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Do global change variables alter mangrove decomposition? A systematic review

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Abstract

Aim: Global change is expected to modify the magnitude and trajectory of organic matter decomposition in mangrove ecosystems. Yet, the degree and direction of that change is unknown, especially considering the large C storage potential that mangroves provide. We performed a systematic review of primary literature to examine the relationships between genus-specific litter quality, latitude or other global change proxies and decomposition of mangrove litter fractions.

Location: Global.

Time Period: 1976–2021.

Taxon: Mangroves.

Methods: We compiled a dataset of 480 decomposition rates, including species, litter fraction, latitude, and relevant biophysical data. We investigated the influence of genera, tissue type, latitude, and global change proxies on decomposition rates using linear models and qualitative approaches. We also performed calculations to determine the potential importance of the decomposition process on the root litter biomass C pool in the context of blue C significance.

Results: Collectively, latitudinal relationships suggest that factors other than temperature, such as tissue type and genus, may regulate decay rates within mangroves' distributional range. Decay rates of leaf litter, roots, and wood converged on a value of 0.009 ± 0.0005, 0.002 ± 0.0001, and 0.001 ± 0.0003, respectively, across continents and geomorphological settings. Our calculations suggest that small changes in decomposition rate will not elicit large changes in blue C storage potential.

Conclusions: The main drivers behind variability in mangrove biomass decay rates detected across the distributional range remain uncertain. However, the small latitudinal range that mangroves inhabit and the submerged environment within which litter decomposes suggest that decay depends on species-specific responses or biotic interactions among species to global change drivers. Few studies have examined global change impacts directly, and variability in decay and lack of representation of some mangrove groups in the literature suggest that implications for blue C are important to consider.

KEYWORDS
carbon storage, decomposition, global change, leaves, mangrove, roots, systematic review, wood

1 | INTRODUCTION

Decomposition of organic matter (OM) refers to the physical and chemical processes involved in reducing OM to its elemental chemical constituents (Aerts, 1997), and is a key process regulating carbon (C) storage and nutrient cycling in many ecosystems (Hessen et al., 2004). Globally, decomposition is thought to be regulated primarily by climate and secondarily by litter quality (Couteaux et al., 1995; Hättenschwiler et al., 2005; Rien, 1999). Additionally, rates of decay often differ among tissue types, with roots usually decomposing more slowly than leaf litter (Sun et al., 2018) and coarse roots decomposing more slowly than fine roots (Zhang & Wang, 2015). The environmental conditions in which decay occurs also affect the rate at which microbially mediated decomposition proceeds. Latitude, mean annual temperature, and mean annual rainfall are key correlates of decomposition across studies conducted in terrestrial environments (Zhang et al., 2008), with rates generally increasing with rising temperatures and precipitation (Conant et al., 2008; Davidson & Janssens, 2006; Kirshaum, 1995). Further, nutrient enrichment has been shown to stimulate decomposition in terrestrial habitats through an increase in primary and secondary production (Rosemond et al., 2014; Smith et al., 1999). The same factors are thought to regulate decay in tidal wetland ecosystems; however, data have not been explicitly collated to test this hypothesis in tropical wetlands.

Counter to terrestrial ecosystems, OM decomposition is often slower in vegetated coastal wetlands like mangroves, marshes, and seagrasses because their flooded, low-oxygen conditions restrict the enzymatic breakdown of phenolic compounds (Chapman et al., 2019; Freeman et al., 2001). In addition to oxygen availability, decomposition in wetlands typically depends on abiotic exogenous conditions (e.g., temperature, nutrients, water, soil type), litter quality (i.e., nutrient and chemical composition), and decomposer activity (e.g., Aerts, 1997; Holguin et al., 2001; Prescott, 2010; Reddy & Delaune, 2008; Zhang et al., 2008), and decay rates can differ among plant species or plant tissue types (e.g., Jones et al., 2016; Macy et al., 2019; Perry & Mendelssohn, 2009). Tropical ecosystems show no difference between root and leaf litter decomposition (Cusack et al., 2009), and root and wood decomposition in terrestrial ecosystems may be driven by litter quality more than climate (Hu et al., 2018; Silver & Miya, 2001). It remains unclear to what extent climate, litter quality, and other factors affect decay in coastal ecosystems, and whether or not patterns observed for terrestrial ecosystems adequately explain processes in other ecosystems, like vegetated tidal wetlands (Spivak et al., 2019). Here, we aimed to deliver a thorough systematic review of the decomposition literature to investigate how global change (which in this paper encompasses temperature, precipitation, nutrient loading, and sea level rise) influences mangrove litter decomposition rates.

Mangroves are highly productive ecosystems that occur in the intertidal zones of tropical and subtropical regions (Alongi, 2015) and provide numerous ecosystem services and benefits (Barbier et al., 2011). Mangrove forests contribute to the fertility of coastal waters by producing large amounts of OM whose decay products are incorporated into food chains (Granek & Ruttenberg, 2008; Holmer & Bachmann Olsen, 2002; Kristensen et al., 2008). The OM that is not consumed or decomposed (recalcitrant fraction) accumulates in the soil pool, contributing to the storage of blue C (Chmura et al., 2003) that can accrete vertically over time under anoxic conditions (Morris et al., 2002). For example, root growth and sediment binding dynamics drive accumulation of coastal wetland C belowground, but loss of C via decomposition can offset these gains (Cahoon et al., 2021; Neubauer & Megonigal, 2021; Spivak et al., 2019). Redox conditions are the primary driver of OM decomposition in terrestrial systems, but under low-oxygen conditions and where tides can introduce molecular oxygen, such as in temperate and tropical coastal wetlands, it may be less important for microbial C processing and other drivers may increasingly come into play (Chapman et al., 2019). Rates of OM export and C accumulation are strongly influenced by decomposition rates, which are in turn mediated by environmental conditions (e.g., nutrient availability, temperature) (citations within). These factors are expected to be altered by global change (Alongi, 2008; Jennerjahn et al., 2017; Ward et al., 2016) and anthropogenic activity, with implications for decomposition and blue C storage in these highly productive ecosystems.

Mangroves are among the most C-rich forests in the tropics (Donato et al., 2011) due to high primary production and slow decomposition (Cebrian, 1999). Despite their relatively small land coverage, these habitats typically sequester C in their sediments several times faster than terrestrial ecosystems (McLeod et al., 2011). The belowground C pool in mangroves has been shown to constitute over 50% (occasionally over 90%) of the total ecosystem C stock of mangroves (Donato et al., 2011; Kauffman et al., 2011), which can extend several meters beneath the soil surface (Donato et al., 2011; McKee et al., 2007). Mangroves can adjust to changing sea levels through subsurface accumulation of refractory mangrove roots and other OM inputs (McKee et al., 2007), which if left undisturbed, can remain stored for centennial to millennial time scales (Duarte et al., 2005). Therefore, decomposition dynamics are critical in the long-term stability of these ecosystems and represent an important means of mitigating climate change (Duarte et al., 2013).

Mangrove environments constitute sites of significant C processing with a potentially high impact on the global C budget (Alongi, 2008; Dittmar et al., 2006) and to sea level rise mitigation (Menéndez et al., 2020; Saintilan et al., 2020), which strongly depends on the biotic and abiotic conditions that drive decomposition. As such, mangroves are receiving growing attention in the climate change debate in relation to their blue C sequestration potential (Alongi, 2020; Lovelock & Reef, 2020). However, our understanding of controls on soil C in blue C ecosystems and particularly for mangroves, is lacking (but see MacKenzie et al., 2021; Sanderman et al., 2018; Walcker et al., 2018). A systematic assessment of the factors driving mangrove litter decomposition, which includes roots, leaves, and wood, is necessary to better characterize how blue C storage will be modified as ecosystems are altered by global change. Further, decomposition rates are often used in models to calculate

C storage (Belshe et al., 2019; Dai et al., 2018) and better parameterization of the modelled potential of blue C requires an improved quantification of mangrove litter decomposition.

In this systematic review, we explored the body of literature related to decomposition in response to global change drivers. We subsequently report the current knowledge and gaps regarding decomposition in mangrove ecosystems in relation to proxies of global change. Through this exercise, we answer the following research questions: (1) Do mangrove biomass fraction decay rates vary in relationship to different global change drivers (temperature, precipitation, nutrient loading, and sea level rise)? (2) How do litter decay rates vary among different genera in mangrove ecosystems? (3) What is the potential for alterations in decay rate to affect the magnitude of blue C storage in mangrove ecosystems? As of the writing of this review, there were only two papers that explicitly and experimentally studied decomposition under global change variables (Contreras et al., 2017; Yang et al., 2018) given our inclusion criteria. Therefore, we investigated the relationships between decay rate and proxies of global change (i.e., latitude, season, nutrient loading and inundation level) through a systematic review approach using data that could be extracted from relevant research papers. This paper is the first comprehensive global systematic review that we know of that synthesizes decay rates of mangrove litter, roots, and wood in relation to global change variables within the context of blue C. These findings will contribute to an improved understanding of OM decomposition in mangrove ecosystems and the implications therein.

2 | METHODS

We conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) framework (Moher et al., 2009) (Figure 1).

2.1 | Study inclusion process

In developing the search strategy, the authors included a research librarian, who utilized a modified version of the PICO (Population, Intervention, Comparison, Outcome) process to address our research questions (Foster & Jewell, 2017). The search string encompassed terms related to population (mangroves), variables (climate change), and outcome (decomposition) (Table 1). We searched five databases and citation indexes, including databases indexed through Web of Science (Core Collection, Biological Abstracts, BIOSIS Previews), Scopus, and EBSCO GreenFILE. The search string used in each database can be found in Appendix S1. The search fields varied by options available in respective

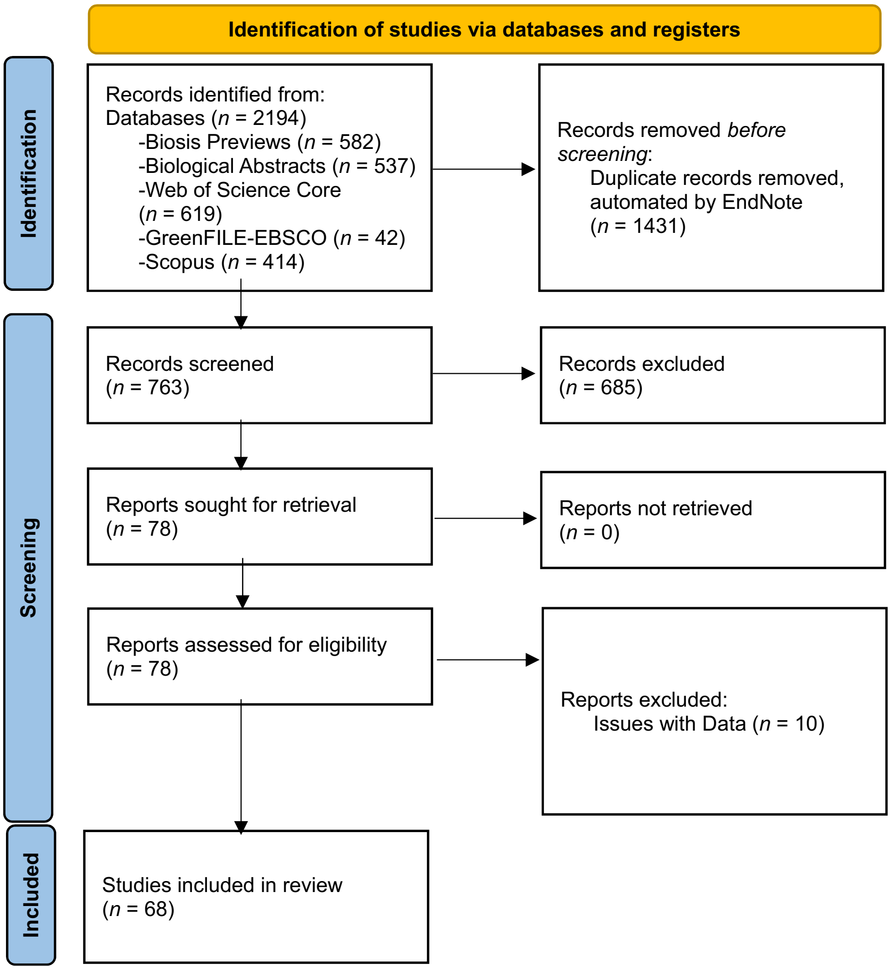

FIGURE 1 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram for this systematic review. Adapted from Page et al. (2021).

TABLE 1 The populations, variables, and outcomes relevant to the systematic review.

Populations	Variable	Outcome
Global mangrove ecosystems (swamp, forest or ecotone). Species included but not limited to:	Variables that may affect decomposition rate directly or indirectly:	Any change in above- or belowground decomposition rate reported with a decay constant (*k*), mass remaining, or ash-free dry mass (AFDM)
Rhizophora	• Sea level rise	
Avicennia	• Elevated carbon dioxide	
Laguncularia	• Precipitation	
Sonneratia	• Salinity	
Ceriops	• Soil temperature	
	• Atmospheric temperature	
	• Nutrient enrichment	

databases. For the Web of Science-indexed databases, we searched using a topic search. For Scopus, we searched using the title-abstract-keyword search. For EBSCO GreenFILE, we searched all fields. For all databases, we narrowed search results to scholarly and peer-reviewed journal articles only. Grey literature, personal communications, and unpublished data were not included. When articles were inaccessible through the databases, inter-library loans were utilized to gain access. Final searches were completed twice during the literature review, with the first on March 5, 2020, and the second final searches on August 16 and 18, 2021. We added August 2021 searches to include any articles indexed between March 2020 and August 2021 because of delays in the review process attributed to institutional closures and interruptions caused by the COVID-19 pandemic in March 2020. All final searches yielded 2194 articles, with the deduplication process removing 1431. The EndNote citation manager was utilized to deduplicate repeated references across databases. Reviewers assessed a final total of 763 articles across two review periods starting on 4 May 2020, and 18 August 2021, respectively (Figure 1).

For the review process, the research team utilized the Rayyan intelligent systematic review tool (Ouzzani et al., 2016). After exporting and deduplicating references using EndNote, the librarian used Excel to randomize the order of the articles to be reviewed, assigned two reviewers to each reference (there were three reviewers total), and then imported the assigned article references (including title, authors, institution, journal, abstract, and when available, keywords) into Rayyan (Ouzzani et al., 2016) for review. The librarian did not take part in reviewing articles. Reviewers used an inclusion/exclusion protocol to make final decisions for each article in Rayyan after screening the title, abstract and full-text levels. Reviewers made inclusion and exclusion decisions with a blind approach and did not review decisions until each team member had completed their respective reviews. Reviewers discussed any discrepancies in the screening process and in their understanding and application of the inclusion criteria. This process was repeated until there was 100% agreement among reviewers for inclusion.

2.2 | Study inclusion criteria

The relevant types of study designs that were included were primary studies that examined quantitative changes in above- and belowground decomposition through a mass loss approach in mangrove ecosystems worldwide (Table 1). Mangroves and mangrove associates are included in the population. Variables included either explicitly manipulated variables of interest or referenced their implications for decomposition. Decomposition outcome, regardless of tissue type (i.e., leaf, root, propagule, pneumatophore, wood) or method (i.e., litter bag, litter box), included any change in above- or belowground decomposition rate reported as a decay constant (*k*), mass remaining, or ash-free dry mass (AFDM) using data generated during field and mesocosm studies. Non-English papers were included when translations were possible. Excluded study designs included qualitative studies that had no primary decomposition measurements (i.e., reviews), modelling or meta-analyses using secondary decomposition data, and studies that used any "proxy" of litter decomposition (i.e., respiration, shear strength, cotton strips, tea bag index). Although there are many more papers in the literature that examine decomposition in mangrove ecosystems, this rigorous inclusion/exclusion process resulted in 78 papers for data extraction.

2.3 | Data extraction

After full-text screening, the 78 remaining studies were appraised by the review team according to their design and relevance to the review. A data extraction workbook was adapted from the Coastal Carbon Research Coordination Network data submission template (https://serc.si.edu/coastalcarbon). Each reviewer extracted relevant data from 26 papers, with each paper being reviewed independently by at least two reviewers. Standard statistical data for mass loss (i.e., mean, standard deviation, standard error, and sample sizes) for each study were extracted. When *k*-values were not reported, authors calculated them from mass loss data or supporting information, using the exponential decay model $y = y_0 e^{-kt}$, where y = final biomass, y_0 = initial biomass, and t = time the bag was deployed in days. If there was not enough supporting data to calculate *k*, the paper was removed from the analysis. If a range of tissue weight was reported for initial litter mass, the average was used when calculating *k*. In one instance, a paper was excluded during this step because the range of tissue weight was so large that it likely overinflated the *k*-value (Woitchek et al., 1997). Reviewers employed the web-based data extraction software WebPlotDigitizer Version 6.5 to retrieve data presented in figures (Rohatgi, 2022) that were not reported in the text or supplemental materials (i.e., mass remaining). A large percentage of the papers did not report sample size, standard deviation, standard error, mass remaining (%), or AFDM, and these metrics could not be calculated due to lack of information. Further, most papers were observational in nature, comparing decomposition among species and tissue types or along environmental gradients, and therefore, they were not conducive to examination of effect sizes across multiple studies. Hence, only *k*-values were investigated in this study, and our analysis followed the systematic review process rather than a meta-analysis using effect sizes.

Other supporting information, such as geographical study location, relevant biophysical data, and detailed decomposition protocol data were extracted from the papers. During the extraction process, latitude and longitude were standardized to decimal degrees (DD) using an online coordinate converter. Points were individually checked for validity and were changed to the general location specified in the paper if the conversion did not properly translate. Once data extraction was complete, 10% of each reviewer's papers were reviewed by another reviewer for QA/QC. If there were discrepancies in extracted data, reviewers discussed for understanding and application until a consensus was reached by all three reviewers. Ten papers were excluded during the extraction process due to lack of data ($n = 4$), issues with data presentation ($n = 2$), inability to translate ($n = 1$), and/or inappropriate experimental design ($n = 3$). The remaining 68 papers were then used for this study (Figure 1), which generated 480 data points for analysis. The full database can be found in Appendix S2 and a comprehensive list of these data references can be found in Appendix S3.

2.4 | Statistical analysis

The data extraction process revealed insufficient quantitative data for a meta-analysis to be conducted (Rinehart & Hawlena, 2020; Scheiner & Gurevitch, 2001). Therefore, latitudinal relationships were investigated through linear regression, and global change proxies were discussed in qualitative terms. Systematic reviews aim to provide a robust overview of the efficacy of an intervention, or field of research, and serve to develop ideas and advance conceptual frameworks.

2.5 | Latitudinal relationships

Due to violations of heterogeneity of variance and normality assumptions, we conducted nonparametric Spearman's rank-order correlations to examine patterns of decay with increasing distance from the equator, thereby allowing us to examine patterns along the full tropical to subtropical temperature gradient reported for mangroves in this study. Analyses included all field-based studies in which latitude and *k*-value for mangrove biomass were reported but excluded mesocosm experiments under controlled environmental conditions. Separate analyses were performed to explore the relationships between (1) all *k*-values and latitude, regardless of genus, litter type, or other factors; (2) *k*-values and latitude by genus; (3) *k*-values and latitude by tissue type; (4) *k*-values and latitude by genus and tissue type; and (5) *k*-values by litterbag placement (e.g., soil surface, buried). Most genera (e.g., mangrove associates) and tissue types (e.g., pneumatophores, flowers) were under-represented in the dataset resulting in low sample sizes. While these data were included in the overall analysis for all *k*-values and latitudes, they were excluded from other analyses unless $n \geq 10$. While this sample size is low for testing null hypotheses of populations' correlations with latitude (Bonett & Wright, 2000), we opted to use it so that general patterns for some under-represented taxa in the literature could be explored. Significance was examined at the $a = 0.05$ level but should be considered cautiously when $n < 30$. Analyses were performed using JMP 15.0 (S.A.S Inc., Cary, North Carolina, U.S.A.).

2.6 | Biotic drivers

While litter genus and species were documented for each paper, species were not evenly represented across studies, resulting in uneven and often small sample sizes (Table 2). Therefore, species were collapsed, and only genus-level *k*-values were summarized. Biomass (leaf, root, wood) decay rates were averaged across genus. Due to low sample size of the other substrate types (i.e., pneumatophores, flowers, stipules), only leaves, roots, and wood were documented (however, see Albright (1976) and Kamal et al. (2020) for additional biomass fractions).

2.7 | Abiotic drivers

We categorized *k*-values of leaf, root, and wood litter in relation to bag location (i.e., where the decomposition bag was incubated). Bag locations used included air, buried (belowground), soil (surface), and submerged (in water). Most of the samples were incubated on the soil surface ($n = 339$), rather than buried, suspended in the air, or submerged in water, likely due to the prevalence of leaf litter as a substrate as compared with root and wood fractions.

2.8 | Global change drivers

There were only two papers that explicitly and experimentally looked at decomposition under global change variables (Contreras et al., 2017; Yang et al., 2018). Therefore, we investigated the relationships between decay rate and proxies of global change that could be extracted from relevant research papers. Out of the 68 papers included in this systematic review, only 22 recorded decomposition rates under a variable that could be used as a proxy for global change (i.e., temperature, precipitation, nutrient loading, and sea level rise) (Figure 2). Only three papers could be binned for the temperature proxy, hence the small

TABLE 2 *k*-values across mangrove genus and tissue type.

Genus	*n*	*k* average (leaves)	*n*	*k* average (roots)	*n*	*k* average (wood)
Acanthus	2	0.04 ± 0.006				
Acrostichum	2	0.008 ± 0.0004				
Avicennia	140	0.009 ± 0.0005	30	0.003 ± 0.0002	24	0.002 ± 0.0001
Bruguiera	25	0.009 ± 0.001	8	0.002 ± 0.0003		
Ceriops	2	0.008 ± 0.003	2	0.002 ± 0.0007		
Heritiera	2	0.006 ± 0.004			1	–
Kandelia	10	0.02 ± 0.005			2	0.002 ± 0.001
Laguncularia	12	0.01 ± 0.003			17	0.0005 ± 0.0001
Rhizophora	90	0.008 ± 0.0006	8	0.002 ± 0.0003	23	0.001 ± 0.0005
Sonneratia	6	0.03 ± 0.007				
Thespesia	1	0.002 ± 0.000			1	–
Xylocarpus	2	0.02 ± 0.001			2	0.0006 ± 0.001
Mixed	32	0.009 ± 0.002	22	0.002 ± 0.0002		
Total mean	327	0.009 ± 0.0005	69	0.002 ± 0.0001	70	0.001 ± 0.0003

Note: Means ± standard error are reported.

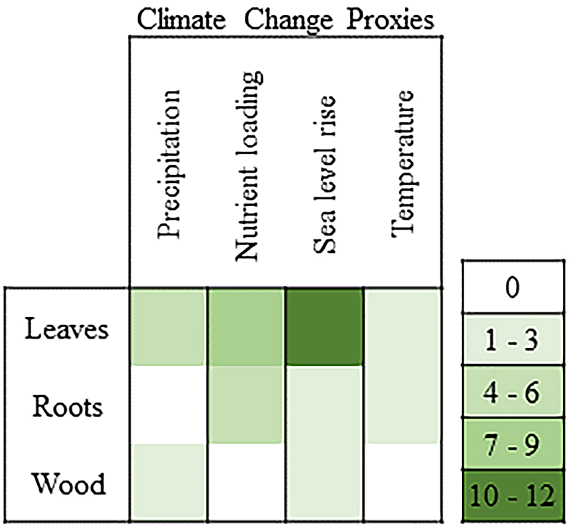

FIGURE 2 Number of references reporting decay rates for mangrove biomass fractions (leaves, roots, and wood) under each of the four global change proxies (precipitation, nutrient loading, sea level rise, and air temperature). Darker shades indicate more sources (maximum = 10) and white indicates zero sources.

sample size provided insufficient direct or proxy experimental data to investigate temperature trends. Precipitation data were categorized into seasonal treatments because levels of precipitation could not be extracted from the literature. These categories were based on the seasons (wet and dry) reported in the paper, which are not standardized across latitudinal gradients due to low sample size. Nutrient loading was binned by nutrient addition studies, which could not be standardized due to varying treatments and levels within. Leaf and root decomposition data were presented in several papers ($n = 8$, $n = 4$; respectively) and could be collated into nitrogen (N) only, phosphorous (P) only, N + P (NP), and control (C) categories. Intertidal inundation was used as a proxy for sea level rise (SLR), as there were no papers that explicitly manipulated water levels or inundation regimes. Because elevation or amount of inundation could not be defined for most papers, *k*-values were categorized into low-, mid- and high-intertidal categories. Data are reported as mean ± standard error throughout the manuscript.

3 | RESULTS

Out of the 763 papers screened, 68 met the inclusion criteria for the systematic review. The papers represented a wide geographical distribution (Figure 3a) with methodological heterogeneity, and were published between 1976 and 2021, with the bulk published between 2015 and 2021 (Figure 3b). The majority of papers used the litter bag technique (92%), which encompassed varying sizes of bags and mesh, as well as the amount of biomass incubated. Experiment duration for biomass decomposition varied considerably, from a 28-day minimum to 5475-day maximum, with a median duration of 165 days. Study duration also varied by litter type; leaf litter studies ranged from 28–1460 days, roots from 150–584 days, and wood from 182–5475 days. Most papers reported decay of leaf litter (86%) on the soil surface. Only 18%, 11%, 1%, and 1% measured decay of belowground roots, wood, pneumatophores, and floral parts, respectively. There was insufficient data to perform a meta-analysis using effect sizes from the results of this systematic review. Of the 68 papers, only two explicitly manipulated conditions for decomposition, and only 22 recorded decomposition rates under a variable that could be used as a proxy for climate change.

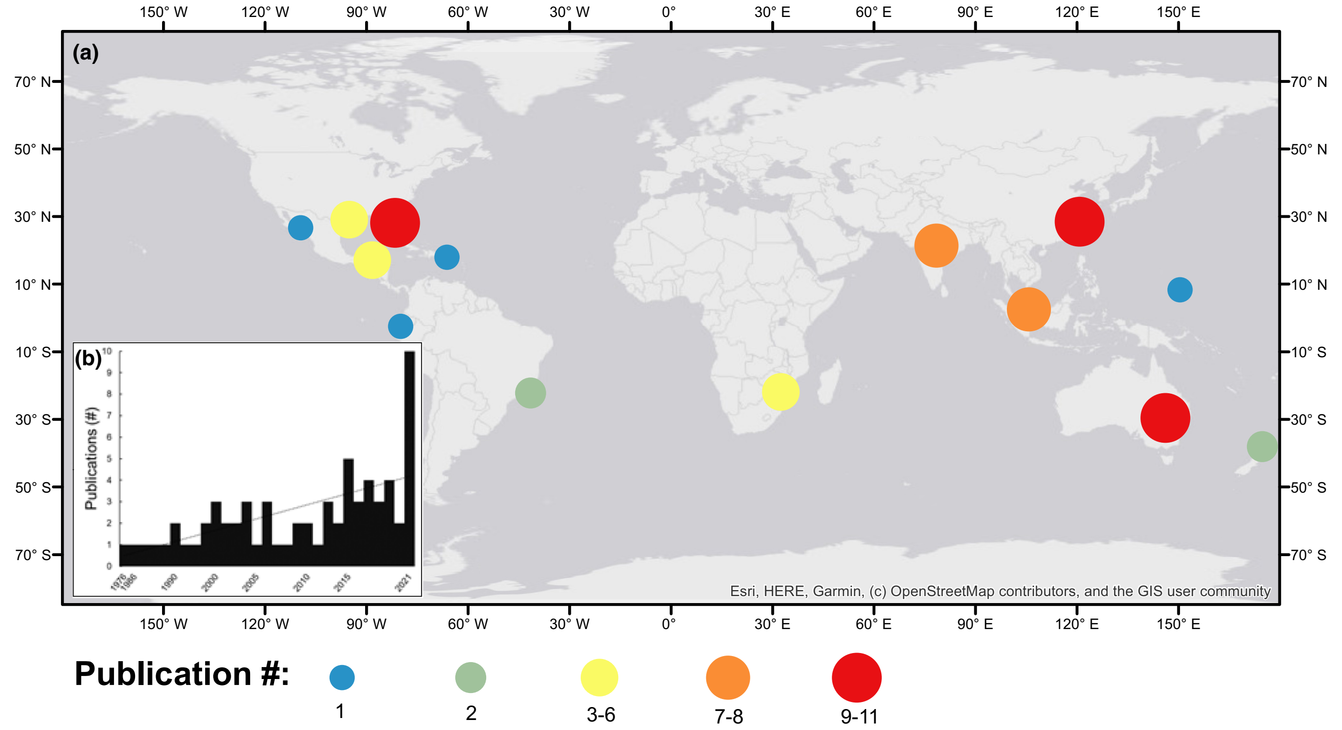

FIGURE 3 (a) Distribution of decomposition study sampling sites ($n=70$), and (b) number of publications per year from 1976 through 2021.

3.1 | Latitudinal relationships

The studies included in this analysis encompassed the full tropical to subtropical latitudinal gradient of mangroves (2.49–36.71°), which spans a mean annual temperature gradient of ~7°C. Across this latitudinal gradient, the decay of all mangrove litter ranged from <0.0001–0.07 g/d. Overall, rates of OM decomposition were not correlated with absolute latitude ($\rho_{444}=-0.04$, $p=0.4$; Figure 4a). Decay did vary with latitude for some genera (Figure 4b–f) and tissue types (Figure 5). Decay rates for *Laguncularia* and *Rhizophora* litter declined significantly with increasing absolute latitude ($\rho_{27}=-0.9$, $p<0.0001$; $\rho_{125}=-0.4$, $p<0.0001$, respectively), regardless of litter type (Figure 4e,f). Whereas decay rates of *Bruguiera* litter increased with increasing latitude ($\rho_{28}=0.5$, $p=0.003$; Figure 4c), while those for *Avicennia* and *Kandelia* litter were not related to absolute latitude ($\rho_{176}=0.1$, $p=0.2$; $\rho_{11}=0.2$, $p=0.5$, respectively; Figure 4b,d).

When examined by tissue type across all genera, there was no relationship between the decay of mangrove leaves and latitude ($\rho_{301}=-1.1$, $p=0.3$; Figure 5a). However, decay rates of mangrove roots and wood, which were lower overall than those for leaves, were correlated with latitude, although the patterns were opposite (Figure 5b,c). Decay of roots increased with increasing absolute latitude ($\rho_{57}=0.4$, $p=0.003$), while decay of wood decreased ($\rho_{68}=-0.4$, $p=0.003$). When these tissue-specific patterns were examined within genera, there were no significant relationships between decay of roots and latitude for any genus, and most genera did not show a significant relationship with leaf or wood decay. However, decay of *Laguncularia* and *Rhizophora* leaves and wood significantly declined with increasing latitude (leaves: $\rho_{11}=-0.7$, $p=0.02$; $\rho_{89}=-0.3$, $p=0.003$; wood: $\rho_{16}=-0.5$, $p=0.03$; $\rho_{21}=-0.6$, $p=0.005$, respectively).

There were no significant latitudinal relationships for litter placed on the soil surface, submerged in water, or buried in the soil, although, for those studies in which litter was suspended in the air, decay declined with increasing latitude ($\rho_{18}=-0.7$, $p=0.001$).

3.2 | Biotic and abiotic drivers

Decay constant varied across biomass fractions (Figure 6). Regardless of taxa, leaves appear to decompose 4.5 times faster than roots, and roots decompose 1.8 times faster than wood (Table 2). Decomposition of mangrove leaves and roots varied across genus (Table 2). Wood decay exhibited slow decomposition rates as compared to leaves and roots (Figure 6, Table 2).

There was low variance across bag incubation location (soil surface, submerged, buried, in the air) *k*-value means (Table 3) (Figure 7). Conversely, wood appears to decompose much more slowly when buried or hanging than when incubated on the soil surface (Table 3). When leaf and root substrate types were collapsed for visualization, bags incubated at the soil surface or submerged appear to decompose faster than buried bags (Figure 7, Table 3).

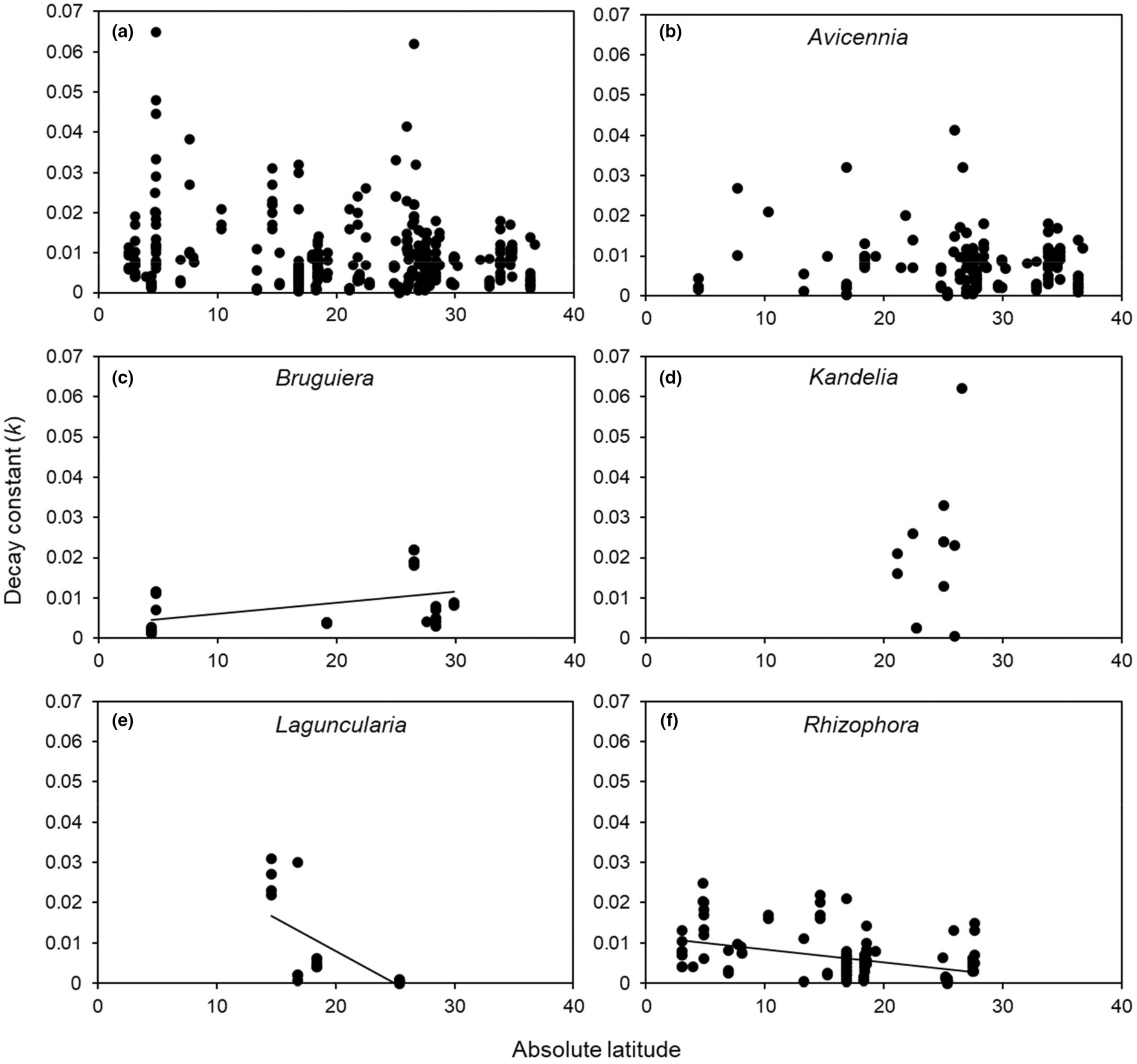

FIGURE 4 Relationship between decay rate (g/d) and absolute latitude for (a) all mangrove litter regardless of genus or other factors ($n = 445$); (b) *Avicennia* litter ($n = 177$); (c) *Bruguiera* litter ($n = 29$); (d) *Kandelia* litter ($n = 12$); (e) *Laguncularia* litter ($n = 29$); (f) *Rhizophora* litter ($n = 126$). Lines depict linear trends for variables with significant correlations ($p < 0.05$).

4 | DISCUSSION

4.1 | Latitudinal relationships

Decomposition rates have been shown to decline as temperature decreases with increasing latitude or altitude and are generally predicted to increase with warming (Aerts, 1997; Couteaux et al., 1995; Kirwan et al., 2014; Tiegs et al., 2019). Within the tropics, however, where temperature gradients and annual variation are less pronounced, the effects of climate warming on ecological process rates have been less well-studied and assumed to be less severe than in temperate and polar regions (Feeley et al., 2017; Sheldon, 2019). Yet, some have suggested that the impacts of warming on tropical communities and ecosystems may be more significant than previously assumed, leading to species' latitudinal range shifts and changes in ecosystem functions (reviewed in Sheldon, 2019). To understand the implications of climate change on the global C cycle, it is important to examine patterns of mangrove OM decay along latitudinal or other temperature gradients. Overall, rates of OM decomposition were not correlated with absolute latitude. While this lack of relationship likely reflects the weak temperature gradient across the latitudinal range, it may also be due to the overrepresentation of some papers in the dataset and of some latitudes across the full latitudinal range. For example, on average,

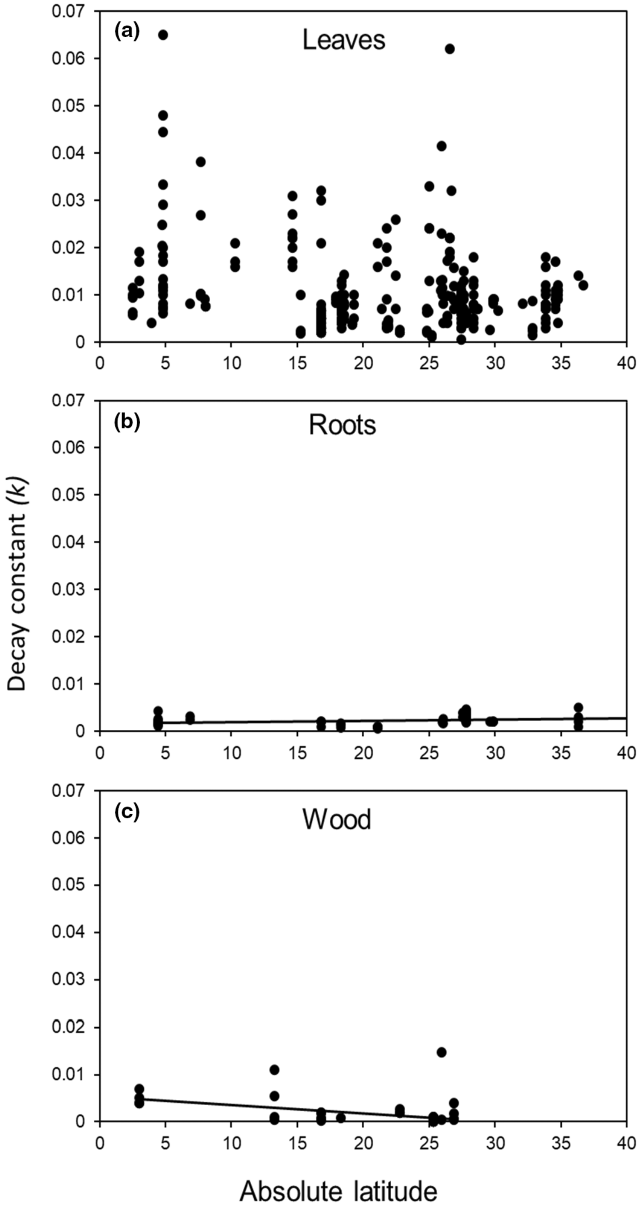

FIGURE 5 Relationship between decay rate by litter type (g/d) and absolute latitude for (a) leaves ($n = 302$); (b) roots ($n = 58$); and (c) wood ($n = 69$), regardless of genus or other factors. Lines depict linear trends for variables with significant correlations ($p < 0.05$).

studies contributed six data points to the full dataset, but this was highly variable, ranging from 1 to 33 data points per study. Further, the number of studies generally increased with increasing distance from the equator, with the majority occurring between 20° and 30°.

Despite the lack of an overall relationship with latitude, decay did vary with latitude for some genera and tissue types. This pattern of decreasing decay with increasing latitude (i.e., decreasing temperature) is consistent with those reported for other taxa, including terrestrial and wetland groups (e.g., Aerts, 1997; Couteaux et al., 1995; Kirwan et al., 2014; Tiegs et al., 2019), and suggests temperature may exert some influence on OM decay for these genera. On the other hand, decay rates of *Bruguiera* litter increased with increasing latitude counter to what would be expected if temperature regulated its decay, while those for *Avicennia* and *Kandelia* litter were not related to absolute latitude. The lack of relationship for *Kandelia* is not surprising given the narrow range (21.11–26.55°) in which these studies were conducted, as temperature likely did not vary much across these study sites. *Avicennia*, which is a relatively freeze-tolerant genus found at the poleward limits for mangroves (Cavanaugh et al., 2014; Osland, Day, et al., 2020), spanned the widest latitudinal gradient (4.42–36.71°) of all taxa included in this analysis, thereby encompassing the broadest temperature gradient. If its decay were primarily governed by temperature, we would have expected rates to decline with increasing latitude. Because this was not the case, it is likely that other factors regulate the decay of *Avicennia* litter.

Latitudinal decay patterns appear to be largely independent of litterbag location during the studies. We did not observe significant latitudinal relationships for litter placed on the soil surface, submerged in water, or buried in the soil, although, for those studies in which litter was suspended in the air, decay declined with increasing latitude. This pattern may reflect a temperature effect, as litterbags exposed to air would be less insulated by water or soil, and therefore may be more sensitive to variations in air temperature with latitude. Collectively, these latitudinal relationships suggest that factors other than temperature are more likely to regulate the decay rates of most mangrove litter. While decay has been shown to decline with increasing latitude or with decreasing temperature (e.g., Kirwan et al., 2014; Tiegs et al., 2019), these patterns were demonstrated across much broader geographic or temperature ranges than those encompassed by mangroves, and as such, temperature likely overwhelmed the influence of litter quality and other factors, like microbial activity, on OM processing in those cases. Across these broader ranges, atmospheric temperature increases are predicted to drive globally important losses of soil C in terrestrial and wetland ecosystems in the coming decades by stimulating decomposition (Crowther et al., 2016; Kirwan & Blum, 2011); however, there was insufficient direct or proxy experimental data to test this claim through our systematic review, as well as in Feher et al. (2017). With the tropical to subtropical distributions of mangroves, in which temperature variance is relatively low, biotic drivers, like litter source (e.g., taxa) and tissue type (e.g., leaves, roots, wood), and abiotic drivers, like soil anoxia and nutrient availability, may exert a stronger influence on litter decay. Thus, it is important to consider the indirect impacts of global change on decay through its effects on shifting species' distributions, biomass allocation, and litter quality.

4.2 | Litter taxa and type

Latitude does not appear to exert a strong influence on mangrove litter decay, suggesting that biotic drivers, such as litter taxa and tissue type, play a larger role in decomposition. Leaf litter and root detritus are primary resources for decomposers, and their quality and quantity have strong effects on decomposer activities in various ecosystems (Couteaux et al., 1995; Hobbie et al., 2012;

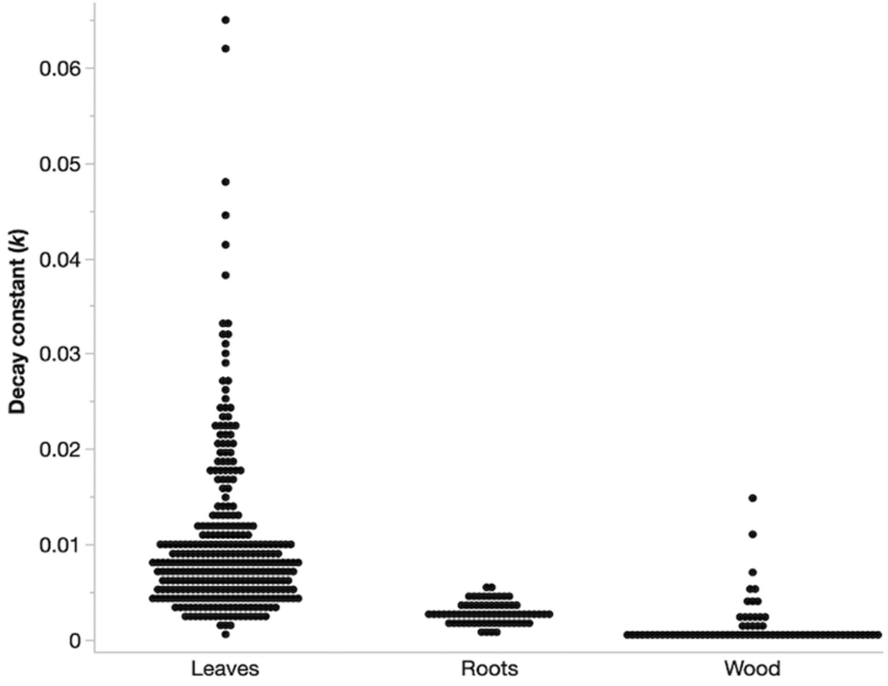

FIGURE 6 Column scatter graph depicting litter type variability across substrate *k*-values. Leaves (*n* = 305), roots (*n* = 42), wood (*n* = 66).

TABLE 3 The influence of bag location on tissue type decomposition (*k*).

Litter type	Bag location	*n*	*k* average
Combined			
	Air (hanging)	–	–
	Buried	32	0.003 ± 0.0003
	Soil surface	245	0.01 ± 0.0008
	Submerged	26	0.02 ± 0.007
Leaves			
	Air (hanging)	–	–
	Buried	7	0.006 ± 0.0008
	Soil surface	283	0.01 ± 0.0005
	Submerged	30	0.01 ± 0.002
Roots			
	Air (hanging)	–	–
	Buried	57	0.002 ± 0.0001
	Soil surface	12	0.002 ± 0.0003
	Submerged	–	–
Wood			
	Air (hanging)	18	0.0005 ± 0.0001
	Buried	15	0.0004 ± 0.0000
	Soil surface	37	0.002 ± 0.0005
	Submerged	–	–

Note: Means ± standard error are reported. Leaf and root fractions were collapsed for the combined category.

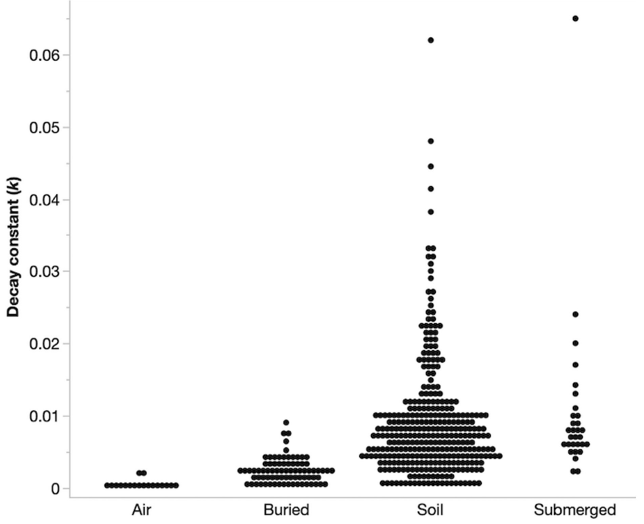

FIGURE 7 Column scatter graph depicting variability of *k*-values across decomposition bag incubation location for all litter and root types. Air (*n* = 18), buried (*n* = 84), soil (*n* = 346), submerged (*n* = 30).

Mooshammer et al., 2012; Strickland et al., 2009). Decay constants varied across biomass fractions and leaves appear to decompose faster than roots, while roots decompose faster than wood. This accelerated decomposition rate of leaf litter may be driven by litter quality or by the environment in which the litter is decomposing.

It has been suggested that different litter and species types decompose at different rates, and thus contribute to nutrient cycling and C storage differently (e.g., Couteaux et al., 1995). Decomposition of mangrove leaves varied across genus, which may reflect differences in stoichiometry. While there are many environmental variables that drive decomposition, litter C:N can be an important control (Couteaux et al., 1995; Enríquez et al., 1993; Valiela et al., 1984); plant matter with higher C:N ratios (refractory, low quality) generally decomposes more slowly than material with lower C:N ratios (labile, high quality) (Enríquez et al., 1993; Webster & Benfield, 1986). Similar to other tree species, mangrove leaves are known to have higher nutrient concentrations than roots or wood, which likely renders them more decomposable by microbes that are nutrient-limited (Khan et al., 2007).

Additionally, root biomass decay rate varied across genus, suggesting that C:N may help drive the decay rate in submerged, anoxic environmental conditions more so than other biotic drivers. Mangrove roots decompose slowly and are an important component of elevation building in tropical ecosystems (Cahoon et al., 2021; Coldren et al., 2019; Krauss et al., 2014; McKee et al., 2007; Osland, Feher, et al., 2020). Thus, their decomposition rate is important to constrain for both blue C estimates and for determining wetland resilience to SLR.

Wood decay exhibited slow decomposition rates as compared with leaves and roots. Woody debris in mangrove ecosystems is common due to hurricane-induced mortality and occasional drought (Castañeda-Moya et al., 2020; Krauss et al., 2005; Krauss & Osland, 2020; Simard et al., 2019; Smith et al., 1994) and can be an important initial source of N in ecosystems, eventually becoming a net N sink (Robertson & Daniel, 1989; Romero et al., 2005; Zimmerman et al., 1995). Wood is also important in blue C budgeting, particularly as it decomposes slowly and can sequester large amounts of C (Lovelock, Fourqurean, et al., 2017). Differences in litter taxa and fraction breakdown suggest that stoichiometry is a driving force in mangrove decay and should be investigated in greater detail under indirect global change scenarios and along latitudinal gradients.

4.3 | Incubation location

While litter quality is a major driver in mangrove decay rate, the environmental conditions in which decay occurs also affect the rate at which microbially mediated decomposition proceeds. Abiotic exogenous conditions (e.g., oxygen availability, temperature, nutrients, water, and soil type) and decomposer activity should drive rates of decomposition in mangrove ecosystems. There was low variance across bag incubation location (soil surface, submerged, buried, in air) *k*-value means, suggesting that site-specific environmental conditions may not dictate decay rates in mangrove systems as much as previously postulated. Conversely, wood appears to decompose much more slowly when buried or hanging than when incubated on the soil surface, suggesting that higher oxygen availability and tidal flushing likely encourage leaching and bacterial colonization in this environment (Romero et al., 2005). Bags incubated at the soil surface or submerged (i.e., the soil water interface) appear to decompose faster than buried bags, which is likely driven by the rapid leaching of nutrients by microbial breakdown or the physical impact of tides (Boulton & Boon, 1991). Alternatively, the slow decomposition rates of hanging litter are likely limited by moisture and decomposer organisms (Lee et al., 2014), while the decomposition of buried litter is limited by oxygen (Chapman et al., 2019; Middleton & McKee, 2001). Overall, the stable conditions of air and belowground environments translate into slow decomposition rates, as opposed to the variable conditions at the soil–water interface. However, these conditions may be further modified by global change variables, ultimately affecting blue C storage potential.

4.4 | Precipitation

Extreme precipitation is expected to intensify with global change over large parts of the globe (Ingram, 2016; Tabari, 2020). Decomposition is hypothesized to be affected by increases in precipitation due to changes in nutrient concentrations (Twilley et al., 1997), soil moisture (Twilley et al., 1986), reduction in salinity (Olsen et al., 1996; Zhang et al., 2021), and resulting alterations to the microbial community (Mackey & Smail, 1996; Sinsabaugh & Shah, 2011). Unfortunately, there were no papers that manipulated precipitation intensity and/or duration that were extracted from the literature through this systematic review process, representing a significant gap in our understanding of decay processes in a changing climate. However, comparisons of decay rates between wet and dry seasons may provide some insights. Several researchers have found that mangrove leaves decayed faster in the wet season than in the dry season (Aké-Castillo et al., 2006; Chanda et al., 2016; Torres et al., 2018; Twilley et al., 1997; Van Vinh et al., 2020), whereas Kamal et al. (2020) found that litter exhibited higher decay rates in the dry season. When leaves are wetted, there is an initial rapid leaching stage of the most labile OM and water-soluble compounds (Mfilinge et al., 2002) are broken down due to fungal and bacterial action. Additionally, increases in leaf decomposition could be related to the seasonal population growth of aquatic organisms (Aké-Castillo et al., 2006) or the physical impact of waves arising from precipitation events. Habitat location may be a larger driving force as precipitation events increase globally; mangroves found at the mouths of rivers or along estuaries may experience more indirect impacts on decomposition (e.g., freshwater runoff, nutrient loading) than those found on oceanic cays. This suggests that precipitation does not play a dominant role in mangrove litter decomposition and that other confounding biotic and abiotic factors should be considered when forecasting decomposition rates in these systems.

4.5 | Nutrient loading

Coastal habitats are especially vulnerable to nutrient enrichment due to their location between land and sea. Given the high levels of nutrients in global ecosystems (e.g., Paerl, 1997), there is the potential for nutrient enrichment to affect decomposition in coastal sediments. Nutrient loading to mangrove habitats has the potential to increase decomposition indirectly through altered litter quality (Hobbie et al., 2012; Prescott, 2010) and microbial community productivity (Alongi et al., 2005; Norris et al., 2001; Rivera-Monroy & Twilley, 1996). Of the 11 nutrient addition studies included in this systematic review, several found no significant differences in leaf or root litter decomposition under N, NP, or P treatments as compared with controls (Contreras et al., 2017; Feller et al., 1999; Hayes et al., 2017; Jessen et al., 2021; Keuskamp et al., 2015), whereas Ainley and Bishop (2015) found that *Avicennia marina* decomposed faster in eutrophied vs. unmodified estuaries. Simpson et al. (2020) found that decomposition was significantly different across nutrient treatments after 30 and 60 days, but by 180 days decay rates had stabilized across treatments. Furthermore, some researchers found that nutrient treatments had no significant effect on root litter decomposition (Jessen et al., 2021; McKee et al., 2007; Simpson et al., 2020), while others found that decay rates were nutrient-specific (Albright, 1976; Huxham et al., 2010; Poret et al., 2007). This may suggest that nutrient enrichment does not necessarily play a dominant role in mangrove litter decomposition, but that other biotic and abiotic factors, which are spatially and temporally dependent, are more important covariates to be considered for an accurate prediction of decomposition rates.

4.6 | Sea level rise

SLR is of particular concern for mangroves; increases in SLR are associated with erosion of the mangrove seaward fringe and inland migration of mangrove systems (Gilman et al., 2007, 2008) unable to keep pace with relative SLR. Alterations in tidal inundation due to SLR (IPCC et al., 2021) may affect the magnitude of OM decomposition, and therefore the contribution of litter to biogenic accretion. To persist under SLR scenarios and avoid submergence, mangrove ecosystems must adjust to rising sea level by building vertically (Cahoon et al., 2021). The decay rate (k) of leaves in the low-, mid- and high-intertidal incubation locations averaged 0.016 ± 0.002, 0.012 ± 0.001, and 0.005 ± 0.0008, respectively. In general, decay rates of mangrove leaf litter are greater in highly (e.g., low- and mid-) inundated locations, as compared with leaves in high-intertidal sites (de Oliveria et al., 2013; Imgraben & Dittmann, 2008; Mackey & Smail, 1996; Mfilinge et al., 2002; Middleton & McKee, 2001; Steinke & Ward, 1987). Tidal inundation plays a key role in decomposition as litter submersion results in a rapid leaching of nutrients by microbial breakdown, macrofauna, or the physical impact of tides (Boulton & Boon, 1991). Submerged conditions provide a more stable, predictable environment for small heterotrophs involved in the decomposition process and frequent submergence promotes leaching and maintains moisture and temperature conditions conducive to saprophytic decay (Reice, 1984; Robertson et al., 1993). The highly variable decomposition environment of the upper intertidal zone, with major fluctuations in temperature and degree of water cover (Webster & Benfield, 1986), leads to the slower development of bacterial flora, and hence, a slower decay rate.

A better understanding of decay in intertidal locations has implications for the export of nutrients from mangroves to the open ocean (Granek et al., 2009) and for the internal cycling of nutrients in mangrove ecosystems. If decomposition is most rapid at the interface between water and sediment, tidal flushing may be a big driving force in the decomposition and nutrient release of mangrove leaf litter. Hence, alterations at the soil water interface due to global change factors may alter the ability of mangroves to mitigate SLR (Arnaud et al., 2020) through changes in inundation regime. Additionally, root biomass decomposition (k), which is the basis for sediment OM, averaged 0.001 ± 0.0002 along the entire inundation gradient. This low decay rate, likely due to the highly saline and anoxic environment in which decay was progressing, suggests minimal alteration to vertical accretion potential or long-term C storage. Ouyang et al. (2017) also found that root decomposition was very slow across multiple biotic, climatic, geographic, and temporal drivers. This further suggests that belowground fractions of mangrove litter may not be as affected by global change variables as once presumed.

4.7 | Decomposition and estimation of blue carbon

Burgeoning interest in blue C conservation and restoration has led to calls for better estimates of blue C accumulation in mangrove ecosystems (Crooks et al., 2018; Lovelock & Reef, 2020). Given this interest and models that examine blue C storage under different climate change scenarios (e.g., Dai et al., 2018; Lovelock & Reef, 2020), our goal in this section is to provide context for how the above-described variation in litter C processing could influence blue C storage. By using the variation gathered in this systematic review of the literature, we aim to provide some simple estimates of blue C variation. We note that the extrapolations made below are informed by limited data from limited regions of the world. Even so, this exercise is useful because it underscores the necessity for more data on mangrove decay which is needed to help improve modelling efforts and to inform restoration planning with respect to choices like mangrove species; it is not intended to be predictive.

Litter C in mangrove ecosystems has three potential fates: (1) respired by microbes, (2) chemically or biologically altered to become soil organic matter (SOM), or (3) exported to adjacent estuaries or other ecosystems. Here, we perform calculations to demonstrate the need for information on, and potential importance of, the root litter biomass C pool and decomposition process in the context of blue C significance. If we use a literature-based estimate that total mangrove blue C averages 690 Mg C/ha and mangrove aboveground C stocks average 100 Mg C/ha (Alongi, 2022), we posit that belowground mangrove C stocks average about 590 Mg C/ha (Donato et al., 2011; Trettin et al., 2021). The total C storage estimate we used for the purpose of these calculations is likely conservative based on other C stock estimates (Atwood et al., 2017; Donato et al., 2011; Kauffman et al., 2020; Trettin et al., 2021). To assess the magnitude of changes in k on blue C, we use g/m^2 units. Assuming that mangrove aboveground productivity is 1000 g/m^2 and belowground productivity is 1500 g/m^2, our average k constant of 0.002 day^{-1} for root litter (Table 2) would yield a remaining litter pool of 200 g C/m^2 after 1 year. This pool is very small compared with the 69,000,000 g/m^2

of blue C in the ecosystem, and thus, any alteration in the size of this pool caused by a change in *k* is also likely to be small.

Assuming a constant belowground productivity of 1500 g/m^2 and equilibrium conditions over multiple years, the total root litter pool with a decay constant of 0.002 day^{-1} will be 1395 g/m^2 (and approximately 697 g/m^2 of C). A doubling of *k* would yield a litter pool which is 452 g/m^2 and reduce the total blue C in this hypothetical ecosystem by only 0.7% (470 of 69,000 g C/m^2). According to the average *k* constant for leaves that we found (0.009 ± 0.0004), the majority of leaf litter decays within 1 year and thus has little input into the ecosystem C pool. Additionally, up to half of the quantity of the aboveground litter, mainly leaves, can be exported to adjacent ecosystems, tidal flats, and the open ocean (Granek et al., 2009; Robertson et al., 1993) where the degradation process releases nutrients and does not become SOM. Furthermore, this number is likely underestimated due to the shredding of litter by crabs (e.g., Lee, 1998), which is not accounted for in these litter bag studies. Thus, we suggest that as long as a wetland remains hydrologically intact, changes in belowground litter decomposition will not have a large impact on blue C storage. However, episodic climatic events (e.g., hurricanes, cyclones, drought, or storm surges) and habitat alterations can influence decomposition rate on a large scale due to oxidation or alteration to plant biomass production or mortality (Duke et al., 2017; Lovelock, Feller, et al., 2017; Mafi-Gholami et al., 2020; Sippo et al., 2018) and can dramatically influence blue C (e.g., Sippo et al., 2020) in these important ecosystems.

Our review suggests that small changes in decomposition rate, as they are currently measured using litterbags, will not elicit large changes in blue C storage potential. We suggest that biomass quality and quantity, and potential shifts in its allocation between above- and belowground components, will be the main drivers of SOM incorporation into blue C stocks. Biomass quality is likely altered by mangrove species identity, as is suggested in Table 2 and Figure 6, and decay will depend on species-specific responses or biotic interactions among species to global change drivers. However, our knowledge of chemical and physical controls on SOM development and decomposition in mangrove ecosystems is very limited (but see Breithaupt et al. (2020) and Steinmuller et al. (2022) who effectively used both radio and stable isotopes to assess mangrove SOM development), and these conclusions need to be further substantiated with experimental work that explicitly manipulates global change variables in decomposition and SOM processing studies.

4.8 | Experimental design and future directions

As this systematic review revealed, there are significant knowledge gaps relating to mangrove decomposition dynamics under global change scenarios, yet, this review provides a robust overview of decomposition under proxies of global change drivers that can inform hypotheses and advance conceptual frameworks. It is our hope that the data collated in this review will propel further research and model development regarding global change impacts on mangroves. In general, we found that there is a very narrow range of average *k*-values for mangrove litter, independent of biotic and abiotic drivers, suggesting that blue C storage will not be affected to the magnitude presumed. However, this work also highlights that most studies overwhelmingly focus on leaf litter decaying on the surface, which is less likely to contribute to blue C stocks compared with roots and woody debris. Furthermore, assessment of global change impacts on mangrove decay processes needs to be explored in hypothesis-driven experiments. This review revealed that these types of experiments are currently lacking, and consequently, the conclusions presented here need to be approached cautiously. To fill the gaps identified in this review, we implore researchers to publish their mangrove decomposition studies, regardless of significance, and to conduct experiments that explicitly manipulate global change drivers.

To identify broader ecological patterns regulating the decay of OM and the potential impacts of global change on C storage and nutrient cycling, it is critical that we are able to compare studies across space and time in a robust statistical manner (e.g., meta-analysis using effect sizes to test for practical significance). Our review reveals the current difficulty in using such an approach due to a general lack of, and inconsistencies in the design of, mangrove decomposition experiments, including variation in litter type and quality, litterbag construction and deployment location, study duration, and calculation of decay among studies. To perform a robust experiment that can be compared across wetland ecosystems, decomposition protocols must be standardized, and *k*-values must be reported within the paper. We suggest that bags are 1-mm mesh size to standardize the microbial and herbivorous communities that can act on the litter. When using leaf litter, senescent leaves should be plucked directly from the trees and should be air-dried, not oven-dried. Air-drying will standardize the C:N ratios of the litter being used and will not forcibly change the chemical composition of the litter prior to the experiment. Additionally, use and report a standardized biomass weight (g) per litter bag, not a range or number of leaves. Whenever possible, report surface elevation data and soil redox potential associated with decomposition, which can help answer questions in relation to inundation, SLR and site specificity. Most importantly, always report *k*-values, preferably determined using exponential decay models, with their standard error or deviation, and sample size. The inclusion of standard deviations and sample size will allow researchers to calculate an effect size and perform a meta-analysis that provides meaningful insights into the relationship between global change variables and decay. This approach will allow for the comparison and synthesis of the individual studies in a quantitatively rigorous study (Scheiner & Gurevitch, 2001). With these standardized methods, we recommend that researchers pursue experimental designs that test hypotheses regarding global change variables, especially in a multi-factorial lens if possible. Other suggested future directions include:

- *Belowground decomposition studies*. Belowground decomposition studies with roots and wood placed in wetland sediments are lacking in the literature, but this information is important to better understand vertical accretion in wetland ecosystems. Studies should consider pairing above- and belowground decomposition bags, which will give a holistic understanding of the factors driving decomposition in the ecosystem. Furthermore, SOM is more important than fresh litter in driving blue C storage and yet we have limited knowledge of the drivers of SOM formation in coastal wetlands (Breithaupt et al., 2020; Spivak et al., 2019; Steinmuller et al., 2022). Examinations of the biogeochemistry of mangrove SOM, and its sensitivity to decomposition during environmental perturbations such as drought, fire, or hurricanes, is an important future direction of research.
- *Salinity studies*. Increased precipitation due to climate change is anticipated to lower sediment salinity (Ward et al., 2016), which could modify microbial substrate, enhance microbial breakdown and increase mangrove primary production. Experimental work, especially focused on SOM, will help forecast the indirect implications of SLR and increased precipitation on soil C storage in mangrove ecosystems.
- *Woody encroachment studies*. Many studies have focused on the decomposition of mangrove and marsh leaf litter on decay and SOM pools while overlooking the decay of recalcitrant coarse woody debris. Experimental work should focus on the increase of woody biomass in these systems and the implications to blue C storage. For example, species range shifts may alter litter quality ratios, resulting in changes to turnover rates (e.g., Kelleway et al., 2017; Macy et al., 2019; Simpson et al., 2020) and C storage (Osland et al., 2022). Additionally, the dramatic increase in woody biomass, which is much more recalcitrant and tends to decay more slowly with increasing latitude (i.e., cooler climate), has the potential to alter decay rates and C storage to a much greater extent than more labile litter sources.

5 | CONCLUSIONS

Mangrove OM decomposition is a key process that regulates energy conversion and nutrient cycling in mangrove ecosystems (McKee & Faulkner, 2000), thereby influencing the net ecosystem C storage and blue C sinks of tropical and subtropical areas (e.g., Alongi, 2014). Decomposition is expected to be altered by global change variables, and ecologists have long postulated that decomposition in wetland ecosystems would act similarly to terrestrial systems under such stressors. Decay rates of leaf litter, roots, and wood converged on a value of 0.009 ± 0.0005, 0.002 ± 0.0001, and 0.001 ± 0.0003, respectively, across continents and geomorphological settings. This narrow range in decomposition rate may be due to the small latitudinal range (e.g., temperature) that mangroves inhabit, and the submerged environment within which the litter decomposes. Despite low variability across decomposition rates, our understanding of belowground dynamics in mangrove systems needs to be expanded to better forecast changes in long-term soil C storage. Future work should incorporate suggested methods for ease of study comparison across space and time and focus on experimentally manipulating global change variables.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data used for this review can be found in its entirety in Appendix S2. Data can also be accessed here: "Mangrove Decomposition—A Review of k-Values", Mendeley Data, V1, doi: 10.17632/8b29bwjm84.1

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BIOSKETCHES

L.T. Simpson, S.K. Chapman and J.A. Cherry are wetland ecologists with over 50 years of cumulative experience in field-based ecology. The teams research occurs at the intersection of ecosystem processes and the abiotic and biotic factors that influence them, with an emphasis on blue C storage and accumulation. L.M. Simpson is a research librarian with an emphasis on systematic reviews.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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