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Commentary

Terrestrial and Aquatic Carbon Dynamics in Tropical Peatlands under Different Land Use Types: A Systematic Review Protocol

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Abstract: Peatlands are both responding to and influencing climate change. While numerous studies on peatland carbon dynamics have been published in boreal and temperate regions for decades, a much smaller yet growing body of scientific articles related to tropical peatlands has recently been published, including from previously overlooked regions such as the Amazonian and Congo basins. The recent recognition of tropical peatlands as valuable ecosystems because of the organic carbon they accumulate in their water-saturated soils has occurred after most of them have been drained and degraded in Southeast Asia. Under disturbed conditions, their natural carbon storage function is shifted to an additional carbon source to the atmosphere. Understanding the effect of land-use change and management practices on peatlands can shed light on the driving variables that influence carbon emissions and can model the magnitude of emissions in future degraded peatlands. This is of primary importance as other peatland-covered regions in the tropics are at risk of land-use and land-cover changes. A systematic review that synthesizes the general understanding of tropical peatland carbon dynamics based on the published literature is much needed to guide future research directions on this topic. Moreover, previous studies of biogeochemical cycling in tropical peatlands have largely focused on terrestrial stocks and fluxes with little attention given to document lateral and downstream aquatic export through natural and artificial drainage channels. Here, we present a systematic review protocol to describe terrestrial and aquatic carbon dynamics in tropical peatlands and identify the influence of land-use change on carbon exchange. We described a set of literature search and screening steps that lay the groundwork for a future synthesis on tropical peatlands carbon cycling. Such an evidence-based synthesis using a systematic review approach will help provide the research community and policymakers with consistent science-based guidelines to set and monitor emissions reduction targets as part of the forestry and land-use sector.

Keywords: land-use change; AFOLU; GHG emissions; peatland bibliometrics; emissions factor

1. Introduction

There are only a few ecosystems on Earth with the ability to accumulate carbon over centennial to millennial time scales. This is usually the case when atmospheric carbon uptake by vegetation-primary productivity is greater than ecosystem respiration. These long-term carbon sinks are of primary importance since they have the potential to be natural and cost-effective solutions to mitigate anthropogenic greenhouse gas (GHG) emissions [1]—although the most effective mitigation strategy is to decrease emissions at the source [2]. Peatlands are a good example of such valuable long-term carbon sinks. They store about 604 ± 130 GtC of carbon [3–5], equivalent to 31% of the terrestrial carbon pool [6], while only representing 3% of the terrestrial surface area [7]. However, peatlands have increasingly turned from carbon sinks to carbon sources owing to widespread drainage and degradation associated with land-use and land-cover changes. Their disturbance leads to large ecosystem carbon loss, primarily through GHG emissions. Moreover, the rapid loss of old carbon cannot be restored on timescales relevant for the climate, forcing mitigation strategies [8].

While the importance of peatlands for the past and present global carbon balance is well established [4,7,9], less is known about the impact of land-use and climatic changes on the future of peatlands. This is of primary importance since these two threats continue to grow in magnitude, with 2020 being the warmest year on record [10] and 2016–2019 being the highest period for primary forest loss, which includes tropical peatland forest burning [11]. A recent bibliometric study reported that only 11.2% of the total publications on peatlands published since 1991 were conducted south of 30° N [12], despite tropical peatlands comprising up to 25% of the global peatland area [13]. This means that tropical peatlands are underrepresented in the literature and also that our knowledge on tropical carbon dynamics is limited despite its importance in informing appropriate land management strategies and regulations. Within the tropical peatland literature, most reviews on peatland carbon dynamics have mainly focused on the Southeast Asia region [14,15]. This is largely because peatlands in other parts of the tropics, such as Central Africa and Latin America, have only been recently discovered, mapped and characterized [3,16]. Even with these recent mappings, potentially large areas of tropical peatlands remain unmapped (e.g., in the Amazon basin) due to their remoteness and inaccessibility. Nevertheless, a global-scale synthesis on tropical peatland carbon dynamics incorporating newly identified and mapped peat areas could further highlight current gaps and availability of knowledge, data, and monitoring approaches between continental regions and countries.

Peatland degradation can significantly worsen the annual national GHG emissions for countries where peatlands occupy extensive areas, such as in Indonesia, Malaysia, Peru, Brazil, the Democratic Republic of the Congo, and the Republic of the Congo. For instance, 48% of Indonesia's national emissions are driven by land-use change, with most of its peat carbon released to the atmosphere [17]. Land-use change on peatlands leads to significant losses of living biomass as well as millennial-old carbon stored within peat soils. Once natural peatlands are drained and converted to other land uses at a large scale, soil carbon is released through several forms and via different pathways: (1) terrestrial GHG emissions from the drained, dried, and burnt soil surface; (2) aquatic-mediated downstream export of particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC); and (3) GHG emissions from drainage canals to the atmosphere. Moreover, carbon sequestration potentials via net primary productivity and subsequently peat carbon accumulation ceases once peatlands are degraded.

Previous literature review studies on the carbon dynamics of tropical peatlands have focused on terrestrial carbon density and stocks [4] and the impacts of land-use change on carbon stocks and GHG fluxes [14,15]. However, none had described aquatic carbon losses and their linkage with terrestrial peatland carbon dynamics. Carbon export and evasion from the aquatic component is of importance for tropical peatlands considering that at least 48% of the total peatlands of Southeast Asia were deforested or drained as of 2006 [18]. Recent studies on aquatic carbon losses in tropical peatlands also suggest that this component may represent a substantial fraction of the tropical peatland carbon balance [19,20]. For example, it is estimated that peatland drainage and deforestation in Eastern Sumatra, Indonesia would increase fluvial carbon export from inland waters to the ocean by 200% [21]. Therefore, incorporating aquatic carbon pools for tropical peatland carbon dynamics synthesis is necessary to guide future carbon-monitoring programs including for policymakers to set and monitor emissions reduction targets.

While literature reviews aim at presenting the state of scientific knowledge on a specific topic, traditional literature reviews tend to be descriptive and likely to be influenced by the authors' point of view, leading to a lack of objectivity and exhaustivity. Systematic reviews, on the other hand, are defined as reviews of knowledge using a systematic method to summarize evidence on questions with a detailed and comprehensive plan of study [22]. Although the systematic review methodology can be applied to any field of scientific research, the workflow steps and decisions vary between research topics. A systematic review approach has been widely used in the field of conservation and environmental management (see https://environmentalevidence.org/ (accessed on 16 September 2021)); however, this approach has rarely been applied for tropical peatland studies. By describing the numerous steps used to capture, examine, appraise, and select relevant peer-reviewed articles related to carbon cycling in tropical peatlands, we hope to inspire, help, and guide future research groups on the use of systematic reviews for other key research topics in the field of environmental science.

The objective of this systematic review protocol was to describe the rationale, the research questions, and the planned systematic review workflow on carbon dynamics in tropical peatlands. The publication of a systematic review protocol is one of the foundations to improve research transparency and to support study replicability. Previous syntheses on carbon dynamics in tropical peatlands were done by using a meta-analysis approach (see Novita et al. [23], Hergoualc'h and Verchot [14], and Prananto et al. [15]) as well as a traditional review (see Ribeiro et al. [24]). While they notably contributed to increase our general understanding of tropical peatlands biogeochemical mechanisms, we are interested to explore if using a systematic approach will help advance the synthesis outcome. Critical steps necessary for any literature review such as identifying the relevant body of literature and ensuring consistent data-extraction practices between the reviewers are likely to be more exhaustive and accurate when using a systematic review approach.

2. Systematic Review Aim and Objectives

The systematic review presented here has been designed to identify and extract journal articles that present carbon data from the terrestrial and aquatic components—two interlinked elements that play a key role in the mechanism and regulation of ecosystem carbon [25]. The terrestrial carbon component includes carbon stocks, carbon density, biomass productivity, soil carbon accumulation, and GHG emissions, while the aquatic carbon component consists of POC, DOC, DIC, and GHG evasions within and from hydrological catchments (Figure 1). We present a database of extracted carbon dynamics datasets and describe their characteristics based on geographical location (country), land-use type, and hydrogeomorphic setting.

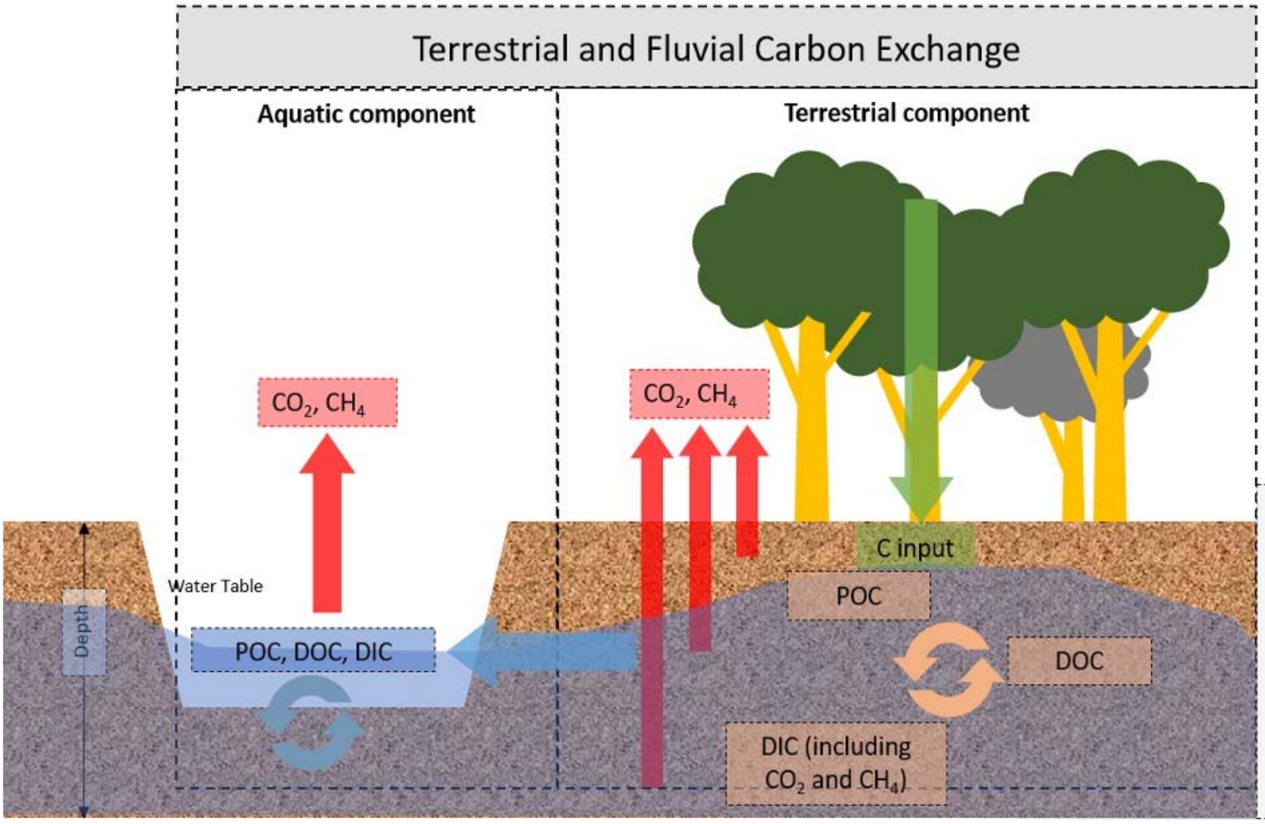

Figure 1. The common measured carbon dynamic pathways across the terrestrial and aquatic continuum in tropical peatlands following anthropogenic disturbances such as drainage.

The primary questions of this systematic review are: what is the current knowledge on tropical peatland carbon dynamics? and how do tropical peatland carbon exchanges respond to land-use change?

The secondary review questions are:

(1) What are the available data and spatial distributions of carbon dynamic studies conducted in tropical peatlands?
(2) What are the most studied and overlooked components of the tropical peatlands' carbon cycle?
(3) What are the most documented peatland regions and countries regarding carbon dynamics descriptions?
(4) What variables and methods are commonly described and part of tropical peatlands' carbon cycling?
(5) What is the temporal evolution of carbon-related studies in tropical peatlands?
(6) What is the magnitude and variation of carbon pools between peatland regions, hydrogeomorphic settings, and land-use types?

We used and adapted the common framework for systematic reviews of the population, exposure, comparator, and outcome heading (PECO; [26]) to define the scope of the review and develop the search string to capture relevant studies to address our research questions. In addition, we added geographical location including the name of countries and regions where tropical peatlands are located (see Figure 1 for peatland location across tropical countries). The exact keywords for each heading are presented in Table 1, with general definitions for the population, geographical location, comparator, and outcome are described as follows.

Population: tropical peatlands and their associated water bodies.

Exposure: anthropogenic driven disturbances such as land-use and land-cover changes.

Geographical location: tropical peatland countries and regions.

Comparator: undisturbed and disturbed tropical peatlands.
Outcome: carbon stocks, inputs, and outputs of any form.

Table 1. Search terms applied to bibliographic databases. Note: Asterisk sign (*) is applied for some search terms and is used to broaden search results that start with the same given letters. Quote sign ("") is used to combine multiple words into a single search term.

Category	Search Terms
Population	peat* OR "black water" OR black*water OR river* OR floodplain OR swamp* OR "organic soil*" OR histosol*
Geographical location	tropic* OR neotropic* OR Amazon* OR Pantanal OR Colombia* OR Guyana OR Peru* OR Venezuela OR Panama* OR "Southeast Asia*" OR Indonesia* OR Malaysia* OR Brunei OR Papua OR Borneo OR Bornean OR Sumatra OR Kalimantan OR Sarawak OR Uganda OR Congo* OR Okavango
Outcome	carbon OR "greenhouse gas*" OR GHG* OR *CO2 OR *CH4 OR methane OR "organic mat*" OR biomass OR C OR humic OR biogeoch* OR DOC OR POC OR DIC OR 13C OR 14C OR radiocarbon

3. Literature Search

This review followed standard guidelines for systematic review by the Collaboration for Environmental Evidence [26] and conformed to the ROSES reporting standards for systematic evidence syntheses [27].

3.1. Searching for Articles

3.1.1. Bibliographic Database Search

The review includes all peer-reviewed literature available from Web of Science and Scopus published before 1 January 2021. Searches were performed in English only since the databases list journal articles titles, abstracts, and keywords in the English language. A search for publication duplicates was conducted and replicates were removed. Once completed, a literature database containing title, abstract, and other relevant bibliographic information was developed for the remaining records.

3.1.2. Search Strategy

The search string that captures the relevant literature as presented in Table 1 was developed over an iterative process. A set of 80 relevant studies from previously published studies [4] and 42 from the personal libraries of three authors were used as reference articles (see Supplementary Information Table S1). The search string was considered satisfactory when all the reference articles were captured within one single search string. This process resulted in the modification of the approach for defining the review scope by adding geographical location keywords. This decision arose from the observation that, in the tropical peatland literature, the peat extent in regions such as Central and South America and the Congo are not always referred to as "peatland" and often unmapped or mapped only several decades or years after carbon dynamics in these regions were studied. Therefore, to avoid overlooking references that do not mention terms related to peatlands but that may have studied carbon dynamics in tropical peat, the "population" category was expanded to include terms such as "river*" and "floodplain," while "geographical location" was included as an additional category. Further details on the generation of search terms for "geographical location" along with the list of reference articles and the exact search string used in each database are provided in Supplementary Information Table S2.

4. Study Inclusion and Exclusion

4.1. Screening Process

Article screening was conducted in two stages, in which we combined title and abstract screening in the first stage followed by full-text screening in the second stage. Articles retained after the removal of duplicates were uploaded to Rayyan—an online platform for systematic-review literature screening [28] for the first stage of screening. Titles and abstracts of all articles were assessed by five reviewers for inclusion or exclusion based on the following two questions:

(1) Does the study present findings from tropical peatlands?
(2) Does the study present carbon-cycle outcomes?

During title and abstract screening in Rayyan, articles were classified as "included," "excluded," or "maybe" according to those two criteria questions. "Maybe" was used if there was insufficient information to justify excluding a study, and that article was retained for the second stage of screening at the full-text level.

The second stage (full-text screening) comprised an assessment of whether articles meet the eligibility criteria for each category in Table 1. Additionally, we used the latest tropical peatlands map (Figure 2) as a reference to ensure that the location of the study site in the literature was situated in an area with peat. When studies satisfied the full-text screening criteria they were included for further data extraction, where we collected the name of the study site and information on the types of study (e.g., field-based study, laboratory-based study, remote-sensing study, modelling, and review). This additional information can be useful to save time during data extraction. More detailed criteria for inclusion and exclusion are described in the next eligible sub-section.

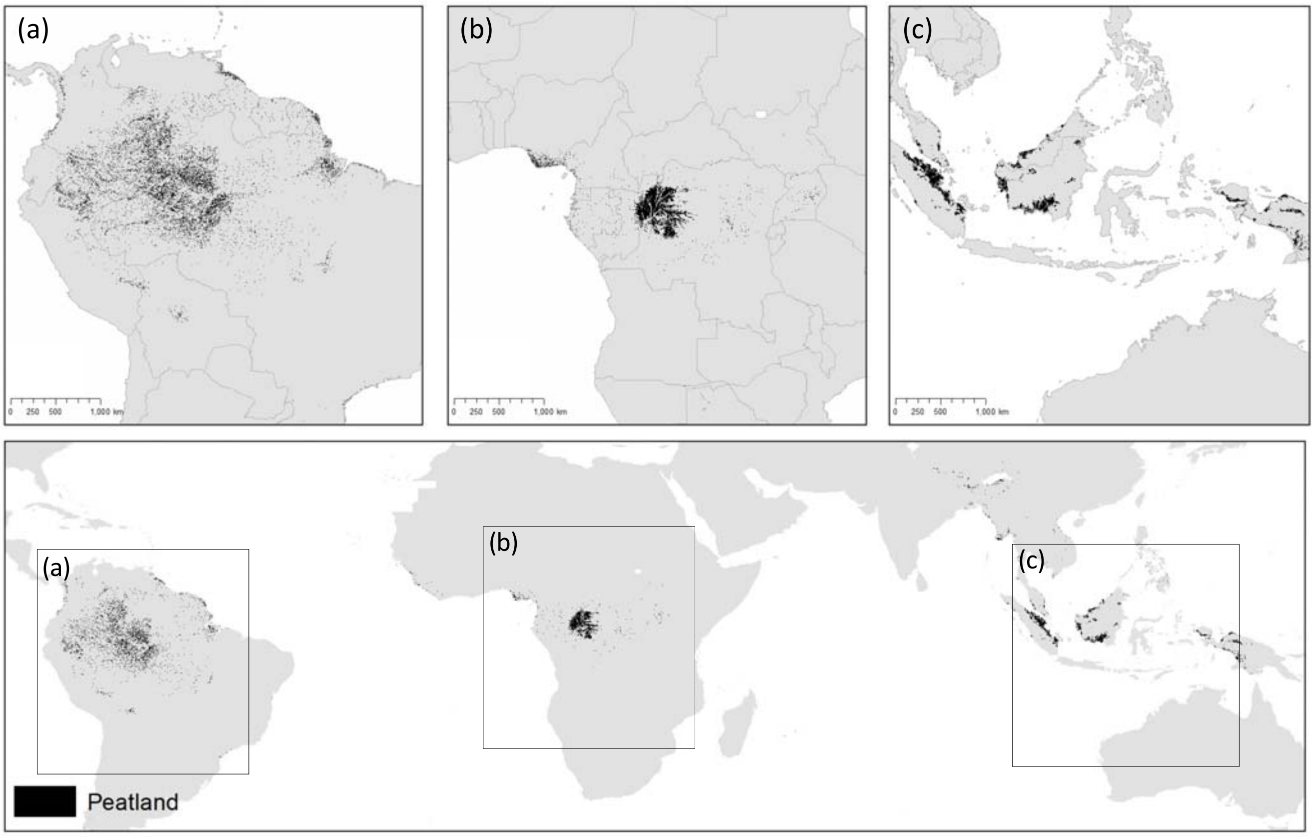

Figure 2. Geographical distribution of tropical peatlands across regions: (**a**) Latin America, (**b**) Central Africa, (**c**) Southeast Asia. Tropical peatlands map adapted from ref. [13].

To ensure that the inclusion criteria were consistently applied across reviewers during the title- and abstract-screening stage, a subset of 300 articles for the first screening stage and 50 articles for the second stage were screened by all five reviewers in separate trials (100 and 10 articles per trial, respectively) until there was sufficient agreement. Cohen's kappa statistic [29] was used to evaluate the degree of agreement among reviewers, with a kappa score of >0.6 denoting acceptable agreement. In each trial, any disagreements were reconciled through discussion such that a common understanding among all reviewers was achieved before beginning the next trial.

4.2. Eligible Populations and Geographical Locations

The review focused on tropical peatlands. The area of study therefore lies within the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S) (Figure 1). To be included in the data extraction, studies must have been conducted in a peatland or in the case where the peat extent was only mapped after carbon dynamics were examined, in an area with peat-type soils (e.g., histosols) or in an environment commonly associated with peat (e.g., swamps, organic soils). Studies collecting water samples in areas that drain catchments containing peat deposits were also included for data extraction, such as rivers classified as blackwaters. Other ecosystems such as mangroves, lakes, reservoirs, and coastal marine waters were excluded. In all cases, reviewers evaluated the site description and the map of the study site against references on tropical peatland distribution, presented in Figure 1, to determine eligibility.

4.3. Eligible Outcomes

Studies on carbon dynamics (e.g., carbon storage, carbon losses, carbon gains) from peat or peat-type soils in the tropics should be included. These comprised those that documented above- and below-ground carbon stocks, soil organic matter, litterfall production, and rates of carbon sequestration or release such as greenhouse gas fluxes (i.e., CO_2 and CH_4). Carbon dynamics in the fluvial component of tropical peat, including concentrations and fluxes of particulate, dissolved, and gaseous forms of carbon (POC, DOC, DIC, CO_2, and CH_4) should also be included. In addition to physical measures of carbon quantity, studies that assessed carbon quality (e.g., origins, age, transformation processes) using stable isotopes ($\delta^{13}C$) and radiocarbon ($\Delta^{14}C$) were included as well.

4.4. Study Validity Assessment

Articles that met the criteria for full-text screening inclusion were critically appraised. This process involved an assessment of internal and external validity. Eleven structured questions requiring a numeric scoring response ("High quality study" = 1, "Medium quality study" = 0.5, "Low quality study" = 0) were used to assess a study's reliability, spatial and temporal variability, sampling strategy, level of methodological detail, replicability, and statistical robustness (see Supplementary Information Table S3). Numerical scores for each study were subsequently tabulated following the given criteria conditions and categorized as either high (overall rating score between 7–11), medium (overall rating score 4–6), or low (overall rating score lower than 4) quality. Low-quality studies were eventually excluded from further review after this screening stage. Reviewers were not allowed to assess the inclusion or exclusion of studies that they had (co)authored at any of the stages of the screening process.

5. Data Extraction

Data extraction was focused on the two main carbon-cycling components, namely, terrestrial and aquatic. Reviewers were divided into two teams according to the reviewers' respective expertise and interest.

To minimize bias during data extraction, each study was extracted by two reviewers. After independent data extraction (Step 1), the two reviewers subsequently compared their results and reached a common agreement were there any differences (Step 2). Thereafter, the data were uploaded onto a common database (Step 3; Figure 3). The detailed list and description of the proposed database for both terrestrial and aquatic carbon dynamic variables are provided in Supplementary Information Table S4.

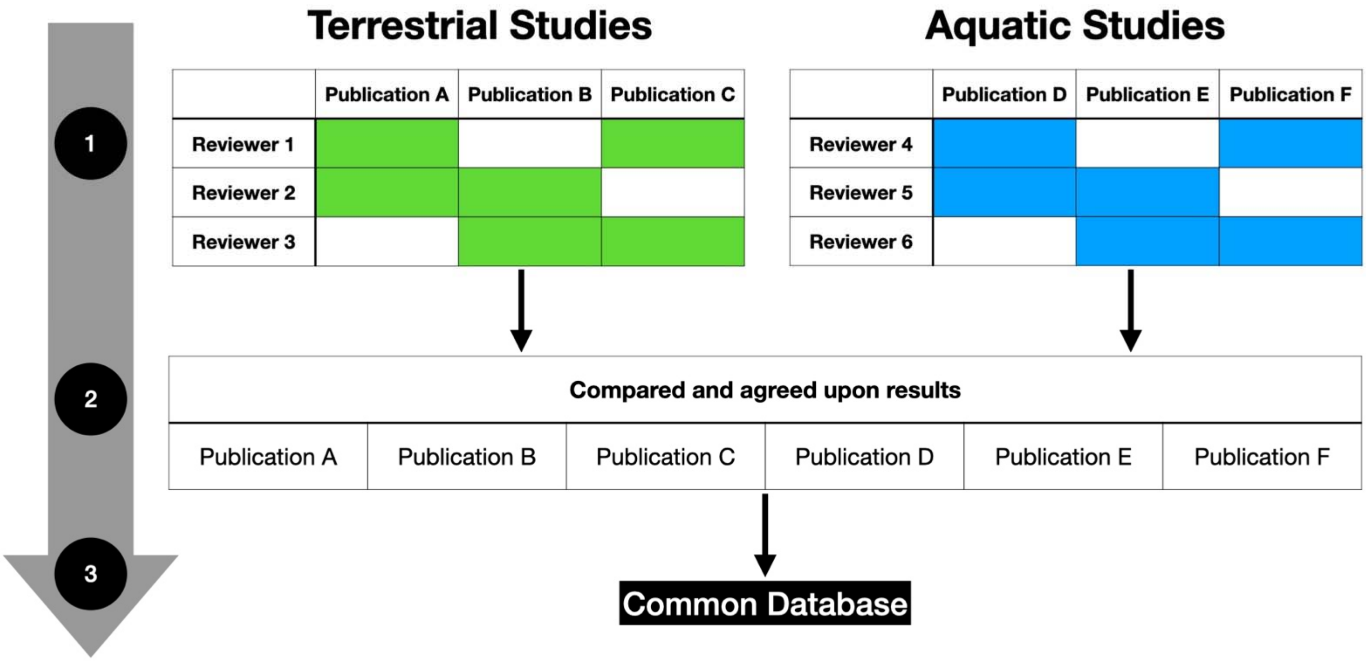

Figure 3. Conceptual model of the data extraction workflow, from (1) individual data extraction to (2) results comparison and common agreement between two reviewers and (3) transfer of the extracted data to the common database.

Data Synthesis and Presentation

The main results of this systematic review will be presented into several outputs, including a global map describing the geographical location of the available data, graphs showing time-series trends of studies, and tables providing in-depth analysis on the range of carbon-cycling magnitudes as well as their measurement approaches. Further investigation and analyses including meta-analysis will be performed to identify knowledge gaps and the effect of different land uses on tropical peatland carbon dynamics. By using a systematic approach to review the state of knowledge on carbon dynamics in tropical peatlands globally, we hope to improve our understanding on tropical peatland ecosystems' functioning and influence on global biogeochemical cycles as well as anticipating their future evolution that is contingent on the human impact on the climate and the landscape.

6. Stakeholder Engagement

This systematic review is part of the Integrative Peatlands Research Program (INTPREP) at the National University of Singapore and was carried out through international collaboration with IPB University in Indonesia. There are several international peatland experts and stakeholders in the INTPREP's Science Advisory Board, and biannual workshops are regularly organized. We presented this draft of a systematic review protocol in the second INTPREP's Science Advisory Board meeting held on 6 July 2021. Feedback and comments during the meetings were addressed in the development of this review protocol, and they were specifically related to the types and variables of the data-extraction template (Table S4). We also discussed the potential of the future outcome and impact from this work, particularly its relevancy to the IPCC Wetlands Supplement and national climate change mitigation for the land-based sector.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12101298/s1, Table S1. List of used publications to test the effectiveness of search string.

Table S2. The development of search string for literature search in the databases. Table S3. List of structured questions to assess study validity. Table S4. List of data extraction variables and sub-variables for tropical peatlands carbon cycling systematic review.

Author Contributions: Conceptualization, S.D.S., P.T., L.S.F., S.J.R., M.L. and D.T.; methodology, S.D.S., P.T. and L.S.F.; writing—original draft preparation, S.D.S., P.T. and L.S.F.; writing—review and editing, S.D.S., P.T., L.S.F., J.W.F.R., H.S., L.W., A.B., N.A.-W., A.S.S., S.T., M.T., S.J.R., M.L., D.T.; visualization, S.D.S., P.T., J.W.F.R. and L.S.F.; supervision, M.L. and D.T.; project administration, S.J.R., M.L., and D.T.; funding acquisition, S.J.R., M.L. and D.T., S.D.S., P.T. and L.S.F. contributed equally to this work and have the right to list their name first in their CV. All authors have read and agreed to the published version of the manuscript.

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