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Review

Are Existing Modeling Tools Useful to Evaluate Outcomes in Mangrove Restoration and Rehabilitation Projects? A Minireview

Victor H. Rivera-Monroy [1,*], Xiaochen Zhao [1], Hongqing Wang [2] and Zuo George Xue [1,3,4]

[1] Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA
[2] U.S. Geological Survey Wetland and Aquatic Research Center, Baton Rouge, LA 70803, USA
[3] Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803, USA
[4] Center for Computation and Technology, Louisiana State University, Baton Rouge, LA 70803, USA
* Correspondence: vhrivera@lsu.edu

Abstract: Ecosystem modeling is a critical process for understanding complex systems at spatiotemporal scales needed to conserve, manage, and restore ecosystem services (ESs). Although mangrove wetlands are sources of ESs worth billions of dollars, there is a lack of modeling tools. This is reflected in our lack of understanding of mangroves' functional and structural attributes. Here, we discuss the "state of the art" of mangrove models used in the planning and monitoring of R/R projects during the last 30 years. The main objectives were to characterize the most frequent modeling approach, their spatiotemporal resolution, and their current utility/application in management decisions. We identified 281 studies in six broad model categories: conceptual, agent-based (ABM), process-based (PBM), spatial, statistical, and socioeconomic/management (ScoEco). The most widely used models are spatial and statistical, followed by PBM, ScoEco, and conceptual categories, while the ABMs were the least frequently used. Yet, the application of mangrove models in R/R projects since the early 1990s has been extremely limited, especially in the mechanistic model category. We discuss several approaches to help advance model development and applications, including the targeted allocation of potential revenue from global carbon markets to R/R projects using a multi-model and integrated approach.

Keywords: mangrove; modeling; agent-based; process-based; restoration; rehabilitation; hydrodynamic; ecosystem services; carbon markets

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1. Introduction

Mangrove restoration is defined as the substantial recovery of the native biota and ecosystem functions [1], whereas mangrove rehabilitation is defined as the re-establishment of the structural and functional characteristics of mangrove ecosystems [2] that may use nonnative species to provide targeted ecosystem services (ESs) [3,4]. The implementation of wetland restoration and rehabilitation (R/R, henceforth) projects has two primary challenges: (1) to identify what management strategies are necessary to eliminate or reduce the original causes of vegetation degradation or mortality and (2) to forecast their long-term (>10 years) recovery trajectories [5–9]. Because wetland development in R/R projects can take from a few years to decades, it is necessary to implement long-term monitoring and adaptive management programs to decide if the project's goals were achieved to declare its success based on "performance measurements" (PMs) [10]. These PMs involve structural (e.g., biomass, species diversity, tree height) and functional (e.g., primary productivity, carbon storage) properties. Yet, it is difficult to forecast recovery trajectories based solely on the system's initial conditions and 1–3 years of monitoring data, which is the usual duration of an R/R project, as well as when major hydrological and geomorphological alterations were the original causes of wetland degradation/mortality [6,10,11]. This forecasting limitation is compounded when regional or landscape-level environmental conditions causing the impact in the first place (e.g., precipitation, freshwater availability, sediment sources, nutrient status) are beyond the R/R project's spatial boundaries (2 ha to <1 km^2).

Ecosystem modeling has become a useful tool to overcome this forecasting limitation by evaluating potential outcomes of R/R wetland projects at different levels of analysis. For instance, some of these models focus on population dynamics, hydrological and hydrodynamic spatiotemporal patterns, or biogeochemical transformations; each model attempts to couple several processes, including vegetation development, sedimentation, and soil fertility gradient effect on plant productivity [12–21]. Yet, the utility of these models has been constrained by the lack of data and information for model calibration and validation at large spatial scales [9,22,23], especially when they are constructed to "mimic" the natural system's spatiotemporal patterns under a range of environmental and management conditions. Still, the construction of models overall to test hypotheses about ecosystem system behavior since the 1970s has been one of the major reasons for their successes over the last several decades [11,24–26]. These models are vital tools that help to evaluate how these systems—including wetlands—function under a range of environmental conditions and human impacts.

Although mangrove wetlands are recognized as one of the most productive and extensive coastal wetlands in subtropical and tropical latitudes, there is a scarcity of ecological models simulating their functional attributes or explicitly being applied in R/R projects. This is despite the economic importance of these wetlands on regional and global scales. For example, the capacity of mangrove wetlands to store organic carbon (above and below-ground) is potentially worth billions of dollars in the context of global climate mitigation plans [27]. This economic value has catapulted this mangrove ES as a top conservation priority in countries where mangrove area is extensive [28–30].

Yet, even in cases where mangrove areas are protected at the country level and under well-defined boundaries (i.e., national protected areas, biosphere reserves), they continue to be lost at different rates depending on the country's economic status [28,31]. This is because the most critical drivers controlling mangrove productivity and ESs are a complex combination of human activities (e.g., river discharge, hydrological alteration, land use change), extreme climatic events (e.g., drought, flooding), and increasing poverty [32]. The wide range of impacts at different spatiotemporal scales is well represented by the severe reduction of freshwater and sediment in both deltaic regions and large river watersheds at regional scales; another example is the rapid sea-level increase due to climate change, particularly in tropical latitudes where mangrove wetlands are dominant. This synergy of negative impacts is difficult to forecast in short-term management plans, thus highlighting the need to develop modeling tools at different levels of resolution to help identify significant threats to mangrove wetland sustainability under climate change and increasing societal pressures and needs [10,22,33,34].

Indeed, modeling tools—including ecological, hydrological, and geomorphological models—have been widely used in most coastal restoration projects, especially where long-term spatial scales are needed to forecast potential outcomes depending on the type of restoration (e.g., hydrological vs. planting) [6,7,9,35,36]. However, in the case of mangrove wetlands, the development and application of models have been limited. One of the reasons for this limitation is the lack of models that explicitly simulate mangrove forest development where mixed-species forest stands are considered at the outset. Ideally, the simulation should include the species-specific population dynamics, the regulatory role of multiple environmental gradients driving species reproductive output, tree growth rates, and the net primary productivity (NPP) [6,7,10]. Therefore, developing wetland models in R/R projects has been challenging overall, given the complex interaction among biotic and abiotic variables in coastal regions, which are increasingly altered by the compounded effect of human impacts (e.g., urban development and hydrological alterations) and climate change (e.g., tropical cyclones, sea-level rise, and a warming climate).

The main objective of this minireview is to identify in the published literature what mangrove models have been explicitly used in mangrove R/R projects and assess their utility in forecasting mangrove forest establishment, growth, and sustainability. Given the variety of approaches taken for constructing, calibrating, and validating models, we also aim to categorize and summarize the different modeling approaches. This synthesis could be the first step to assembling a "toolbox" to help identify research priorities in mangrove R/R projects and guide the application of a multiple-model integration strategy [6,10,22,23]. Thus, this paper does not review in detail the mangrove model structure or output, but we do provide a preliminary analysis to characterize the most frequent modeling approaches (e.g., agent-based, process-based, and statistical models). This includes the level of spatiotemporal resolution and current utility/application in management decisions related to R/R projects.

Because we hypothesize that there are no mangrove models addressing specific scaling issues from local to global scales when simulating multiple structural (e.g., diameter and height) and functional (e.g., carbon uptake, phosphorus availability) properties—as is the case in other types of forests (e.g., temperate [24,37]; tropical [38])—we focus this analysis on assessing research gaps; specifically, gaps related to applying models for the long-term effectiveness assessment and outcome prediction of mangrove R/R projects. Since we consider these projects as "mesocosm" experiments given their experimental origin and size [8], this minireview aims to (1) advance the identification of key biophysical processes to further develop the applicability of mangrove models in R/R projects and (2) demonstrate the urgency of the incorporation of modeling in mangrove R/R projects to strengthen current and new conceptual frameworks. These frameworks have historically been used to understand and quantify mangrove spatial distribution [39,40], recovery, resistance, resilience, vulnerability, and tipping points [34,41–43], as well as how these processes are triggered by the synergy of human and natural disturbances at multiple scales under a warming climate with rising sea level and increasing storm intensity.

2. Materials and Methods

2.1. Literature Review

We first searched for peer-reviewed publications that were related to the general statement "mangrove model" in the Web of Science bibliographic database (last accessed on 2 May 2022) to obtain an overview of the mangrove R/R projects using modeling tools. We used "mangrove" and "model" as "Topic" (TS) keywords to perform a broad search query ("TS = (mangrove) AND (TS = (model))") to obtain a raw dataset. The "Topic" included the search string "Title, Abstract, Author Keywords and Keywords Plus".

After refining this raw dataset using "restoration", "rehabilitation", "management", and "replant" as "Topic" queries, we manually filtered this dataset and removed the papers that were not related to the following themes and topics: mangrove spatial distribution/extent, carbon storage and flux, nutrient biogeochemistry, hydrology and hydrodynamics, management, and ESs to generate a final dataset for analysis. This exclusion narrowed the search to identify publications focused on understanding mangrove ecological processes (e.g., forest dynamics, biogeochemistry, and hydrology), management/conservation strategies, and the value of ESs assessment at different spatiotemporal levels to implement, monitor, and evaluate R/R projects. Some mangrove model publications, using "expert knowledge", were not included in the final dataset since they focused mainly on model development or advancements in incorporating ecosystem processes and thus did not fall within our classification criteria focused on the utility of modeling tools in the context of R/R projects.

To provide an overall background of the applications of mangrove modeling, we briefly describe the development history for some of the models in Section 4. We expect that this description can help mangrove ecologists and modelers to identify the research gaps in mangrove modeling applications and promote the implementation of novel research topics and directions.

2.2. Model Classification

The dataset was classified into six broad model categories: conceptual, agent-based (ABM), process-based (PBM), spatial, statistical, and socioeconomic/management (ScoEco) (Table 1). ABM and PBM are two dynamic models that can simulate dynamic processes over time and at multiple spatial scales. The other model categories are mostly static models, which implicitly simulate the system's temporal variability.

Table 1. Model classification and description of different model types.

Model Type	Sub-Type	Principle	Features
Conceptual model		• Conceptual models use a list of state variables and forcing functions in an ecosystem to describe and illustrate the interactions among state variables and associated processes.	• Since this tool is created to present the abstraction of reality in a system, these processes can be deployed at a relatively higher complexity level regardless of the final model version/development.
			• In some cases, prior knowledge and research products are included in the conceptual model and diagram; the model can be directly used to translate science concepts to management issues for management decisions and to communicate with government agencies and the public.
Agent-based model (ABM)		• ABM tracks the life history of individual trees (tree establishment, growth, and mortality).	• ABM captures the emergent forest properties and spatial patterns at the population level based on species-specific tree properties. • ABM requires larger computation resources as the selected modeling spatial scale increases. • ABMs can assess mangrove forest structure and carbon storage with a spatially explicit model implementation.
Process-based model (PBM)	Hydrodynamic model	• PBM calculates the water dynamic movements by solving differential equations over time and space. • PBM highlights hydrodynamic processes that depict drivers and state variables that control ground surface materials flux and interactions with adjacent ecosystems (e.g., freshwater marsh, salt marsh, and estuary)	• PBM incorporates mass and momentum conservation as well as drag force and the eddy viscosity caused by complex mangrove tree structure; thus, it underscores the vegetation influence on water movements. • PBMs are commonly applied to assess the role of mangrove wetlands in coastal protection, especially coastlines threatened by sea-level rise and other extreme weather/climate events (e.g., tropical cyclones and tsunamis)
	Hydrological model	• Hydrological and mass-balance models are considered two different types, yet both share common attributes of the mass-balance approach that ignore specific dynamic momentum of water movement across the system boundaries. • These models only consider the differences in the amount of material at the initial and at the end of a simulation time step.	• Models focus on water and material exchanges driven by system physical processes, such as water level, salinity, nutrient, and others (e.g., propagule dispersion). • Models can be used to investigate the impacts of SLR and flooding in coastal regions.
	Mass-balance ("Box") model		• Models highlight energy or materials transport or exchange between mangrove wetlands and their adjacent system by considering the mangroves as a closed "box". • Models are commonly used to assess carbon and energy fluxes across mangrove forests.

Table 1. *Cont.*

Model Type	Sub-Type	Principle	Features
	Climate model	• Global/regional climate model outputs/products are used in mangrove modeling research in either a direct or indirect way.	• The climate model output can be used as initial boundary conditions or as an independent input to initialize other models. • Some studies directly analyzed the climate model output to inform mangrove R/R activities.
Statistical model		• The statistical model is an empirical model based on observation/sampling datasets. • Models include traditional statical analysis (i.e., regression and principal component analysis) and advanced machine learning (e.g., Structure Equation model and Artificial Neural Network).	• This model is the most widely used, especially regression, not only in mangrove research but also in other ecological studies. • Statistical models are widely applied to assess forest distribution, defining allometric relationships (structure, carbon) and other ecological interactions. This model can be used directly to provide management alternatives.
Spatial model	GIS-based model	• Model mainly uses remotely sensing products.	• The spatial model largely depends on the Geographical Information System (GIS) and other geographical and spatial surveys. • Models are commonly used to investigate the spatial, and sometimes temporal, changes in mangrove distribution, extent, and some other structural attributes (e.g., biomass). • Models are used to map mangrove carbon and nutrient spatial distribution. • Models are applied to a wide range of spatial scales, from local to regional and global scales.
	DEM-based model	• Models involving the application of digital elevation model (DEM) products.	
	Statistics-based model	• This group uses some other spatial or statistical analysis techniques (e.g., Kriging).	
Socioeconomic/management model (ScoEco)	ScoEco-ES	• ScoEco models produce comprehensive evaluations based on statistical analysis, expert-based knowledge, and other survey methods (questionnaire and interview) aiming to guide and support decision-making and to plan mangrove R/R projects.	• Human activities and interferences are usually considered or summarized as statistical indexes to represent the human disturbance level. • Models are developed to evaluate the value of mangrove ecosystem services (ESs) to inform management plans by state/federal agencies.
	ScoEco-management		

In this classification scheme, a conceptual model is considered the first step in model development. It aims to "mimic" a reality using a list of state variables and forcing functions (e.g., [44]). ABM, also known as the individual-based model (IBM), uses a bottom-up methodology by tracking the behavior of individuals (or entities, e.g., trees) in the system, capturing the interactions among them and other processes. In contrast, PBM incorporates an array of mathematical or empirical equations to explicitly represent and simulate sets of bio-physical processes within a bounded domain or target system; this includes energy and/or material fluxes or exchanges.

We separated PBM into four sub-type models: hydrodynamic, hydrological, mass-balance ("Box models"), and climate models. Although most spatial and ScoEco models are rooted in statistical models, we only considered publications that reported or used statistical analyses as part of the statistical category. Structural Equation Models (SEMs) are included in the statistical model class since statistical methods are used in SEMs to determine the direct and indirect impacts of stressors and their interaction on mangrove functional properties (e.g., soil porewater salinity, moisture content, soil texture, and temperature on soil organic matter decomposition and soil organic carbon sequestration) (e.g., [45]) (Figure 1). The spatial models overall focus on the spatial assessment of the mangrove's structural and functional properties by applying cutting-edge remotely sensed datasets (images and digital elevation models). In contrast, ScoEco models are mainly used to provide comprehensive assessments of the system focused on the availability and use of ESs (ScoEco-ES) or help to plan a management program (ScoEco-Management) (Figure 1).

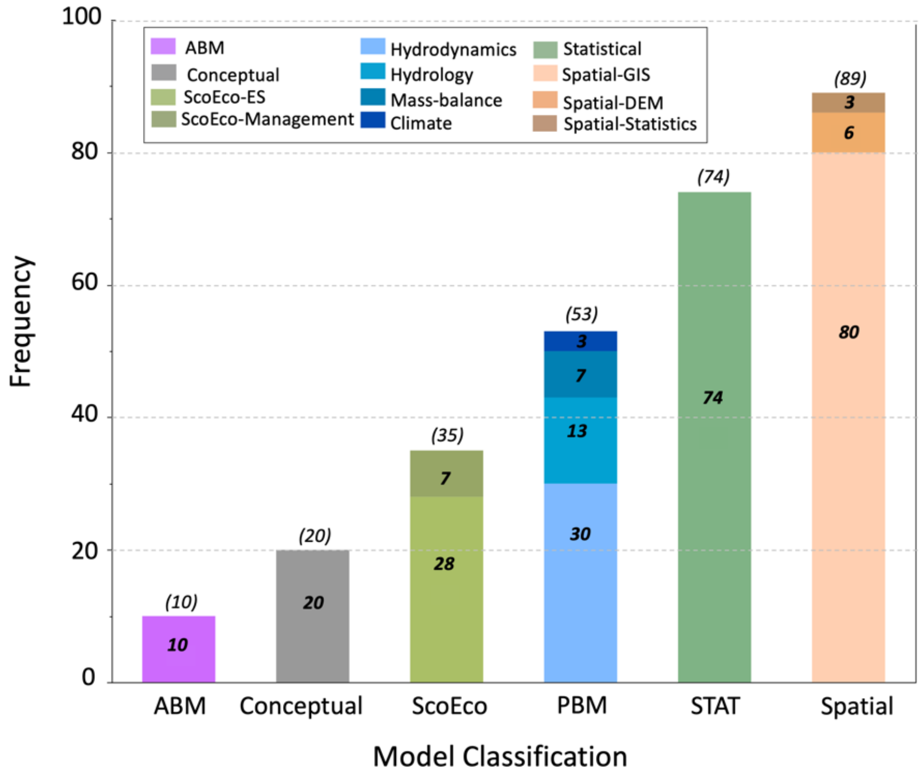

Figure 1. Total number of publications for different types of models identified in the analysis up to 2021. ABM: agent-based model; conceptual model; ScoEco: socioeconomic/management model; PBM: process-based model; STAT: statistical model; spatial based model. See model type/subtype description in the Section 2.2 and in Table 1. The number in parentheses on top of the bars is the total number of publications for each model category.

A description of the six main model types is listed in Table 1. The complete reference dataset used in the analysis is available in Supplementary Table S1. Using the classification criteria, we also identified publications focused on only mathematical, physical, or paleoecological models (n = 10) and review papers on modeling (n = 14); all publications used in our analysis are dated up to 2 May 2022 (Figure 2A) (Supplementary Tables S1–S3).

We grouped the publications into five chronological periods: <2000, 2000–2009, 2010–2014, 2015–2019, and 2020–2021. Two radar graphs were used to show the absolute counts (Figure 2B) and relative counts (Figure 2C) of each model type within the different periods; these graphs depict the trend of mangrove modeling research regarding R/R projects during the last three decades (the 1990s–2021).

Additionally, given the global differences in mangrove species diversity and extension in both the Atlantic East Pacific (AEP) and the Indo West Pacific (IWP) biogeographical regions [46], we also identified the number of publications per country within each region (Figure 3). The AEP region includes countries in North, Central, and South America and West Africa, while the IWP region encompasses East Africa, the Middle East, Asia, and Oceania [22] (Figure 3A). Because some publications modeled mangrove wetlands (e.g., remote sensing) or empirically made inferences at a global scale without explicitly indicating the study site, we grouped these publications in a “Global” category. Thus, Figure 3 shows a higher number of publications than the total number of studies (Figure 1) since a modeling tool was applied to different sites, especially in the statistical and spatial model category (Tables 1 and S1).

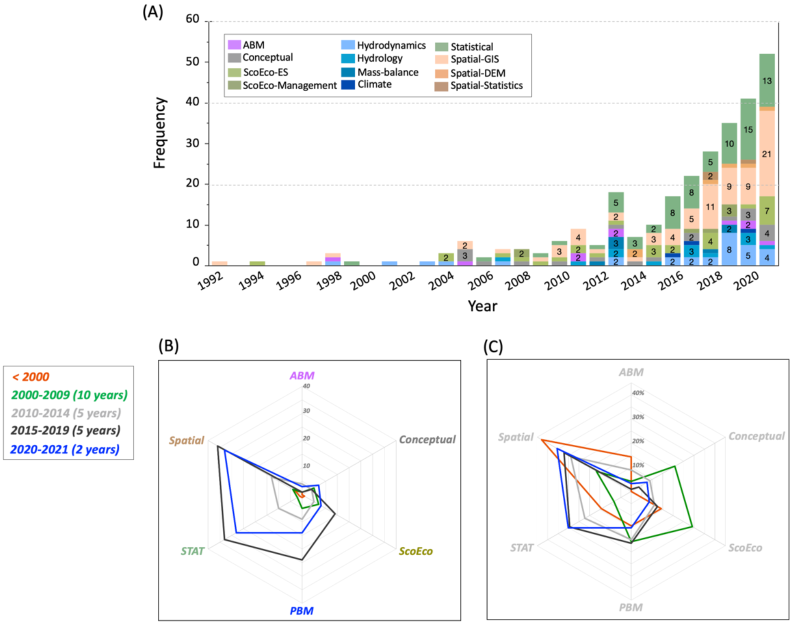

Figure 2. Number of publications (total) on mangrove modeling research explicitly applied to mangrove restoration and rehabilitation projects by 2021. (**A**) Chronological trend of publications for different model types. Radar graphs show the absolute count (**B**) and relative count (**C**) of publications for each model type within different periods (<2000; 2000–2009: 10 years; 2010–2014: 5 years; 2015–2019: 5 years; and 2020–2021; 2 years).

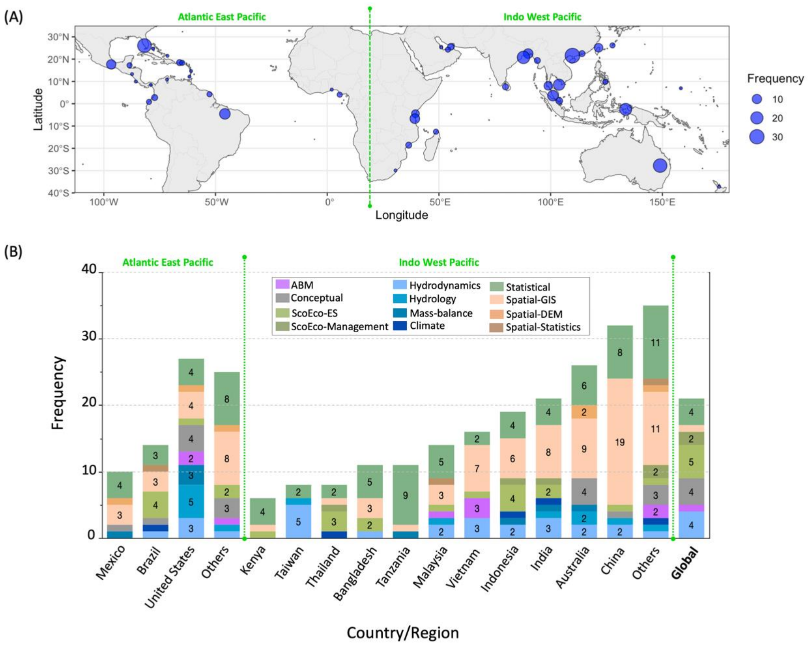

Figure 3. Number of publications (total) explicitly using mangrove models in R/R projects per biogeographical region (**A**) and country (**B**). The Atlantic–East Pacific (AEP) region includes countries in North, Central, and South America and West Africa; the Indo-West Pacific (IWP) region groups East Africa, the Middle East, Asia, and Oceania [46]. The "Global" category refers to publications focused on more than one single site or region; the "Others" category comprises countries with a low number of publications per model type/subtype. See Table S1 for further information about specific locations; notice that the bars with no number inside the bar in panel B equal 1.

3. Results

Based on the general categories used in the literature search, we found a total of 2738 entries; this list was reduced (i.e., 726 studies) using a refined search. Further filtering identified 281 papers fitting the criteria and objectives of our analysis (Figure 1, Table S1).

During the last three decades, the most widely used modeling tools are spatial and statistical models, followed by PBM, ScoEco, and conceptual models, while ABMs were the least frequently used (Figure 1). Only seven modeling studies published before 2000 explicitly addressed the direct or indirect evaluation of mangrove R/R projects (Figure 2). Five of these seven studies used static GIS-based spatial or ScoEco models. The earliest dynamic models directly addressing mangrove R/R projects were published in 1998 [6,47]. After this year, more dynamic models emerged, including ABM and PBM, but mentions of these were still low in number compared to the other model categories (Figure 2A). By 2021, only 10 papers applied ABM to plan or evaluate mangrove R/R projects (Figures 1 and 2A).

Interestingly, PBM, particularly hydrodynamic/hydrological models, became more frequent since 2013, as was the case for statistical models; this pattern is probably due to increasing data availability from mangrove ecological studies overall, which led to an improved understanding of the physical and ecological processes in determining the establishment and succession of mangrove forests. Similar to this trend, the application of spatial models also increased, perhaps as a result of the advancements in readily available remote sensing tools, methods, and datasets (Figure 2A–C).

The number of conceptual and ScoEco models increased by >50% since the early 2000s, suggesting an increase in the relevance of mangrove R/R projects and associated management and conservation issues and probably related to global mangrove area reduction and increasing demands for cost-effective mangrove restoration (Figure 2C). Although the relative count of publications is similar in the periods after 2010 (Figure 2C), spatial and statistical models became the dominant modeling tools in mangrove R/R research, while the use of other models remained at a relatively low frequency. This pattern shift also suggests an advance in sampling techniques and more mangrove research field studies [22].

Although the number of publications using modeling tools to assess or plan mangrove R/R projects showed, overall, an exponential increase during the last three decades (Figure 2A), the applications of modeling tools in R/R are still limited with greater dedicated use of static models (e.g., spatial, conceptual, statistical and ScoEco) in contrast to the inclusion of more dynamic processes that define the ABM and PBM modeling approaches (Table 1; Figures 1 and 2).

Overall, publications explicitly using modeling tools in mangrove R/R projects have been reported for mangrove sites in 44 countries within the AEP (N = 19) and IWP (N = 25) regions (Table S1, Figure 3A,B). Of the total publications, approximately 74% (n = 209) explicitly reported R/R project objectives in 14 countries (Figure 3B). The higher frequencies of publications (i.e., >20) originated in China, the United States, Australia, and India and were followed by other countries and regions in Asia (Indonesia, Vietnam, Malaysia, Bangladesh, Thailand, and Taiwan), America (Mexico and Brazil) and Africa (Kenya and Tanzania). Other countries/regions reported <5 publications (Figure 3B).

4. Discussion

4.1. Mangrove Models Inventory and Utility in R/R Projects

As mentioned, the major challenges in evaluating the success of mangrove R/R projects are not only to clearly define quantitative PMs to gauge forest recovery in the short term but also to forecast the trajectory of these measures in the long term [10]. Overall, one common strategy to assess mangrove R/R project success is to select “pristine”, “mature”, or less impacted forest located close to the restoration area to define how the forest should look after R/R projects are completed [8]. In general, as the restored area recovers, ecological structural (e.g., tree diameter and height) and functional (e.g., litterfall, soil porewater salinity) variables are measured to determine the potential outcomes of the initial conditions and the initial R/R strategy. This strategy could be solely based on propagule/seedling planting ("gardening" or "replanting") or hydrological restoration, and in some cases both [6,7,35,48].

Despite this conceptualization and the critical step of defining specific PMs representing structural and functional attributes, our analysis showed that a high percentage of mangrove models included in our study were based on "statistical" and "GIS-based spatial" approaches, which have been increasing in number since 2015 (Figure 2A). This finding contrasts with the low number of models based on dynamic or mechanistic approaches (e.g., ABM) since the early 2000s (Figure 2, Table 1). Similarly, despite the significant regulatory effect of hydrology—and the associated hydroperiod—on mangrove productivity and spatial distribution, few hydrodynamic/hydrological models have been constructed or validated to couple water exchange between the mangrove forest and adjacent water bodies [14,17,49]. Hydrodynamic and hydrological models coupled with morphological models are needed for R/R projects to allow mangrove seedlings to grow, protect seedlings from hydrodynamic energy, and create site elevations suitable for mangrove establishment [3,19,35]. The need for this type of model is even more critical when assessing productivity in coastal karstic and semi-arid regions where groundwater is the primary source of freshwater (e.g., [50]) or river discharge is seasonal and freshwater limiting under drought conditions (e.g., [51]).

Additionally, wind wave is one of the hydrodynamic forcings that affect mangrove structure and function and a critical ES of great economic significance given the negative catastrophic impacts due to storm surges in coastal areas with a high frequency of tropical cyclones. Although increasing wind wave modeling efforts have been conducted in exploring the wave attenuation capacity of mangroves from the laboratory, numerical experiments, and field studies (see reviews in [52]), few R/R projects incorporate wave modeling into project planning and management. Most of the wave modeling in mangrove wetlands has focused on the effects of only forest width and density on wave attenuation (e.g., [53]). Still, very few studies have examined the impacts of mangrove species diversity, tree age, height, configuration (spatial arrangement), and distance from the shoreline with varying topography and bathymetry on wave dissipation; those factors are often necessary to be considered in R/R project design [54].

4.2. Agent and Process-Based Models

The low number of instances of ABM indirectly reflects the lack of data to calibrate these types of models in R/R projects—even if available, they are limited in number and scope. This is in addition to the computational requirements and capability to run the models at meaningfully large spatial scales (>1 km^2). The construction of ABM requires data and information about species-specific physiological traits and the role of fertility gradients (e.g., soil TP) and stressors (e.g., salinity) during forest development [55]. This requires long-term spatiotemporal datasets to parametrize this type of model under several scenarios (e.g., FORMAN [16]), especially when species diversity is high, as is the case in the IWP biogeographical region [22]. Indeed, the FORMAN model was the first ABM model calibrated for neotropical mangrove species using field data from mangrove stands with minimum anthropogenic influences but subject to significant impacts by natural disturbances (tropical cyclones) in Florida, USA [16]. However, this region is in the AEP region, where species diversity is much lower than in the IWP region (Figure 3B). Another ABM (KiWi) initially adopted equations and parameters used in the FORMAN and incorporated the tree competition within "field-of-neighborhood" (FON); KiWi was initially calibrated using field data from study sites in Brazil [56] (Figure 3B), and one of the countries in the AEP region. Later, the KiWi model was used to evaluate R/R activities in Vietnam, Thailand, and Japan [57–61] (Figure 3B).

Based on model performance, validated by an increasing number of field datasets and applications, there have been advances in the architecture and utility of ABM as more functional properties have been added. This is the case with the mesoFON model, which improved the KiWi model; in this version, the crown plasticity was modified to include tree competition [62]. This model was further calibrated and validated in mangrove restoration projects in Malaysia by proposing solution-oriented model development strategies to inform management [63] (Figure 3B). This effort was followed by another KiWi version (i.e., BETTINA) where both tree competition for resources above- and below-ground were explicitly separated [64,65]. The BETTINA model includes mangrove physiological processes to evaluate how trees adapt to environmental variations in light and salinity, which regulate mangrove productivity and biomass [65].

More recently, plant-soil feedback processes [66] have been implemented in the BETTINA model in addition to the first steps in coupling this model to a groundwater hydrodynamic model to assess mangrove salt tolerance [64,65,67]. Thus, there are a small number of publications (n = 10) currently aimed at implementing the development and application of the ABM approach to restoration sites in both the AEP and IWP regions (Figure 3A,B). Although, more recently, dynamic models, including PBM and ABM, have been able to simulate specific environmental patterns such as salinity and groundwater (e.g., RHYMAN [50], MANHAM [68] and MANGA [67]), there is not yet a model functionally and simultaneously linking hydroperiod, biogeochemical transformation, and forest structure dynamics.

One obstacle to the development and application of PBM, in addition to the lack of long-term data (species- or site-specific, and ecosystem level), is the lack of an in-depth understanding of ecosystem processes and their interaction under various physical conditions regulating mangrove forest structure and functions [69,70]. For example, mangrove forests were usually thought to emit no or very low methane (CH_4) due to the dominant sulfate reduction suppressing methanogenesis under high salinity conditions [71]. However, recent studies found that ecosystem-level CH_4 emissions from estuarine mangroves are not negligible and could substantially offset the CO_2-induced cooling effect, thus reducing the capacity of mangrove forests to achieve climate change mitigation [72,73]. This is because mangrove greenhouse gas (GHG) cycling is presumably more related to soil porewater salinity, which varies substantially in space and time in mangrove soils [50,74]. However, the impacts of soil salinity and the interaction between soil salinity and water level have not been well understood; therefore, such effects from soil salinity and water level on CH_4 emissions are not explicitly incorporated in mangrove biogeochemistry models [69]. Additionally, our knowledge about the interaction between soil salinity and nutrient (N and P) availability on mangrove growth is still limited and cannot be explicitly addressed in biogeochemistry models [70].

4.3. Static Spatial and Statistical Model Utility in Biogeochemical Studies

In contrast to the development and application of ABM, spatial (GIS- and DEM-based models; Figures 1 and 2) and statistical models are the dominant approaches for detecting changes in mangrove forest structure and functions under R/R projects. This is partially due to the improvement in satellite sensor resolution, tools/methods, and data availability (e.g., [75,76]) (Figure 4A). The dominant role of these models is also enhanced by the need to update mangrove inventories at the global scale as mangrove area continues to decline in several regions with significant mangrove extensions (e.g., Indonesia [77]). These inventories are focused not only on evaluating mangrove spatial distribution but also on assessing carbon storage in mangroves, also known as "Blue Carbon". This organic carbon has been recognized as a critical ES in climate mitigation measures during the last decade [28–30]. The potential collection of billions of dollars from this service—in the implementation of still pending carbon markets—has triggered several studies into upgrading regional and global inventories, thus promoting the revision and update of statistical allometric equations for most of the dominant species in both the AEP and IWP regions [22,78,79]. Moreover, the rising attention to this ES is reflected by the highest number of publications using ScoEco models in 2021 (n = 7; Figure 2A).

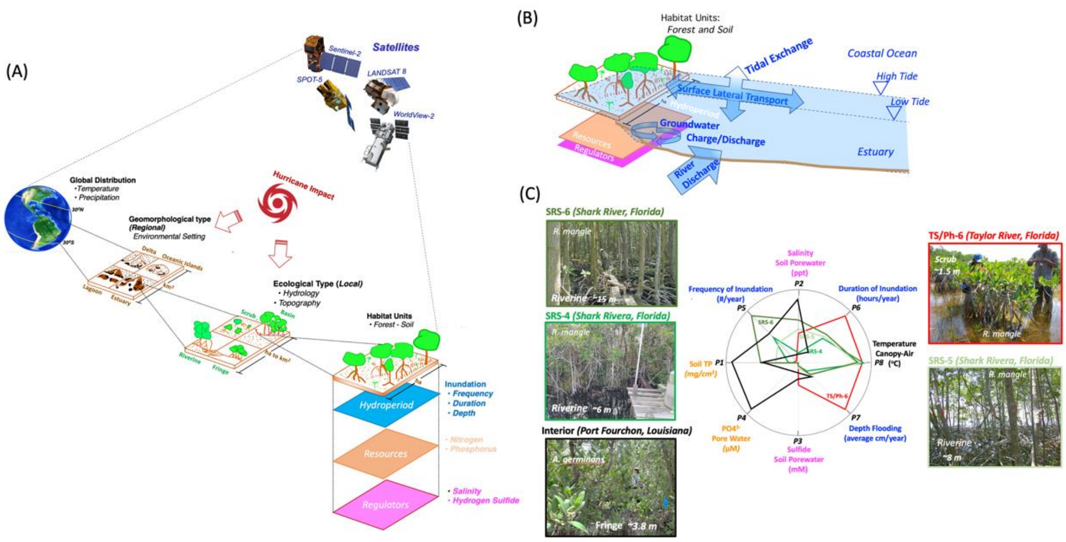

Figure 4. (**A**) Hierarchical classification for mangrove-dominated ecosystems describing abiotic controls (hydroperiod, resources, regulators) on mangrove structural and functional properties at the global (temperature, precipitation), regional (geomorphology, hurricanes), and local scale (ecotype habitats) (modified from [6,80]); remote sensing measurements are depicted to underscore the comprehensive information obtained about mangrove structural properties across these spatial scales and as shown by the high frequency of publications (see Figure 1); (**B**) main hydrological factors (tidal, groundwater, river discharge) regulating the hydroperiod and hydrological connectivity between the forest and adjacent coastal waters; (**C**) radar graph showing the relative role of each hydroperiod, resources and regulators components in the configuration of a eight-dimensional hypervolume "niche" for different mangrove ecotypes (Riverine, Fringe, Scrub) in tropical savanna (Everglades, FL, USA [43]) and humid subtropical (Port Fourchon, LA, USA [81]) climates; the shape of the niche defines the mangrove wetland net primary productivity and structural properties (e.g., canopy height) (Rivera-Monroy et al. unpublished results). For easier identification, notice that the color highlighted in the picture frame in panel (**C**) corresponds to the same color as the niche spaces outlined inside the circle.

The focus on developing statistical models has improved inferences on the indirect relationships between environmental variables and mangrove biomass (above and below-ground). For example, these values have advanced our understanding of the carbon cycle in mangrove wetlands, even when they represent only a portion of this cycle (i.e., stocks). The updates of carbon inventory data have also underscored the lack of data and information on fluxes that could explain the fate of carbon across different mangrove ecosystem boundaries since the late 2000s. This has initiated a research effort to help constrain carbon estimates and elucidate lateral (wetland–estuary) and vertical (wetland–atmospheric) fluxes in "pristine" mangrove forests [82–84].

Yet, although those studies have shown that mangroves could act as sinks and sources at different temporal scales and under different environmental impacts (e.g., deforestation, tropical cyclones), net carbon flux estimates for a wide range of ecotypes and environmental settings are lacking [29]. This information gap represents a stumbling block in validating some existent dynamic models simulating carbon cycling for unimpacted mangrove forests (e.g., [16]), and even more for restored sites. Thus, because mangrove R/R projects are implemented within spatial scales needed to understand the relationship between biogeochemical cycles and environmental drivers controlling stock and fluxes, these projects can be considered in potential field experiments.

For instance, these projects could be potentially used to evaluate how carbon, nitrogen, or phosphorus transformations—which control tree growth and NPP—vary as mangrove forests develop (Figure 4B,C). Since vegetation development is a major goal in R/R projects under different degradation states, this provides an opportunity to understand how specific plant–soil–hydrological interactions respond to changes over time that can contribute to the parametrization of mangrove models. There are now restoration sites with reliable monitoring programs that are old enough (>10 years), which could be used, for example, to assess how soil carbon stocks and sequestration rates vary with forest age and species composition [85,86]. This information is needed to inform calibration and validation steps in the construction of dynamic models. However, to use mangrove R/R projects as a modeling parametrization and validation strategy, it is necessary to design monitoring programs that could track key ecological variables (e.g., stocks and fluxes)—including operational PMs—beyond the project duration (>5 years).

4.4. Implementing and Forecasting the Success of R/R Projects

Unfortunately, one of the major limiting factors in implementing this R/R project monitoring and model validation strategy is financial—particularly in tropical regions, where mangrove area is being lost at high rates [31]. Assuming that carbon markets are eventually implemented to advance climate mitigation programs, then there might be opportunities to divert funding from those economic benefits (i.e., carbon offsets) to design mangrove modeling-based monitoring programs. This proposition could be justified given the need to forecast climate change scenarios in coastal regions. Indeed, recent reviews on global carbon cycling show a major knowledge gap in our understanding of how riverine sources transport the carbon in the coastal areas into the continental shelf and open ocean [83]. The estimation of this lateral flux is needed to "close" the global carbon budget [82,87]. Yet, the magnitude of the coastal/estuarine zone's functional role in linking inland ecosystems and the open ocean is uncertain, particularly in tropical latitudes where mangrove vegetation is dominant.

Under this regional and global perspective, the allocation of funding to advance mangrove modeling for both natural and restored/rehabilitated forests may help to determine the role of mangrove wetlands in storing/sequestering carbon. This role extends to the critical role of mangrove vegetation in modulating soil temperature where several biogeochemical transformations take place [81]. Thus, one primary goal could be to advance mangrove forest models to improve our understanding of the drivers, feedback loops, and thresholds for coastal ecosystems and the Earth System models (ESM) [83,88]. Given the global extension of mangrove loss associated with natural and human impact, R/R projects could become a building block to advance those models as a conceptual tool to identify critical biogeochemical transformations regulating their functioning and sustainability across the AEP and IWP biogeographical regions.

These mangrove biogeochemical transformations regulating mangrove productivity at different spatiotemporal scales (local, regional, global) have been discussed in the context of hierarchy theory as a conceptual framework in the model development [6,55] (Figure 4B,C). This approach builds on the early conceptualization of mangrove wetlands represented by ecotypes under different ecogeomorphic settings [11,89]. Here, the coupling between geomorphology and hydrology determines specific hydroperiods that modulate fertility gradients and the type of mangrove community depending on species-specific physiological adaptations (Figure 4A). This approach has been useful in assessing how biogeochemical and fertility gradients control mangrove productivity in neotropical mangroves: from elucidating the source of phosphorus in controlling NPP [16,20,90] to identifying the role of tropical cyclones on carbon cycling at regional scales [84].

The explicit quantification of processes at different spatiotemporal scales is helpful to quantitatively identify the relationship between hydroperiod, salinity, and belowground productivity across different ecotypes (Figure 4C) (e.g., [89,91,92]). Further, this approach has also been embedded in national mangrove R/R monitoring projects in neotropical latitudes (e.g., Mexico [80]). Those applications demonstrate the utility of this hierarchical approach to communicate—among and between disciplines—the major differences and contributions of ecological, social, and economic drivers in executing mangrove R/R projects and from a coupled natural–human system perspective (Figure 5A,B) [32].

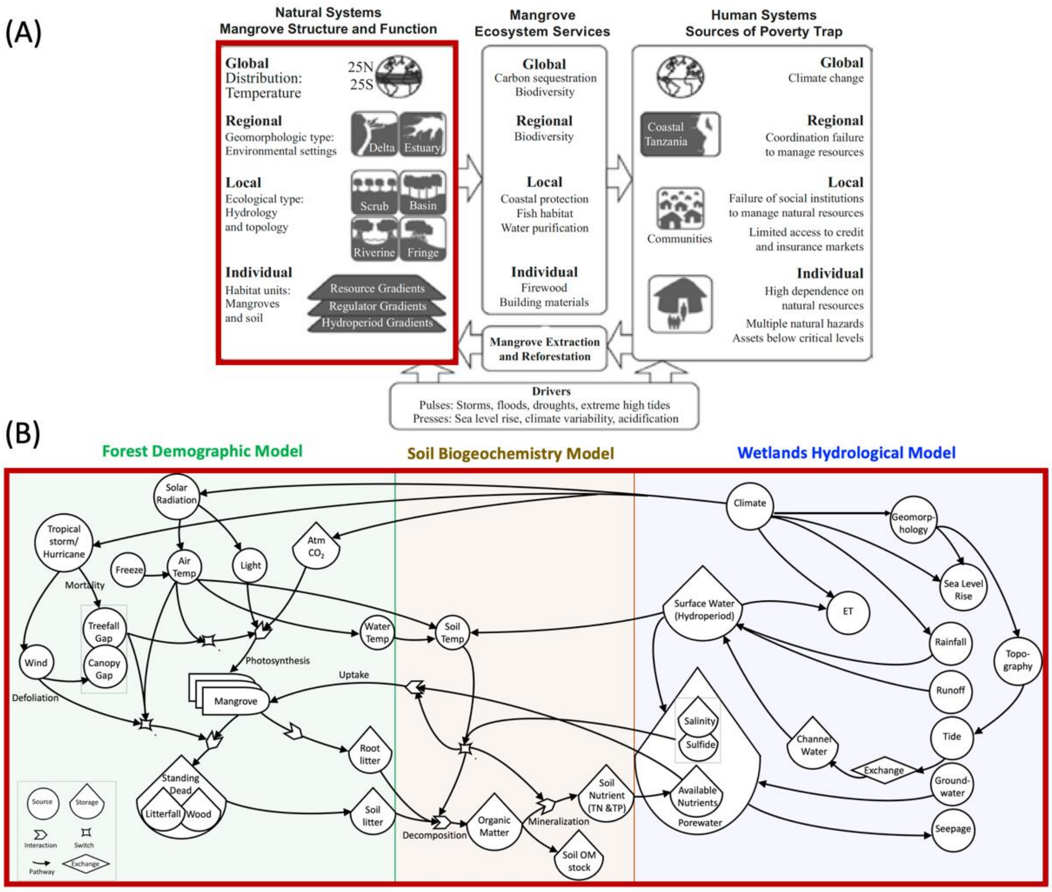

Figure 5. A coupled natural–human system where mangrove ecosystem services (ESs) are critical in countries where poverty is high in coastal communities (e.g., Tanzania; [32]). (**A**) Connectivity among different processes at global, regional, local, and individual scales in socioecological systems highlighting the functional role of mangrove ESs. (**B**) Conceptual model of the natural system as an idealized mangrove modeling tool. This scheme includes three main sub-models (multi-model approach): forest demographic, soil biogeochemistry, and hydrological models; these modules are dynamically coupled to simulate the mangrove forest structural and functional variations under different natural disturbances (e.g., sea-level rise and tropical cyclones) regimes and human activities (e.g., defoliation and freshwater restoration).

4.5. A Multi-Modeling Approach Is Needed

This ecogeomorphic hierarchical approach also underscores the biocomplexity of mangrove wetlands [93] and a conceptual and practical decision: that no single model could represent and simulate all the processes and transformations (Figures 4 and 5). Developing mangrove environmental models currently requires the articulation of a multi-model approach where several models are used to simultaneously determine a variety of system functions and attributes [6,10,94,95]. This could include not only ABM (i.e., forest demographic model) but also other system dynamic models (e.g., biogeochemical and hydrological models), game theory, and machine learning models, as currently used in remote sensing studies [96].

Other examples of model integration include coupling climate, hydrodynamic, and groundwater models to predict soil porewater salinity dynamics; this requires combining a hydrodynamic flow model with sediment transport and a vegetation growth model to anticipate future changes in the channel and wetland morphology of the restored/rehabilitated mangrove forests and coupling hydrological, plant growth, and soil biogeochemistry (e.g., denitrification and decomposition) with the incorporation of disturbances (hurricanes/storms, wildfire) and management actions (e.g., harvesting, fertilization) to examine carbon sequestration and GHG (CO_2, CH_4, and N_2O) emissions (e.g., [21,89]). The statement that "all models are wrong: many are useful" [97] highlights each model's limitation and bias in its initial structure and validation criteria since reality is very complex. However, the combinatory use of a set of models representing different components of that reality does provide a robust representation, as limited as it could be in time and space [6,98].

Thus, using multiple models could be a fundamental strategy to help pose critical questions that need to be answered at different spatiotemporal scales [10,55]. For example, this strategy in the case of mangroves could be "modular", where other models simulate specific patterns and transformations (Figures 4 and 5) that could be linked under the same scale; it could also be a single model with different levels of granularity depending on data availability and original purpose. We have used both approaches to inform an array of models, and this has helped us to discern and quantify the role of stressors (e.g., salinity [50]) in controlling mangrove NPP associated with the regulatory impact of hydrological restoration [42] in riverine and basin mangroves and the pulsing effect of tropical cyclones on mangrove carbon and phosphorus cycling [84,99]. Indeed, increasing the level of detail in any model is reflected in the modeling complexity that can rapidly challenge the availability of computer power resources. Thus an a priori definition of the drivers, feedback loops, and thresholds of functional value in mangrove R/R projects could help us to reach both modeling efficiency and utility.

5. Future Research Directions and Conclusions

Because mangrove ESs—in the context of R/R projects—are basic wetland structural and functional properties (Figure 5), it is desirable to construct mangrove models based on a list of priorities related to ESs conservation and socioeconomic preferences [100,101]. Hence, the deployment of R/R projects can be a source of data for modeling calibration and validation. Paradoxically, the global destruction and replacement of mangrove wetlands by other land uses/land changes (planned or accidental) have produced a wealth of information to be used in model construction, calibration, and validation; this represents an opportunity to orchestrate a multi-modeling effort, not as an afterthought to understand "natural" or "pristine" forests, but as a powerful tool to demonstrate the economic impact of mangrove loss at different scales.

Historically, mangrove mortality has been associated with major alterations in hydrology/hydroperiod and deforestation caused by landscape-level land use/land change. Hence, one research direction needed in R/R projects informing modeling efforts is to establish how soil stressors (e.g., salinity, hydrogen sulfide) regulate tree growth rates at spatial scales generally used in R/R projects (2–4 ha [8]) and the subsequent step used at the landscape level. Unfortunately, although the hydroperiod is known to be a critical driver controlling mangrove establishment and productivity, there is a lack of long-term data from both natural and restored sites, with frequent measurements inside the mangrove forest (Figure 4B). This knowledge gap remains, as shown by the low number of hydrological models published in the last 15 years.

The socioeconomic dimension of deforestation requires the explicit inclusion of people as "agents of change" in models to determine the social and economic cost of mangrove area loss driven by poverty, particularly in tropical latitudes (Figure 5A) [32]. Although several publications underscore the vulnerability status of mangrove ESs [102,103], there are few dynamic models (ABM or PBM) depicting the functional connectivity between mangrove productivity, management decisions (e.g., wood harvesting, charcoal production, hydrological alterations), and their social cost (Figure 5A). The resurgence of studies on carbon cycling triggered by the negative impacts of global warming and climate change—including sea-level rise—opens a major opportunity to advance and develop a "consortium" of mangrove models focused on the direct linkage between the social and ecological realms in mangrove systems.

Moreover, the exponential growth (Figure 2A) in the publication of GIS-based models to update global mangrove inventories is a reminder to start and/or continue developing dynamic, game theory, and machine learning models at more granular scales. Indeed, the economic incentive to conserve organic carbon as a strategy in climate change mitigation potentially represents a major opportunity to fund these modeling efforts at local scales. Yet, we recognize that this direct and evident economic incentive has been ignored in the past when considering other ESs. For example, even when the role of mangrove wetlands in sustaining local and commercial fisheries (habitat, food sources) has been demonstrated for the vital socioeconomic well-being of impoverished coastal communities, mangrove deforestation has continued (e.g., [104,105]). This cumulative decline in mangrove areas has resulted in the decline—and even collapse—of fisheries, associated with the loss of millions of dollars (e.g., [106,107]).

5.1. Explicitly Linking Mangrove Models and ESs

There is a growing need to incorporate ESs into the monitoring and adaptive management of mangrove R/R projects locally and globally [3,6]. Consequently, current and future mangrove models need to focus on answering ecological questions and urgent management questions (Figure 5A). This is because socioeconomic variables are major drivers controlling mangrove sustainability in the following decades, especially when mangrove deforestation continues at different rates depending on the country within each biogeographical region [31]. It is necessary to supplement the statement that "not all mangroves are created equal" [4] when referring to the differences in quantity and quality of ESs provided by different mangrove ecotypes with the statement "not all countries' mangrove management programs are created equal" when explicitly comparing conservation strategies and priorities on a country-by-country basis [28,35,107]. This regionally ecological and social distinction is helpful given the major differences in the enforcement of mangrove conservation laws, if existent, and the current political systems driving national economic priorities; this is even more true when financing and implementing R/R projects. Based on the present threats to mangrove-dominated ecosystems, global efforts in mangrove conservation should be built at the country and town/village level.

It is expected that if carbon markets become a reality—specifically at the country level (e.g., [80])—it might be possible to acquire funding to advance R/R projects within a modeling context where carbon storage and sequestration become a central justification, as in the case of international organizations, foundations, and NGOs that are interested in the accurate assessment of mangrove "Blue Carbon" inventories to justify long-term investments in those markets. To forecast and evaluate these inventories with reduced uncertainty at different scales—especially a high resolution (m^2)—will require modeling tools to identify potential trajectories as financial systems evolve in the following decades [3,8,94]. Thus, for instance, modeling carbon biogeochemistry regulated by hydrology and nutrient availability using a multi-model approach can become an economic strategy validated by implementing R/R projects across several geomorphic settings and latitudes.

Although we underscored the role of hydrology and hydroperiod as key drivers controlling mangrove productivity and spatial distribution (Figure 4), it is also paramount to consider the global and regional changes that relative sea level rise (RSLR) will impose on those drivers as a result of climate change [108]. Recent work indicates that vertical accretion in mangrove wetlands—fueled by local sediment deposition and in situ organic production—will not be able to keep up with increasing sea level (e.g., [109,110]). It is expected that mangroves will "drown" if RSLR exceeds 6.1 mm $year^{-1}$, which is a boundary that several coastal regions will reach or will have already reached [111] within the next 20–30 years in a warming world [108,112]. Thus, R/R projects need to consider this threat to mangrove wetlands in the long term, particularly if a substantial monetary investment is required. In this context, it would be beneficial that any R/R project explicitly includes a comprehensive risk assessment of the potential role of local and regional RSLR along with mitigation and adaptation measures to warrant a sustainable restored or rehabilitated coastal ecosystem.

5.2. Conclusions

Therefore, the answer to the question "Are existing modeling tools useful to evaluate outcomes in mangrove restoration and rehabilitation projects?" stated in the title is—unfortunately—a very tepid "*yes*". Our analysis shows that despite the wide recognition of the utility of R/R projects to recuperate lost mangrove areas, the use of mangrove models in these projects has been extremely limited over the last 30 years, even when their use and utility in other types of coastal wetlands (e.g., freshwater and saline marshes) is more extensive (e.g., Louisiana Coastal Master Plan [113]; Florida Everglades Restoration [114]). The explanation for this trend rests on the lack of data for mangrove model construction (conceptual/heuristic frameworks) and model calibration/validation; paradoxically, in a decade where "Big Data "availability in other ecosystems is becoming more the norm than the exception [115,116]. Another reason is the lack of funding to advance modeling efforts in countries where most of the mangrove area is found in the AEP and IWP regions [117].

The targeted allocation of the potential revenue to R/R projects that will be obtained in future global carbon markets could now be considered to implement climate mitigation measures owing to climate change, including sea-level rise. Most of that mangrove organic carbon is stored in countries undergoing social unrest and significant economic constraints, which increasingly threaten mangrove wetlands conservation, sustainability, and resilience [118,119]. Hence, potential funding from that source could alleviate national budgetary limitations to advance mangrove socio-ecological research in the context of R/R projects. The construction of models could guide such research under a multi-model (integrated) approach at different spatiotemporal scales and societal needs.

Given the urgency to forecast the impact of climate change on the biosphere overall, mangrove modeling could also contribute to advancing the linkage between the Earth System models and climate models in tropical and subtropical coastal regions [81]. It is in this latitudinal range where the combined impact of increasing sea level, temperature, and land use/land change represents a major challenge to the construction of not only global carbon models but also environmental models to be used in R/R projects when the future of mangrove wetlands is uncertain in the Anthropocene [120,121].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13101638/s1, Table S1: Supplementary Table S1. Publication list focused on mangrove modeling research applied to restoration and rehabilitation projects (R/R) by 2021; Table S2: List of publications using other model types, including review articles; same search procedure as described in Table S1; Table S3: List of publications published in the period from January–April 2022; same search procedure as described in Table S1.

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