands Forestry (IPIF)	http://www.fs.fed.us/psw/programs/ipif/
International Institute of Tropical Forestry (IITF)	http://www.fs.usda.gov/iitf
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	http://www.csiro.au/
Smithsonian Tropical Research Institute	http://www.stri.si.edu/
IUCN Mangrove Specialist Group	http://www.iucn.org/content/support-grows-mangroves
International Blue Carbon Initiative	http://thebluecarboninitiative.org/
Conservation International	http://www.conservation.org/projects/Pages/mitigating-climate-change-on-coasts-blue-carbon.aspx
Universities	
School of Earth and Environmental Sciences, University of Wollongong	http://smah.uow.edu.au/sees/index.html
Department of Geography, National University of Singapore	http://www.fas.nus.edu.sg/geog/
RIEL, Charles Darwin University	http://riel.cdu.edu.au/
Global Change Institute, University of Queensland	http://www.gci.uq.edu.au/
School of Life and Environmental Sciences, Deakin University	http://www.deakin.edu.au/life-environmental-sciences
Mangrove Research Group, Auckland University of Technology	https://www.aut.ac.nz/study-at-aut/study-areas/sciences/research/mangrove-research-group
Faculty of Forestry, Bogor Agricultural University (IPB)	http://www.fahutan.ipb.ac.id/
The Biology Department, Vrije Universiteit, Brussels, Belgium	http://we.vub.ac.be/en/biology-department
State Key Laboratory of Marine Environmental, Xiamen University, China	http://mel.xmu.edu.cn/
Department of Life Science, National Chung Hsing University, Taiwan	http://lifes.nchu.edu.tw/
Department Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong	http://www.grm.cuhk.edu.hk/eng/index.html
Center for Earth System Science, Tsinghua University, China	http://www.cess.tsinghua.edu.cn/
The Ecosystems Center, Woods Hole USA	http://www.mbl.edu/ecosystems/
Department of Geography, University College London	http://www.geog.ucl.ac.uk/

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Table 4. Continued

Institution name	Official website address
IFAS, University of Florida	http://ifas.ufl.edu/
Southeast Environmental Research Center, Florida International University	https://sercweb.fiu.edu/
Louisiana State University, Department of Oceanography and Coastal Sciences	http://www.oceanography.lsu.edu/
Government departments	
Forestry Research and Development Agency (FORDA), Indonesia	http://www.forda-mof.org/
Agency for Marine and Fisheries Research, Indonesia	http://www.balitbangkp.kkp.go.id/
United States Forest Service (USFS)	http://www.fs.fed.us/
Wetland and Aquatic Research Center, United States Geological Survey (USGS)	https://www.usgs.gov/centers/wetland-and-aquatic-research-center-warc
National Oceanic and Atmospheric Administration (NOAA)	http://www.noaa.gov/
Forest Research Institute Malaysia (FRIM)	http://www.frim.gov.my/
Kenya Marine and Fisheries Research Institute (KMFRI)	http://www.kmfri.co.ke/
Private sector	
PT. Bintuni Utama Murni Wood Industries, Indonesia	http://www.bumwimangrove.com/home/
PT. Kandelia Alam	http://www.kliamangrove.com/Home/

3.3.4 Call for literature within the mangroves and coastal wetlands fields

A call for literature to researchers and recognized experts within the mangrove field will be used to collect possible studies that may have been missed or unpublished data relevant to the review. Similarly, the review team will use a small group of experts as an advisory council to appraise the protocol and full review to strengthen the research approach and analysis. A full list of individuals consulted will be included with the literature search information as an appendix to the review.

3.4 Study inclusion process and criteria

Study relevance will be determined by using the inclusion criteria presented in Table 5.
For inclusion in the review, studies must meet the following relevant criteria: population, intervention, comparator and outcome of interest. After duplicates are removed from the search results, all studies will go through a three-stage screening process at the title, abstract and full text levels by at least two reviewers. The title screening stage will exclude obviously irrelevant studies that are not related to mangroves, while the abstract and full text screening stages will apply the criteria and study designs as explained below. Before abstract screening begins, reviewers will use Cohen's kappa statistic (McHugh 2012) to compare agreement in applying the inclusion criteria to the same 100 articles. A kappa score of >0.6 will be used to denote acceptable agreement and this score must be reached before abstract and full text screening continues. If reviewers disagree about the inclusion of articles during the kappa tests, then any discrepancies will be discussed to improve understanding, with any modifications made to the inclusion criteria noted for the final review.

Table 5. The populations, interventions, comparators and outcomes relevant to the review.

Relevant populations	Interventions	Comparators	Outcomes
Global mangrove ecosystems; This includes hydro-geomorphic settings and species clusters such as mangrove palm (*Nypa fruticans*) and mangrove associates	Land-use and land-cover changes physically and chemically impacting mangrove areas, such as: • aquaculture and fisheries • oil palm • agriculture • urban development • mining • tourism • deforestation • rehabilitation or restoration projects • coastal disturbance (storm events, shoreline erosion, climate change impacts) • organic and inorganic pollution	Undisturbed or natural mangroves used as 'controlled' comparator plots which were set up and analyzed at the same time, or before and after comparisons on the same areas or plots	Any measured change in above- and below-ground carbon stocks and fluxes of natural and impacted mangroves: this includes above- and below-ground carbon stocks, soil organic matter content, net primary production, carbon burial, CO_2 and CH_4 efflux from sediment, CO_2 and CH_4 efflux from water, particulate (POC) and dissolved (DOC, DIC) lateral fluxes

The relevant types of study designs that will be included in the review include primary studies that examine quantitative changes of carbon dynamics in mangroves worldwide. Studies that use remote sensing will also be reviewed and only included if they use primary data. Excluded study designs include:

- pot or greenhouse studies
- nutrient enrichment studies
- seedling or sapling studies
- modeling studies based on secondary data
- qualitative studies that have no primary carbon measurements.

3.5 Critical appraisal of studies and confounding factors

After full text screening, all included articles will be critically appraised for the internal and external validity of their study designs. At least two reviewers will use structured questions to assess a study's relevance, reliability, time scale, replication, spatial variability and the level of methodological detail that are documented. These criteria will be used to sort studies into high-, medium- and low-quality categories based on a numerical scoring system. High-quality studies will have high study relevance, an acceptable level of replication, methodological detail and clear presentation of results. Medium-quality studies will meet at least 60% of these criteria and low-quality studies that do not meet our minimum inference criteria (i.e. a sufficient amount of replication) will be excluded from the review.

As many factors affect the measurements of above- and below-ground carbon dynamics in mangrove ecosystems, additional confounding factors that are part of the climatic, hydrological, geomorphological, biological or anthropogenic variables will be described for each study. All of these regional parameters will be listed in the data extraction database and noted for the full review.

3.6 Data extraction strategy

Data will be extracted by at least two reviewers into a database according to the categories listed below. We aim to plot the spatial and temporal scales of mangrove study sites for presentation in the final review and care will be taken to avoid duplication. After all of the data have been extracted, a third reviewer will randomly check 20% of studies to ensure consistent data recording. All of the findings will be extracted as follows:

1. General information

   Bibliographic information

   - Study title
   - Author(s)
   - Publisher
   - Date of publication

   Headlines

   - PICO (population, intervention, comparator and outcome) identification
   - Research objective(s)
   - Main finding(s)
   - Carbon parameters assessed (stock, flux in sediment, biomass or water)

2. Biogeographical and study interventions characteristic (study site)

   2.1. Geographical locations

   - Latitude
   - Longitude
   - Country

   2.2. Environmental variables

   - Seasonality types (wet or dry)
   - Annual minimum, maximum and mean temperature (°C)
   - Annual mean precipitation (mm)

   2.3. Hydrological conditions

   - Tidal regime (diurnal or semidiurnal)
   - Tidal amplitude (maximum and/or average)

   2.4. Mangrove biogeomorphological information

   - Mangrove total surface area (ha)
   - Total converted area – if available (ha)
   - Coastal morphology (e.g. lagoon, river delta, tidal estuary, carbonate island)
   - Adjacent ecosystem habitats (salt marsh, sea grass, coral reef)
   - Mangrove dominant species and vegetation diversity (amount and type of species recorded)

   2.5. Land-use change description

   - Type of land-use change/disturbance if any
   - Year the shift occurred
   - Interval between the time of shift and when the survey was conducted

3. Study methods

   3.1. Number of plot replication (spatial and/or temporal)

   3.2. Plot(s) size

   3.3. Plot(s) description and experimental design

   3.4. Collected and/or measured sample types

   3.5. Methods and protocols used for each measurement

4. Study results and outcomes

   All quantitative data – or carbon stocks and fluxes measured before and after LULCC – presented in the studies will be organized as follows:

   4.1 Carbon stocks in biomass

   4.1.1 Above-ground biomass (tonne of dry weight per ha)

   4.1.2 Below-ground biomass (tonne of dry weight per ha)

   4.1.3 Litter and down dead wood (ton dry weight per ha)

   - Tree density (trees per hectare)
   - Basal area (meters square per hectare)
   - Mean diameter at breast height (DBH)

   4.2 Carbon stocks in sediment and pore water

   - Sediment core depth and amount of layers it was sectioned (cm)
   - Bulk density (gram per cubic centimeter)
   - Total carbon content (TC) (gram carbon per cubic centimeter)
   - Soil organic carbon (SOC) content (gram carbon per cubic centimeter)
   - Nitrogen content (gram nitrogen per cubic centimeter)
   - Carbon and nitrogen content ratio (C/N)
   - Water CO_2 partial pressure concentration (pCO_2) efflux (µatm)
   - Water CH_4 concentration (µatm)
   - Particulate organic carbon (POC) (µM)
   - Dissolved organic carbon (DOC) (µM)
   - Dissolved inorganic carbon (DIC) (µM)

   4.3 Carbon content in creek water

   4.3.1 CO_2 partial pressure concentration (pCO_2) efflux (µatm)

   4.3.2 CH_4 in water concentration (µatm)

   4.3.3 Particulate organic carbon (POC) (µM)

   4.3.4 Dissolved organic carbon (DOC) (µM)

   4.3.5 Dissolved inorganic carbon (DIC) (µM)

   4.4 Carbon fluxes in biomass

   - Net primary productivity (grams of C per square meter per year)
   - Litter fall productivity (grams of C per square meter per year)
   - Fine root productivity (grams of C per square meter per year)

   4.5 Carbon fluxes in sediment

   - Carbon burial rate (grams of carbon per mm per year)
   - Sediment CO_2 efflux (mmol of CO_2 per square meter per day)
   - Sediment CH_4 efflux (mmol of CO_2-eq per square meter per day)

4.6 Carbon fluxes in water creek

- Water CO_2 efflux (mmol of CO_2 per square meter per day)
- Water CH_4 efflux (mmol of CO_2-eq per square meter per day)
- Particulate organic carbon (POC) flux (µM per day)
- Dissolved organic carbon (DOC) flux (µM per day)
- Dissolved inorganic carbon (DIC) flux (µM per day)

If a study has incomplete data that could be useful for the review (such as baseline information), reviewers will attempt to contact the author(s) for missing information. If a study has unusable data, then the study will be recorded and excluded from the analysis and noted as an outcome of the review process.

3.7 Data synthesis and presentation

This review will use a quantitative synthesis to assess the differentiating impacts LULCC has on mangrove carbon storage and flux. This synthesis will be based on analyses across 14 groupings, organized as:

- carbon stocks in biomass
- carbon stocks in sediment and pore water
- carbon content in creek water
- carbon fluxes in biomass
- carbon fluxes in sediment
- carbon fluxes in creek water.

If sufficient data are provided, the reviewers will conduct a meta-analysis to understand the magnitude of the effect on mangrove carbon changes. Some descriptive synthesis will be used to explain the differing impacts LULCC have on mangrove ecosystems and the implications LULCC and restoration activities have upon the carbon loss or gain in mangroves ecosystems worldwide. In summary, the review will focus on the spatial and temporal effects of land-use changes since 1970 and if differences can be seen between human and nonhuman influences on mangroves.

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Coastal mangrove forests are known as one of the most productive ecosystems and efficient carbon (C) sinks on the planet. Mangroves store a substantial amount of organic C in below-ground sediment, which is known as "blue carbon (C)". As anthropogenic factors have caused greenhouse gas (GHG) emissions and sea levels to increase, mangrove blue C has become a part of global climate change negotiations due to its potential for storing C and mitigating GHG emissions. However, these coastal forests are also currently under threat from major land-use and land-cover changes (LULCC) for aquaculture and agriculture, resulting in large amounts of deforested and degraded mangrove areas globally. Little is known about the range of impacts different LULCC have upon mangrove C dynamics (e.g. C storage, emission and sequestration). This systematic review protocol outlines the methodology to identify and quantify the impacts of LULCC upon the C dynamics of global mangrove forests. The forthcoming review will assess the magnitude of LULCC on natural and impacted mangroves and identify where research gaps remain on mangrove C dynamics.

RESEARCH PROGRAM ON
Forests, Trees and Agroforestry

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