Evidence Library for Mangrove Degradation and Recovery

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National Estuarine Research Reserve System Science Collaborative

The National Estuarine Research Reserve System Science Collaborative supports science for estuarine and coastal decisionmakers. Managed by the University of Michigan Water Center, through a cooperative agreement with the National Oceanic and Atmospheric Association, the Science Collaborative coordinates regular funding opportunities and supports user-driven collaborative research, assessment, and transfer activities that address critical coastal management needs identified by the reserves.

Mangrove Coast Collaborative

In 2017, strong hurricanes hit the Jobos Bay Research Reserve in Puerto Rico and the Rookery Bay Research Reserve in Florida, causing damage to local mangrove forests. Both reserves realized a need to understand storm impacts and recovery trends in mangrove forests. A team of scientists, managers, and educators from Florida and Puerto Rico was created to address these needs through the Mangrove Coast Collaborative. This work will strengthen partnerships between the two reserves, increase understanding of the factors influencing recovery from hurricanes in Puerto Rico and Florida, and will be used to better maintain resilient mangrove forests.

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Introduction

Mangrove ecosystems deliver numerous benefits to both people and nature, including provision of important habitat for wildlife species, nursery habitat for fish and shellfish, recreational opportunities, and protection for coastal communities. Humans interact with mangrove habitats in a variety of ways, and each mangrove ecosystem and the communities that interact with it represent a unique socioecological system. Interest in mangrove ecosystem services[1] and their associated socioecological systems has resulted in numerous scientific studies all around the world. The evidence library contained in this document attempts to synthesize the scientific literature to share information on what is known—and not known—about mangrove ecosystem services in two mangrove habitats in southwest Florida and southern Puerto Rico.

In 2017, Hurricane Maria passed through Jobos Bay Research Reserve in Puerto Rico and Hurricane Irma passed through Rookery Bay Research Reserve in Florida. Both reserves have sizeable mangrove ecosystems that were affected by these storms. Reserve managers realized that these simultaneous events presented an opportunity to better understand storm impacts and recovery trends in mangrove forests. A team of scientists, managers, and educators from Florida and Puerto Rico developed the Mangrove Coast Collaborative (MCC) project with the goal of providing increased understanding and tools to aid in restoration and management of these forests.

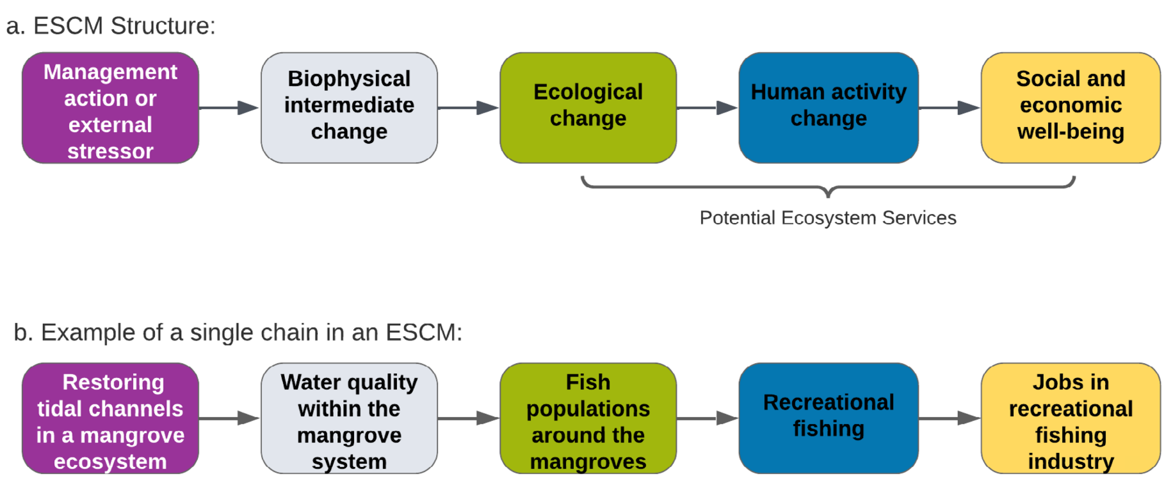
[1] The Mangrove Coast Collaborative project defines ecosystem services as the benefits that flow from environmental systems to people; for example, the production of food and timber, life-support processes such as water purification and coastal protection, and life-fulfilling benefits such as places to recreate or to be inspired by spiritual or religious connections with nature.

Mangroves have evolved with hurricane disturbance, but research is needed to understand whether and how increased frequency and intensity of hurricanes might result in mangrove habitat changes (Krauss and Osland 2020) and subsequent changes to the ecosystem services they provide. The MCC project examined this question at the two focal research reserves. The project not only focused on understanding whether and how mangrove habitats at both sites are changing from an ecological perspective, but also how changes to mangrove systems might affect ecosystem service provisioning to nearby communities.

Ecosystem services conceptual models (ESCMs) represent a possible entry point for incorporating a suite of ecosystem services considerations into a program or project. These models illustrate the way that a stressor or management intervention cascades through an ecological system and results in changes to ecosystem services and other human well-being outcomes (Figure 1). To begin an assessment of the mangrove socioecological system, we built an ESCM that traces how mangrove ecosystem degradation[2] and recovery could influence ecological, biophysical, and ultimately social and economic outcomes (ecosystem services) (Figure 2).

We then created an evidence library to synthesize information from the scientific literature about the linkages represented in the ESCM. Evidence libraries represent rapid literature reviews that document known information about each link (arrows in Figure 2) in an ESCM to

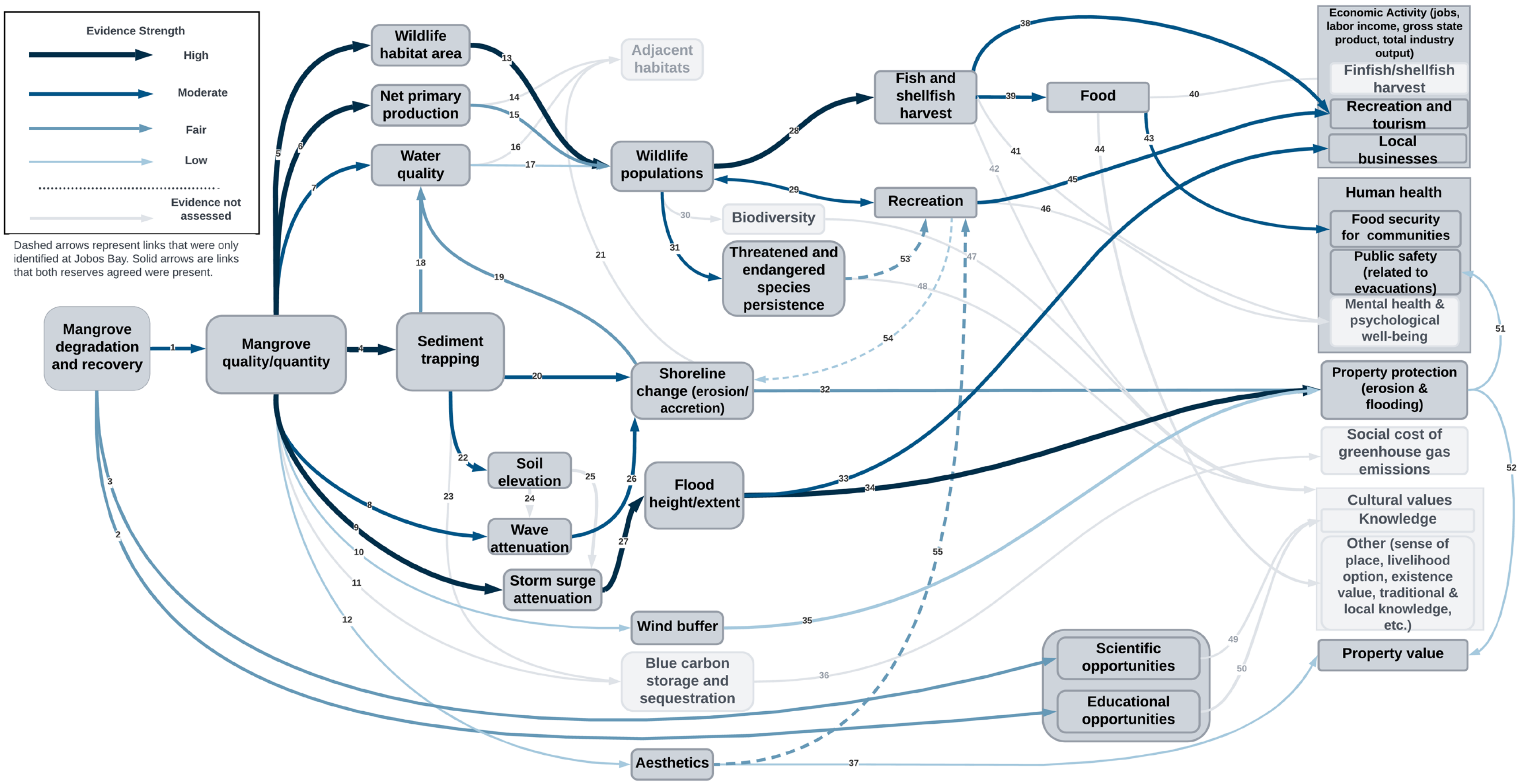
Figure 1. (a) Structure of an ESCM and (b) an example ESCM chain



Note: Ecosystem services can include different types of benefits that ecological (natural) systems provide to the social and economic well-being of people.

[2] The Mangrove Coast Collaborative project defines *mangrove ecosystem degradation* as a transitional state resulting from one or more stress factors caused by anthropogenic drivers or the effect of anthropogenic activities on nonanthropogenic drivers. Degraded mangroves are indicated by loss of diversity, structure, function and associated services, and/or the ability to recover within an expected period of time following disturbance. Ecosystem ecologists may use more precise indicators (temporal and spatial) for this term; natural resource managers may need to use this term to justify and describe management actions.

Figure 2. Ecosystem service conceptual model for mangrove degradation and recovery with links (arrows) color-coded by strength of evidence rating



Note: Link (arrow) numbers correspond to sections that follow.

provide easy access for managers and scientists interested in understanding where evidence is strong and where research gaps exist in a particular socioecological system, which ecosystem services outcomes are most likely to be affected by changes to the system, and where monitoring might be focused to assess how certain outcomes are changing.

MANGROVE ESCM AND PRIORITIZED ECOSYSTEM SERVICES

The mangrove ESCM (Figure 2) was developed through an iterative process including literature review, input from mangrove ecologists, and workshop engagements with local scientists and managers at both focal research reserves. The resulting ESCM has been specified to conditions at both reserves and represents flows of ecosystem services that are relevant to these sites. During workshop engagements, participants were asked to prioritize the services that they felt were most important to include in the evidence library. Prioritized services were identified as property protection, food security, recreation and tourism, fishing, economic activity and local business, public safety, property value, science and educational activity, and water quality. These priorities determined which links we focused on for the evidence library literature review. Links not connected to prioritized services were not included in the evidence library.

The evidence library starting on page 7 contains summaries of the evidence for each of the links in the mangrove ESLM (Figure 2). Summaries include an assessment of the strength of evidence for each link; links in Figure 2 are color-coded by strength of evidence rating (evidence rating system described in detail below). Each link in the model has an identification number. When reading this as a PDF, readers may find the evidence library entry for a particular link by clicking on the link number on the conceptual model figure, using the bookmarks tab on the left-hand side, or using the search function (keyboard shortcut Control + F and search for "Link #" [e.g., "Link 3"]).

EVIDENCE LIBRARY FOR THE MANGROVE ESCM

The evidence for each link in the mangrove ESCM (Figure 2) is summarized as follows. Each evidence summary has the following components:

Description of Relationship

Short description of the relationship between the starting and ending nodes (boxes) based on the evidence found.

Summary of Evidence

Overview of the evidence found to support the relationship, including the types of methods used, geographic location of evidence, applicability to the Puerto Rico and Florida contexts, and major findings.

Strength of Evidence

Rating of the overall strength of evidence for the relationship based on the criteria described in Table 1.

Table 1. Strength of evidence criteria

Confidence Level	Criteria			
	Evidence Types	Results Consistency	Methods	Applicability
High	Multiple	Direction and magnitude of effects are consistent across sources, types of evidence, and contexts	Well-documented and accepted	High
Moderate	Several	Some consistency	Some documentation, not fully accepted	Some
Fair	A few	Limited consistency	Limited documentation, emerging methods	Limited
Low	Limited, extrapolations	Inconsistent	Poor documentation or untested	Limited to none
None	None	N/A	N/A	N/A

This strength of evidence assessment method was adapted from Tallis et al. (2019).

Other Factors

List of external factors (including biophysical, ecological, and social factors) that influence the relationship between the starting and ending nodes (boxes), how each factor affects the relationship, and the magnitude of the effect, if known.

Predictability

Evaluation of how predictable a change in the ending node is, given a certain change in the starting node. For example, the relationship between two nodes may be unpredictable due to influences from external factors or gaps in scientific knowledge. Any models or tools designed to predict the relationship are noted.

Local Context

Certain entries in the evidence library contain a local context box that describes how that relationship plays out at one or both of the focal research reserves. This anecdotal information is not necessarily represented in the scientific literature, but was gathered from local experts through workshop conversations and discussions following workshop engagements.

References

List of evidence sources for the relationship.

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Evidence Library Entries

LINK 1: MANGROVE DEGRADATION AND RECOVERY → MANGROVE QUALITY/QUANTITY

Description of Relationship

Hurricanes impact mangroves, both in terms of ecosystem state and characteristics. Effects can be separated into those that are short-term or long-term. Short-term effects of hurricanes on mangroves include initial tree mortality, erosion of surface sediments, and canopy reduction. Long-term effects are major hydrogeomorphic changes and permanent losses of coastal wetland area, which can lead to peat collapse. These effects are understudied but are important to understand to fully determine hurricane impacts. There are numerous factors that can influence mangrove recovery, such as the intensity of the storm, tree size, and species type. *Recovery*—defined as a return to prestorm canopy density and closure, seedling growth, stem density, peat recovery, stand resilience, and more—can vary by storm and mangrove location.

Summary of Evidence

Mangrove ecosystems have evolved to withstand many effects of hurricanes and tropical cyclones. Cyclones can actually cause a positive effect in hypersaline and/or nutrient-poor environments by alleviating physiological stress and stimulating productivity (Krauss and Osland 2020). However, extreme climate events (such as frequent and intense hurricanes) can degrade mangrove forests (Branoff 2020; Jamaluddin et al. 2021). Wind, rain, surge, and excessive sedimentation are the main stressors associated with storms that can lead to degradation (Krauss and Osland 2020). Degradation can include structural injury, biomass removal, root burial, peat collapse/compaction, anaerobiosis, increase invasion susceptibility, and in extreme cases, irreversible ecological transformation (Branoff 2020; Krauss and Osland 2020; Osland et al. 2020). Hurricanes and tropical cyclones can also effect soil elevation through processes such as sediment deposition, erosion, soil shrink, and root growth (Feher et al. 2020). Woody debris movement during a cyclone can cause physical damage to seedlings, saplings, and trees (Krauss and Osland 2020). As tropical cyclones become more intense and sea level rise accelerates, there is increasing potential for localized cyclone-induced mortality, peat collapse, and conversion of mangrove forests to mudflats (Osland et al. 2020). The extent of forest impact depends on the intensity of the hurricane, the amount of site exposure, and the relative position within the path of the eye. The highest disturbances have been found to be in zones close to shorelines (Piou et al. 2006).

Hurricanes can cause mass tree mortality, but the extent of the impact varies by storm, location, size, and time. Storm-induced mortality can continue for months after a hurricane (due to hydromorphological changes preventing seedlings from growing and causing delayed mortality), so it is integral for long-term monitoring to determine the full effects of a storm (Krauss and Osland 2020; Walcker et al. 2019). For example, after the 2017 hurricane season in Puerto Rico, only 1% of trees across 20 study sites were determined dead one month after the hurricane. However, survival probability decreased with time, resulting in a mean mortality of 22% after 11 months across all sites (Branoff 2020). Massive tree mortality associated with storms has been seen in Southwest Florida, Puerto Rico, and the Dominican Republic, but the amount of degradation has varied by forest structure, proximity and direction of the hurricane, mangrove species, tree size, hydrogeomorphology, and storm intensity (Branoff 2020; Jamaluddin et al. 2021; Krauss and Osland 2020). Generally, hurricanes can lead to massive tree mortality and forest structural shifts, which influence biogeochemical processes, forest regeneration, and succession (Krauss and Osland 2020). After Hurricane Georges in the Dominican Republic, mortality (which ranged from 14% to 100%, with an average tree mortality of 47.7%) increased over nine months between surveys 7 and 18 months post-hurricane (Sherman et al. 2001). Further, reduction in basal area has been observed post-storm and can have wide ranges. After Hurricane Georges, reductions in total basal area post-hurricane ranged from 9% to 100% (Sherman et al. 2001). It was also observed that Hurricane Irma in Saint Martin decreased stem density (down to hundreds of stems per hectare) (Walcker et al. 2019).

Different mangrove species can have varying recovery patterns. Recovery patterns also vary across the literature according to tree size and geomorphology (Branoff 2020). To fully understand mangrove recovery, at least 18 months of monitoring is necessary to detect resilience (Walcker et al. 2019). After the 2017 hurricane season in Puerto Rico, it took 11 months for mangroves to recover to 72% canopy closure and nearly 60% of their prestorm growth rates; however, closure recovery rates decreased with time. Canopy closure can be one of the most important determining factors in successional and structural dynamics. Overall canopy recovery averaged 2% per month, but the rate decreased with time following the 2017 hurricane season in Puerto Rico. Further, canopy closure for some forests was not forecasted to return to pre-storm levels within the next 20 years (Branoff 2020). Following Hurricane Charley in Southwest Florida, it was found that canopy recovery was slow and that canopy density was significantly lower at all sites, independent of species. Bigger trees had greater initial mortality in Southwest Florida (Milbrandt et al. 2006).

Hurricane sediments can help mangroves maintain elevation under rising sea levels. Rates of elevation change were greatly influenced by storm sediments after Hurricane Wilma in the Florida Everglades. There was an initial post-hurricane period of elevation loss caused by erosion of hurricane-deposited sediments and subsurface contraction, and then a secondary period of elevation gains caused by accretion (Feher et al. 2020).

Strength of Evidence

Moderate. While the short-term effects of hurricanes and/or cyclones on degradation and recovery are well-studied, the amount of research on long-term effects of tropical storms in the Caribbean and Southwest Florida are much less studied. Further, the complexity of other factors such as hurricane intensity, mangrove resilience prior to the hurricane, tree size, tree location, and mangrove species complicate the certainty of predicting how degradation resulting from tropical storms can affect mangrove quality and quantity.

Other Factors

The condition of a mangrove site before a cyclone or hurricane can affect its degradation and recovery post-storm (Krauss and Osland 2020). In a 2017 Saint Martin study, it was found that there were distinct rates of forest recovery that differed by site: some mangrove sites had early and rapid recovery, while other sites were unable to recover 14 months after the disturbance. Human-induced degradation before the storm was hypothesized to be the main factor contributing to different rates of mangrove recovery (Walcker et al. 2019). Similarly, mangroves in urban environments that are subject to higher contaminants, altered hydrology, and structural abnormalities negatively influence the resilience of ecosystems to tropical storms (Branoff 2020). The synergistic effect of multiple anthropogenic stressors needs to be further studied.

The literature is conflicted over whether there is an effect of mangrove tree species on mortality and recovery. Different mangrove species have different tolerance levels for different stressors (e.g., wind stress, sedimentation, erosion) which could explain the differences by species seen in hurricane damage (Krauss and Osland 2020). Interspecific differences in susceptibility to wind damage appeared to be a primary factor contributing to spatial patterns in mortality (Sherman et al. 2001). Overall, many studies of sites in the Caribbean region (including Puerto Rico, Saint Martin, and Dominican Republic) found *L. racemosa* mortality and canopy loss lower than *R. mangle* or *A. germinans* (Branoff 2020; Krauss and Osland 2020; Walcker et al. 2019). Further, *L. racemosa* was found to recover more quickly than *A. germinans*, and after 18 months the health of *L. racemosa* was found to be improving (Branoff 2020; Krauss and Osland 2020). However, one study found that the effects of Hurricane Irma on tree health, size, and density was not species-dependent (Walcker et al. 2019). Instead, this study found that tree mortality was determined by tree size—remaining live trees after Irma were larger in diameter and lower in height (Walcker et al. 2019). Tree size was also found to be linked to mortality in Puerto Rico after Hurricanes Irma and Maria—larger trees suffered 25% more mortality post-storm (Branoff 2020). Lower forest structure can buffer stands against major wind pulses, and taller trees are more likely to suffer breakage and can significantly alter basal area (Krauss and Osland 2020). Differences in forest structure could have an effect on mangrove degradation and recovery; however, it is important to study mangrove recovery on multiple temporal scales. The time frame after a hurricane can change the factors to look for as signs of degradation. On a short-term scale, immediate effects can include defoliation, tree mortality, and erosion of surface sediments. However, long-term effects can include permanent losses of mangrove area, substantial decreases in soil elevation, and peat collapse (Feher et al. 2020). As shown, the effect of speciation on degradation and recovery is complex.

Mangrove location can also influence the amount of damage that a certain site incurs from a particular storm. Mangroves on the fringe are more directly exposed to storms and therefore experience greater erosion of surface sediments and tree mortality that lead to peat collapse and elevation declines (Feher et al. 2020). Mangroves in tidally restricted canals experiences more canopy loss but faster recovery rates than mangroves in open systems (Branoff 2020).

Predictability

The cause-and-effect predictability for this relationship is confounded because of unclear effects of species, species size, location, hurricane intensity, and preexisting conditions. Structural complexity, hydrogeomorphic setting, antecedent environmental change, orographic positioning, and angle of cyclone trajectory generate a spatial signature of response/effects of cyclones (Krauss and Osland 2020). There are site-dependent responses to mangrove mortality and recovery, and more research must be done to determine the factors that influence mangrove disturbance by hurricanes in the Caribbean.

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LINK 2 AND LINK 3*: MANGROVE DEGRADATION AND RECOVERY → SCIENTIFIC AND EDUCATIONAL OPPORTUNITIES

*Links 2 and 3 were assessed together because of overlapping evidence

Description of Relationship

Planting new, restoring existing, or observing natural recovery of mangrove forests following severe storm and hurricane events facilitates scientific research and promotes productivity in the field of mangrove ecology. Numerous studies and review papers focus on the effects of severe storms and hurricanes on mangrove areas, how mangroves respond to storm impacts, and the external factors that affect these relationships. Observations of the recovery process as well as restoration of mangrove habitats also provide opportunities for education. Several organizations around mangrove forest areas host educational and community outreach programs related to the restoration and conservation of mangroves. The Mangrove Coast Collaborative Project is just one example of a scientific and educational opportunity that arose as a result of mangroves' response to storms.

Summary of Evidence

Scientific Opportunities

Mangrove degradation and recovery provide numerous societal benefits in the wake of storm events (Krauss and Osland 2020), including research and scientific opportunities. Numerous scientific studies and review papers have examined the relationship between severe storms and hurricanes and mangrove forests, how mangroves respond to storms, and the external factors that affect these relationships, such as mangrove characteristics, topography, and storm characteristics. Many scientific studies also focus on the best practices for mangrove rehabilitation or restoration. It can be reasonably inferred that planting new or restoring existing mangrove forests requires careful consideration, organization, and planning to be effective, which logically requires extensive background research on the topic and therefore facilitates scientific activities.

Krauss and Osland (2020) conducted an extensive review of the numerous studies that examine the effects of storm events on mangroves and how they recover. This review specifically looked at the influence of tropical cyclones on structural characteristics of mangrove forests and how that is affected by storm characteristics, topography of the land, and features of the mangrove forest (Krauss and Osland 2020).

Godoy and de Lacerda (2015) conducted a review to analyze the literature published over the last 25 years on the documented response of mangroves to environmental change caused by global climate change, taking into consideration 104 worldwide case studies and predictive modeling. One of the main threats posed to mangrove forest areas from climate change is the increase in frequency and severity of storms and hurricanes; thus, this review paper documents much of the scientific research that examines the response of mangroves to increased frequency and severity of storms (Godoy and de Lacerda 2015).

The Nature Conservancy also published a report synthesizing existing scientific literature on the increasing effects of storms and hurricanes on mangrove forests; the extent, location, and severity of impact on mangrove forests; and what actions can be taken to restore mangroves following a storm event (Herrera-Silveira et al. 2022). While not directly stated in the literature, mangrove degradation and recovery facilitate scientific opportunities through research and scientific inquiry.

Educational Opportunities

Mangrove degradation and recovery after storms also provides opportunities for education. Many local organizations provide educational programming and community outreach programs centered around the recovery and conservation of mangrove areas. This information is mostly not found in scientific literature and is instead found on the websites of these organization. However, there is no information on the efficacy of the educational opportunities provided.

Multiple National Estuarine Research Reserves conduct educational programming around the response of mangroves to increased storm activity. See the local context box that follows for more detail.

The Fund for Communication and Environmental Education has developed a program of education and environmental recovery in the mangrove areas of Yucatán, Mexico. The ultimate aim of this project is to create the basis for carrying out environmental restoration projects in surrounding mangroves and garnering community support through education. This goal is achieved through community participation in three community mangrove nurseries and an awareness and training program implemented in local schools to promote significant learning and the building of a culture of caring for and sustainably developing forestry, fishing, and tourism resources (Guitérrez Mercadillo 2016).

In the Caribbean, the Khaled bin Sultan Living Oceans Foundation facilitates mangrove education and restoration program which aims to increase environmental awareness and restore mangrove forests. This organization partners with local educational institutions to teach students and teachers about the ecological importance of their mangrove forests and help them get involved in mangrove restoration efforts (Khaled bin Sultan Living Oceans Foundation n.d.).

In the United States and the Caribbean, the Mangrove Action Project (MAP) is a small, education-focused nonprofit run by the International Union for Conservation of Nature that works in partnership with mangrove-interested parties such as individuals, community groups, academics, governments, international nongovernmental organization networks, and supranational organizations. MAP has two training products: a best practice Community-Based Ecological Mangrove Restoration process, and a "Marvellous Mangroves" schools education curriculum that educates younger generations on the value and benefits of conserving mangroves (IUCN n.d.). Mangrove restoration is not always performed as a response to storms; there are many other reasons that a mangrove forest may be damaged or degraded. However, restoration post-storm is one application of these materials.

The Nature Conservancy also produces education materials on mangrove restoration and facilitates educational outreach programming in Florida, such as having young volunteers plant mangroves on the Blowing Rocks Preserve shoreline as part of their field trips (TNC 2023).

Strength of Evidence

Fair. Despite there being limited information of the nature of this relationship and no literature that directly addresses this link, several academic studies demonstrate the scientific and educational opportunities that arise out of the degradation and recovery of mangroves following storm events, indicating strong evidence that this relationship exists. Similarly, while several local organizations facilitate educational opportunities related to the degradation and recovery of mangroves in response to storm events, this information is described on their websites, but not in the scientific literature. Nonetheless, the lack of direct information on these links does not seem to indicate the lack of a relationship.

Other Factors

The amount of available funding for scientific opportunities can have an effect on the frequency and extent of research that can occur. The less funding received for mangrove degradation and recovery following storms, the less research into that topic can be conducted. The availability of educational opportunities may also be limited by funding and community dynamics, but this information is not documented.

The frequency and intensity of storms would also impact this relationship. The opportunity to study and provide educational opportunities only happens when storms happen, and with climate change, storms may occur more frequently, providing more opportunities.

Predictability

Because of the lack of direct evidence for these links, there is no existing information on their predictability.

Scientific and educational opportunities exist in degraded and recovering mangrove areas, but there have to be researchers, funding, and educators in place to take advantage of the opportunities provided. There is no way to predict specifically how that will happen.

Local Context

Both Rookery Bay and Jobos Bay reserves report numerous scientific and educational opportunities created through storm impacts on mangroves. Scientific studies were conducted specifically to examine the impacts of hurricanes on these mangrove ecosystems, including the study that funded this work: The Mangrove Coast Collaborative. But additional associated research is ongoing, including research related to changing wildlife communities associated with ecosystem change. For example, a study at Jobos Bay conducted by Schaffner et al. (2019) examined how bird communities in the reserve changed post-hurricane. Additionally, both reserves have taken advantage of the educational opportunities provided by hurricane disturbance. Numerous school groups that visit Rookery Bay are shown the Fruit Farm Creek restoration site. This site was degraded from blockages to normal tidal flow, which was exacerbated by stress from hurricanes.

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LINK 4: MANGROVE QUALITY/QUANTITY → SEDIMENT TRAPPING

Description of Relationship

Mangroves are able to trap sediments and enhance sedimentation through two mechanisms: (1) direct trapping and stabilization of sediments with their root systems and (2) their indirect ability to alter surrounding hydrodynamic forces in favor of sediment deposition, with the latter being the predominant way in which mangroves trap sediment (Chen et al. 2008; Horstman et al. 2015). The role of mangroves in sediment trapping is well-documented and widely accepted, but the extent to which mangrove-facilitated sediment trapping can occur may depend on other factors such as intertidal placement of mangroves, the species of mangrove, the availability of suspended sediment, and variability of hydrodynamic forces (Adame et al. 2010; Chen et al. 2008; Furukawa and Wolanski 1996; Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003; Lynch et al. 1989; Van Santen et al. 2007; Willemsen et al. 2016).

Summary of Evidence

Like many coastal wetland plant species, one of the main services provided by mangroves is their capacity for sediment trapping and retention (Adame et al. 2010; Kamal et al. 2017; Kathiresan 2003). Measures of annual sedimentation rates in mangrove areas range between 1 and 8 mm; through this process, they actively contribute to the creation of coastal mud banks (Furukawa and Wolanksi 1996; Kathiresan 2003). Further, the existence of mangroves is dependent on their ability to maintain a vertical accretion rate greater than the rate of sea-level rise through sediment trapping (Adame et al. 2010; Chen et al. 2008; Furukawa et al. 1997; Lynch et al. 1989; Willemsen et al. 2016). This link is well-documented and widely accepted in the literature, but also recognized anecdotally by residents local to coastal mangrove areas who attribute increasing shoreline erosion partially to the loss of mangroves and their sediment-trapping abilities (Chen et al. 2008).

Mangroves have the capacity to trap both allochthonous (originating from external terrestrial or oceanic sources) and autochthonous (originating from within the mangrove forest ecosystem) sediment (Adame et al. 2010; Victor et al. 2004). The two main processes by which mangroves facilitate sediment trapping are through (1) direct trapping by their vegetative structures and (2) by indirectly influencing surrounding hydrodynamic forces. Most mangrove-facilitated sediment trapping is attributed to the second process (Chen et al. 2008; Horstman et al. 2015).

Direct sediment trapping by mangroves occurs when the vegetation surfaces of mangroves, such as leaves and stems, trap sediment. Mangrove vegetation has the ability to trap particulate organic matter, and these sediments attached to the vegetative surface can contribute up to 0.5 cm to the annual deposition rate of mangroves during their growing season. The sediment-trapping potential of this direct process is highly dependent on the height of the water level relative to the mangrove trees (Chen et al. 2008).

Aside from direct processes influencing mangrove-facilitated sediment trapping, the indirect effects of mangroves on sediment trapping result from the influence of mangrove root and trunk structures on surrounding hydrodynamic forces, and are responsible for far greater mangrove-facilitated sediment trapping than direct processes (Chen et al. 2008; Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003; Van Santen et al. 2007; Willemsen et al. 2016). Mangrove-facilitated sediment deposition occurs during periods of tidal inundation because of the ability of mangrove vegetative structures to slow down hydrodynamic forces such as tidal flows (Chen et al. 2008; Horstman et al. 2015; Lynch et al. 1989; Willemsen et al. 2016). Sediments suspended in seawater from allochthonous sources such as river discharge, dumping of dredged material, or resuspension of bottom sediment by waves and ships are introduced into coastal mangrove areas via incoming flood currents before high tide (Kathiresan 2003). When the complex, dense vegetative structures of mangrove trunks and aboveground aerial root networks interact with surrounding water and tides, these vegetative structures cause an increase in friction and drag force near the mangrove floor and an increase in bottom roughness, reducing tidal current velocities, attenuating waves, and modifying flow patterns (Chen et al. 2008; Kamal et al. 2017; Van Santen et al. 2007; Willemsen et al. 2016). Because of this interaction, high microturbulence and change in flow dynamics caused by flow divergence around mangrove structures cause the sediment particles carried in at high tide to then be maintained in suspension in the mangrove forest waters (Kamal et al. 2017; Kathiresan 2003; Willemsen et al. 2016). Slack tide occurs after high tide and before the tide reverses. During this period, the previously suspended sediments settle on the mangrove forest floor. (Kamal et al. 2017). Following slack tide, during ebb currents in the period leading up to low tide, the physical vegetative structures of mangroves and the friction they induce decelerate the currents to the point that the outgoing water velocity and turbulence are too sluggish and low to resuspend and carry sediment particles back out to the larger waterbody (Chen et al. 2008; Kamal et al. 2017; Kathiresan 2003; Van Santen et al. 2007). Thus, the sediment is left deposited in the mangrove forest. Ultimately, the interactions between mangrove vegetative structures and the tidal cycle induce local sediment deposition and accretion in the mangrove area (Chen et al. 2008; Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003; Willemsen et al. 2016).

Several site-specific studies have documented evidence of mangrove-facilitated sediment trapping resulting from both of these processes. Studies of this sort consistently use methods such as sediment traps, soil cores, changes in surface elevation, ^{210}Pb analysis, and 3-D modeling to determine the effect of mangrove trees on sedimentation (Adame et al. 2010; Furukawa et al. 1997; Kathiresan 2003; Van Santen et al. 2007; Victor et al. 2004).

These studies, of mangroves located in Palau, Vietnam, India, and Australia, found that between 30% and 80% of sediments introduced by incoming flood waters were trapped, resulting in long-term sedimentation rates of between 1.0 and 2.4 mm/yr^{-1} (Adame et al. 2010; Furukawa et al. 1997; Kathiresan 2003; Van Santen et al. 2007; Victor et al. 2004). More specifically, another study measuring sediment accretion rates at mangrove sites in Rookery Bay, Florida, and Terminos Lagoon, Mexico, found mangrove-facilitated sediment trapping contributed to long-term sedimentation rates of 1.6 and 2.4 mm/yr^{-1}, respectively (Lynch et al. 1989).

Strength of Evidence

High. The relationship between mangrove quality/quantity and sediment trapping is well-documented, widely accepted, and consistent within scientific literature. All sources identify the same mechanisms and processes (direct trapping by structures and indirect trapping through vegetative structure influence on hydrodynamic forces) that link mangroves to sediment trapping across different geographic areas, and most sources explain similar influences of various other factors. Sources use a wide variety of methods in conducting both field studies and creating data-driven models and discuss similar conclusions across method types. All but one source use site-specific studies outside the Gulf of Mexico/Caribbean region, but they all have similar conclusions and generalize the mechanisms of mangroves that allow them to facilitate sediment trapping.

Other Factors

Several external factors may influence the magnitude and extent to which mangroves can trap sediment, including the spatial location of mangroves, the species of mangrove, the availability of suspended sediment, and variability in hydrodynamic forces (Adame et al. 2010; Chen et al. 2008; Furukawa and Wolanski 1996; Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003; Lynch et al. 1989; Van Santen et al. 2007, Willemsen et al. 2016).

Several studies have found the intertidal placement of mangrove trees (e.g., fringe or basin) to affect average sedimentation rates and sediment trapping capacity (Adame et al. 2010; Chen et al. 2008; Horstman et al. 2015; Kathiresan 2003; Lynch et al. 1989; Van Santen et al. 2007). During a tidal cycle in Queensland, Australia, the fringe zone has been found to retain the majority of sediment entering the area and had an average sedimentation rate of 0.35 mg cm^{-2} spring $tide^{-1}$ greater than the scrub zone (Adame et al. 2010). Similar results were measured in Florida and Mexico (Lynch et al. 1989). This difference results from the more extensive root systems, higher density of vegetation cover, and well-developed epiphytic algal communities on the mangrove roots that increase friction in the fringe zone of tidal mangroves (Adame et al. 2010; Chen et al. 2008; Horstman et al. 2015; Kathiresan 2003; Van Santen et al. 2007).

The species of mangrove tree may also influence sediment trapping as a result of differences in root structure and complexity that may interact with hydrodynamic forces in varying ways (Furukawa and Wolanski 1996; Kamal et al. 2017; Kathiresan 2003). Different aerial root types from different species of mangroves have different effects on tidal forces and abilities to trap sediment (Kamal et al. 2017). Studies in both India and Australia have measured up to a 10% difference in total suspended sediment trapped depending on the species of mangroves present (Furukawa and Wolanski 1996; Kathiresan 2003). The extent of sedimentation is greatest for trees with more complex roots, which have greater impacts on tidal flows (Furukawa and Wolanski 1996).

The amount of sediment available is also an important factor in the degree to which mangroves can trap sediment (Horstman et al. 2015; Willemsen et al. 2016). With less suspended sediment available (lower suspended-surface concentration) and brought into mangrove areas through flood tides, the mangroves will subsequently trap less sediment (Willemsen et al. 2016). Sediment availability can be negatively impacted by anthropogenic disturbances such as river damming and creation of reservoirs, which severely restrict the sediment supply to coastal mangrove zones (Horstman et al. 2015; Willemsen et al. 2016). A study that modeled the effects of removing a dam in Singapore found that mangrove-facilitated sediment deposition rates would increase by up to 300% after the dam was removed and sediment supply to mangroves was no longer restricted (Willemsen et al. 2016).

Finally, variability in hydrodynamic forces may also affect the extent to which mangroves can facilitate sedimentation because of the complex interactions between them and mangrove vegetative structures (Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003; Van Santen et al. 2007). The transportation of suspended sediments in mangroves is primarily influenced by the existence of tidal flows, flow velocity, and wave energy level, and changes in these processes may affect the ability of mangrove vegetative structures to alter certain properties of the surrounding water that facilitate sediment deposition (Horstman et al. 2015; Kamal et al. 2017; Kathiresan 2003).

Predictability

The literature consistently agrees that mangroves facilitate sediment trapping and concurs on the mechanisms that account for the relationship. While other factors such as intertidal placement of mangroves, species of mangrove, availability of suspended sediment, and variability in hydrodynamic forces may influence the extent to which mangroves can trap sediment (i.e., increase/decrease average sedimentation rate or percent suspended sediment trapped), the relationship between mangroves and sediment trapping still occurs and has been measured in the presence of these factors in a variety of settings. Across a variety of geographic locations, mangroves have the ability to trap between 30% and 80% of suspended sediments, resulting in sedimentation rates of between 1.0 and 2.4 mm/yr^{-1} from the indirect influence of mangrove structures on hydrodynamic forces. An additional trapping rate of up to 5.0 mm of particulate organic matter occurs during the growing season as a result of direct trapping processes (Adame et al. 2010; Chen et al. 2008; Furukawa et al. 1997; Kathiresan 2003; Van Santen et al. 2007; Victor et al. 2004). Three-dimensional models can and have been created using inputs of real-world mangrove forest data to determine the effects of various other factors such as root structure and reduced sediment supply on mangrove-facilitated sedimentation (Horstman et al. 2015; Kamal et al. 2017; Willemsen et al. 2016).

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LINK 5 AND LINK 13*: MANGROVE QUALITY/QUANTITY → WILDLIFE HABITAT AREA → WILDLIFE POPULATIONS

*Links 5 and 13 were assessed together because of overlapping evidence

Description of Relationship

Mangroves are ecologically important to many wildlife species because they provide habitat area for various uses. Different wildlife species use different parts of mangrove forest habitats at various stages in their life cycles. The structural complexity and productivity of mangrove forests creates ideal foraging, nursery, nesting, and refuge grounds for a diversity of fauna including birds, mammals, reptiles, fishes, and aquatic invertebrates. There are three main factors identified in the literature as reasons why mangrove forests are attractive habitats for dependency and use by wildlife: (1) reduced predation within mangrove areas, (2) increased food supply within mangrove areas, and (3) increased living space or shelter because of mangrove structural complexity (Nagelkerken et al. 2001, 2008; Tse et al. 2008; Whitfield 2017; Zakaria and Rajpar 2015).

Summary of Evidence

Mangrove forests play a crucial role in providing habitat to a wide variety of fauna because of the availability of complex vegetation structures and sheltered habitats (Nagelkerken et al. 2001, 2008; Tse et al. 2008; Whitfield 2017; Zakaria and Rajpar 2015). Mangrove habitats provide safe breeding and chick rearing grounds for birds, nurseries for a diversity of fishes and shellfish, ideal foraging grounds for animals such as fishes, birds, and aquatic invertebrates, and refuge from predators (Zakaria and Rajpar 2015). The presence of higher diversity of fauna within mangrove forest systems is thought to result from the complex vegetation structure, composition, and relatively disturbance-free nature of mangrove forests; the availability of food resources such as detritus, fishes, polychaetes, mollusks, crabs, and crustaceans; and low predation risk (Nagelkerken et al. 2001, 2008; Tse et al. 2008; Whitfield 2017; Zakaria and Rajpar 2015). Mangrove habitat loss and degradation pose major threats to a wide array of fauna that depend on mangrove habitats for varying stages of their life cycles, putting them at risk at becoming endangered or extinct (Zakaria and Rajpar 2015).

Mangroves as Habitat for Fish Species

Mangrove forest systems provide habitats and nursery grounds for a multitude of fish species. The productive and structurally complex environment provided by mangrove stands and their pneumatophores (aerial respiratory roots), prop roots, tree trunks, and falling branches makes mangrove forests core habitats used as feeding grounds and refuges by juvenile fishes (Nagelkerken et al. 2008; Tse et al. 2008; Whitfield, 2017; Zakaria and Rajpar 2015). Mangroves are also areas of high food availability, rich in invertebrate assemblages such as crustaceans, mollusks, and worms that fishes feed on, and have low predation risk for small, medium-sized, and juvenile fishes (Tse et al. 2008; Whitfield 2017; Zakaria and Rajpar 2015). The turbid, shallow waters of mangrove forests reduce the effectiveness of large visual fish predators for preying on juveniles that use mangroves as a nursery, exclude large fishes due to depth, and enable small fishes to hide from predators (Nagelkerken et al. 2008; Tse et al. 2008; Zakaria and Rajpar 2015).

Field studies have shown that even artificial mangrove structures attract more juvenile fishes than coastal areas without structures. When artificial mangrove units (AMUs) were removed from a sheltered embayment site, there was a complete collapse of the fish assemblages using the AMUs as habitat and protection against predation (Whitfield 2017). A study in Hong Kong that compared the potential of mangrove forests and surrounding bare mudflats to serve as fish nurseries found that fish abundance was higher in mangrove habitats by about threefold, with the majority of the fishes being juvenile. In this study, mullets were commonly found in the mangrove area because they depend on organic-rich conditions and feed mainly on detritus (Tse et al. 2008). In southwest Florida, another study demonstrated the importance of nearshore mangrove-dominated areas as refuges for juvenile fishes by measuring and comparing catch per unit effort of fish. This study found that average catches were up to an order of magnitude greater in inshore sites near mangroves than at sites just outside the land fringe in 1 to 2 m water depth (Robertson and Duke 1987).

A review of mangroves as habitats for wildlife species found that large tropical and subtropical mangrove systems contain at least 100 species of fishes. The fish communities of mangroves in all four tropical zoogeographic regions of the world (Indo-West Pacific, East Pacific, West Atlantic, and East Atlantic) have many common characteristics, such as containing fishes of marine origin, with more than half of the number of species and individuals being either fully estuarine species or marine migrants (Nagelkerken et al. 2008; Whitfield 2017). This review found that throughout the islands of the Caribbean, most mangroves contain marine fish species dominated by the families *Gerreidae*, *Haemulidae*, *Lutjanidae*, and *Scaridae* (Nagelkerken et al. 2008). In east Malaysia, one mangrove forest stand was found to be home to 36 fish species belonging to 22 families, with the most abundant fish families being *Leiognathidae* (ponyfish), *Lutjanidae* (snapper), and *Sciaenidae* (croaker and grouper) (Zakaria and Rajpar 2015). Worldwide, about 30% of all commercial fishes are mangrove-dependent at some point in their life cycle, producing an annual catch of almost 30 million tons in 2002 (Nagelkerken et al. 2008).

Mangroves as Habitat for Marine Invertebrates

Mangrove forest systems also create habitat area for and support many species of marine invertebrates. The high diversity of invertebrates within mangrove areas results from availability of organic food material, protection from predators because of local water turbidity and soil to burrow in, and larval retention associated with localized hydrodynamic forces. Mangrove aquatic invertebrates are a major dietary component of birds, fishes, and other invertebrates within mangrove systems, helping to support other wildlife populations (Nagelkerken et al. 2008; Zakaria and Rajpar 2015). Mangrove invertebrates dwell on sediment surface, reside in burrows, live on pneumatophores and lower tree trunks or prop roots, burrow in decaying wood, and are even found in the canopies of mangrove trees (Nagelkerken et al. 2008). Invertebrate fauna present in mangrove forest systems include crustaceans (crabs, prawns, and shrimp), mollusks (snails, clams, periwinkles, murex, and oysters), and worms (lug worms, tube worms, eunicid worms, and polychaete worms) (Nagelkerken et al. 2008;

Zakaria and Rajpar 2015). Crabs are the dominant macrofauna in most intertidal mangrove ecosystems. Studies have found higher densities of juvenile prawns and other crustaceans in mangrove forest areas as compared to adjacent nearshore habitats (Nagelkerken et al. 2008).

Mangroves as Habitat for Bird Species

Mangrove trees and their canopies provide important habitat for a wide range of bird species for breeding, nesting, roosting, and feeding (Mancini et al. 2018; Nagelkerken et al. 2008). The vegetation heterogeneity, abundance of food resources, and habitat diversity in mangrove forest areas may be responsible for the increased avian richness and diversity observed in mangrove forests. Mangrove forest systems often provide suitable foraging sites, chick rearing grounds, and protection from harsh weather and predators (Zakaria and Rajpar 2015).

A study examining faunal diversity in a mangrove forest stand in East Malaysia observed 74 species of birds representing 33 families, with the most dominant families observed being *Ardeidae* (egrets, herons, and bitterns), *Scolopacidae* (redshanks, greenshanks, tattlers, sandpipers, and whimbrels), *Cuculidae* (malkohas, coucals, cuckoos), and *Picidae* (woodpeckers, flamebacks, piculets) (Zakaria and Rajpar 2015). A study looking at bird richness, abundance, and seasonal diversity of water birds and terrestrial birds at two mangrove forest sites in Brazil observed a total richness of 84 bird species, with most observed birds being terrestrial species. This study found that mangrove trees form complex habitats and house more niches, increasing microhabitats and niche heterogeneity for the benefit of avian species, and that mangroves are very important for the life cycles of birds—not only for resident species, but also migratory and endangered species (Mancini et al. 2018).

Mangroves as Habitats for Mammals

The vegetation structure, as well as richness of food resources are the major driving factors that attract certain mammal species to mangrove areas. In East Malaysia, species of monkeys, pigs, and squirrels were found to inhabit mangrove forest areas (Zakaria and Rajpar 2015). Manatees are also commonly found in mangrove areas (Allen et al. 2018; de Thoisy et al. 2013; Luiselli et al. 2012). Certain abiotic and biotic factors within mangrove areas, such as the relatively shallow, warm water; the presence of brackish and fresh water; relatively pristine states and quietness; and plant species known to be consumed by manatees, make mangrove areas suitable habitats (de Thoisy et al. 2013). The red mangrove (*Rhizophora mangle*) is an important food item for many manatee species, attracting them to mangrove habitats (Allen et al. 2018; de Thoisy et al. 2013).

Strength of Evidence

High. Evidence for the relationship between mangrove areas, wildlife habitats, and wildlife populations is well-documented and consistent within peer-reviewed scientific literature. Almost all evidence found was sourced from extensive review papers that discussed this relationship for mangroves in general and used data from mangroves in varying geographic locations. The literature was consistent in identifying the ecological importance of mangroves as wildlife habitat areas and in supporting wildlife populations, as well as consistently identifying the attractiveness of mangrove areas as habitats and the functions of mangroves for differing taxa. Some information about which specific species are present in a certain mangrove area may not be generalizable because of differing species ranges, but overall information about which taxa inhabit mangrove areas and the mangroves' habitat functions may be generalizable.

Other Factors

The vegetation structure and composition of mangrove areas may vary depending upon factors such as soil texture and structure, rainfall patterns, and inflow of freshwater from rivers to the sea, which may then influence the type and abundance of wildlife species a mangrove forest can support (Zakaria and Rajpar 2015). Other abiotic factors such as water salinity and turbidity also affect the survival and distribution of wildlife species within mangrove forests. Salinity varies in mangrove forests, which affects survival and distribution of fish species with different salinity tolerances (Nagelkerken et al. 2008). Similarly, turbidity is a major factor affecting the distribution of juvenile fishes in subtropical and tropical mangrove forests and variations in turbidity were found to be correlated with differences in distribution patterns of fishes (Nagelkerken et al. 2008; Whitfield 2017).

Seasonal and spatial differences in current patterns coupled with migratory patterns of larvae and species also affect which species are present in mangroves during different seasons and points within a species' life cycle (Robertson and Duke 1987). The types of species supported by mangrove forest areas also depend on the species' geographic range and distribution. Mangrove habitats often support a richer juvenile fish assemblage than nearby sand or mudflats, but the same is often not true for subadult and adult fishes; smaller fishes move further into mangrove forests because they are more vulnerable to predation by larger fishes. Temporally, some northern Brazilian estuaries have a trend of increasing fish abundance in mangrove habitats at the onset of the rainy season. Further, species inhabiting mangrove forests may vary with tidal cycles. At low tide, mangrove plant structures are often unavailable to fishes within tidal creeks and juveniles may be pushed into main channel habitats. However, at high tide, there is free access to the structural complexity and protection that intertidal mangrove habitats provide for juvenile fishes. Climate change is also likely to cause major changes in the distribution and extent of particular mangrove habitats within estuaries, leading to significant changes in wildlife assemblages within these habitats, particularly in biogeographic transition zones (Whitfield 2017).

Predictability

The literature is consistent in identifying the ecological importance of mangrove forest systems in providing wildlife habitats and supporting populations including fishes, marine invertebrates, bird species, and mammals. The relationship between mangrove forest stands and their ability to provide habitat for various species of wildlife is straightforward and dependent on the structural complexity of mangroves, the availability of food resources they provide, and the protection from predators that they afford. There are no specific models or tools to predict this relationship, but the geographic range and distribution of a particular species can be used to generally predict whether or not the species would inhabit a mangrove forest area (i.e., the species has to occupy the same geographic area of a particular mangrove stand and will probably be a marine or estuarine species that can inhabit a shallow, coastal area).

Local Context

Both reserves have examined how changing mangrove habitats can affect wildlife populations. Some examples include the report by Schaffner et al. (2019), who conducted a study at Jobos Bay that examined how bird communities in the reserve changed post-hurricane, and work by Cheadle (2020) that examined wading bird occupancy of mangroves damaged by Hurricane Irma. There are also reports from both reserves that degraded mangroves can provide enhanced nesting habitat for a variety of bird species. However, there are also observations that indicate birds in degraded mangroves had more exposure to predators in years after a hurricane as a result of defoliation. Additionally, at Jobos Bay there were observations that degraded mangroves did not flower in the years post-hurricane, which negatively affected both pollinators and nectivores.

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LINK 6: MANGROVE QUALITY/QUANTITY → NET PRIMARY PRODUCTION

Description of Relationship

Mangrove forests are among the most productive ecosystems on earth (Castañeda-Moya et al. 2013; Jennerjahn and Ittekkot 2002; Ribeiro et al. 2019). Net primary production (NPP) of mangroves is typically estimated by using summations of total litterfall, wood production, and belowground biomass (Day et al. 1996; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019). Many studies report on the NPP of mangroves, and NPP measurements vary between sites (see the following section). NPP of mangroves is dependent on several external factors such as the location of the mangrove forest, seasonality, environmental regulators, resources, and hydroperiods (Castañeda-Moya et al. 2013; Day et al. 1996; Jennerjahn and Ittekkot 2002; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019).

Summary of Evidence

NPP occurs in mangrove forests when mangroves produce and input organic carbon and biological energy in excess of ecosystem respiration (Castañeda-Moya et al. 2013). Mangrove forests are among the most productive ecosystems in the world, with one study ranking them second only to coral reefs in NPP (Castañeda-Moya et al. 2013; Jennerjahn and Ittekkot 2002; Ribeiro et al. 2019). With high NPP, mangrove ecosystems play an important role as carbon sinks and exporters of carbon to adjacent coastal waters (Castañeda-Moya et al. 2013; Jennerjahn and Ittekkot 2002; Komiyama et al. 2008; Ribeiro et al. 2019). Ecologically, mangrove NPP is also highly important as it provides the energy that enters coastal systems and food webs. Higher NPP from producers (i.e., mangroves in this system) allows for more energy to be available to consumers at all levels of the food chain and leads to higher productivity within the ecosystem (Schowalter 2006). Mangrove total NPP includes both aboveground processes (i.e., wood production and leaf litterfall) and belowground processes (i.e., coarse and fine root production) (Castañeda-Moya et al. 2013; Kamruzzaman et al. 2017; Khan et al. 2009; Ribeiro et al. 2019). Within existing literature, there are inconsistent results on the contribution of belowground processes and root production to mangrove NPP, which may result from the methodological constraints on measuring belowground root biomass (Castañeda-Moya et al. 2013; Kamruzzaman et al. 2017; Ribeiro et al. 2019).

In estimating total NPP in a mangrove ecosystem, many studies employ the summation method, which calculates an aggregate of factors impacting NPP such as rates of growth increment, death, consumption by herbivores, aboveground biomass, or litterfall (Day et al. 1996; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019). Although it only accounts for 32% of total mangrove NPP, litterfall is the most common metric used across sites because of its relative ease of measurement as compared to methodological constraints associated with measuring wood and root productivity (Kamruzzaman et al. 2017; Ribeiro et al. 2019). Litterfall is measured using litter traps (Day et al. 1996; Kamruzzaman et al. 2017). The allometric method is also used to estimate aboveground biomass in NPP measurements and estimates the whole or partial weight of a tree using measurable tree dimensions, including trunk diameter and height, using allometric equations (Kamruzzaman et al. 2017; Khan et al. 2009; Komiyama et al. 2008).

Numerous studies have estimated the NPP of various mangrove forests. A seven-year record of aboveground NPP of mangrove forests in Mexico estimated annual aboveground NPP to range between 319.4 and 759.3 g m^{-2} yr^{-1}, calculating NPP as a sum of total litterfall and wood production NPP. It was estimated that riverine mangrove forests in Sri Lanka and Terminos Lagoon, Mexico, had NPP values of 2415 and 2456 g m^{-2} yr^{-1}, respectively; fringe mangrove forests in Puerto Rico, Sri Lanka, and Terminos Lagoon had NPP values of 1007, 1388, and 1606 g m^{-2} yr^{-1}, respectively; and NPP of a basin mangrove forest in Australia was 518 g m^{-2} yr^{-1} (Day et al. 1996). In Bangladesh, mean aboveground NPP in a mangrove forest was estimated to be 17.2 Mg ha^{-1} yr^{-1} and total NPP was estimated to be 21.0 Mg ha^{-1} yr^{-1}, using summation of allometric relationships between diameter at breast height of mangroves and biomass as well as litterfall (Kamruzzaman et al. 2017). In the Florida Coastal Everglades, annual total NPP in mangrove areas ranged from 7.9 to 19.2 Mg ha^{-1} yr^{-1} (Castañeda-Moya et al. 2013).

Strength of Evidence

High. The factors that determine mangrove NPP both generally and specifically are well-documented and consistent within several types of peer-reviewed scientific evidence, including site-specific studies, reviews, and meta-analyses. Methods of studying and estimating mangrove NPP, including the most frequently used summation method, are well-documented and accepted within the literature. There was some conflicting evidence within the literature about the influence of belowground processes in mangrove NPP, as well as high variability among external factors in different geographic locations, making generalizations about the rates of NPP difficult.

Other Factors

The relationship between mangroves and NPP is highly dependent on other spatial and temporal factors that determine the rate of mangrove NPP. Environmental factors such as regulators (i.e., sulfide, soil salinity), resources (i.e., light, nutrients), and hydroperiod (e.g., frequency, duration, and depth of flooding) vary rates of mangrove NPP temporally and spatially (Castañeda-Moya et al. 2013; Day et al. 1996; Jennerjahn and Ittekkot 2002; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019). In general, it is found that mangroves occurring in coastal systems with higher temperatures, tidal ranges, and riverine inputs (i.e., freshwater and nutrient discharge) are more productive than mangroves exposed to harsh environments (e.g., low temperatures, seasonal droughts, and/or hypersalinity) (Ribeiro et al. 2019).

Many studies note the effects of seasonal changes on mangrove leaf litterfall rates, with mangrove NPP peaking alongside litterfall during wet seasons (August–September) (Day et al. 1996; Kamruzzaman et al. 2017; Khan et al. 2009; Ribeiro et al. 2019). In Japan, litterfall rates ranged from 3.87 to 56.1 kg ha^{-1} day^{-1} for leaves and 0.177 to 46.2 kg ha^{-1} day^{-1} for branches, with peak values occurring during the wet season (Khan et al. 2009). Numerical modeling also predicted that the highest rates of mangrove NPP would occur in areas with high rates of rainfall (>2000 mm/yr) (Ribeiro et al. 2019). Seasonality in temperature also affects NPP in mangroves by influencing rates of photosynthesis and respiration, including reproductive success and carbon storage (Day et al. 1996; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019).

Differences in environmental conditions such as nutrient input, soil salinity, and tidal activity are also important in affecting mangrove NPP (Day et al. 1996; Jennerjahn and Ittekkot 2002). Spatially, mangrove NPP can be influenced by differences in freshwater inflow, nutrient inputs, soil salinity, and water turnover rate. Litterfall and woody production of mangroves are inversely related to soil salinity because extremely high soil salinity causes stress to mangroves, resulting in reduced litterfall (Castañeda-Moya et al. 2013; Day et al. 1996; Kamruzzaman et al. 2017). Better-drained soils and increased nutrient input was found to be related to higher productivity in mangroves (Castañeda-Moya et al. 2013; Day et al. 1996). Mangrove forests that are flushed frequently by tides are exposed to high nutrient concentrations and have higher NPP (Castañeda-Moya et al. 2013; Day et al. 1996; Ribeiro et al. 2019). In carbonate settings (e.g., Florida, Caribbean islands), high permeability of the carbonate soil matrix and lack of riverine inputs limit mangrove development and mangrove litterfall is dominated by scrub mangroves with litterfall values of less than 3 Mg ha^{-1} yr^{-1} (Ribeiro et al. 2019).

Spatially, mangrove NPP has been observed to differ across types of mangrove forests (i.e., basin, fringe, and riverine) which experience different environmental conditions. Mean annual litterfall and stem production increases from basin to fringe to riverine forests, but there is still considerable variability within each forest type. In Mexico, annual litterfall rates were observed to range from 320 to 1700 g m^{-2} yr^{-1} for riverine forests, 430 to 1082 g m^{-2} yr^{-1} for fringe forests, and 250 to 970 g m^{-2} yr^{-1} for basin forests. The turnover rate of litter on the forest floor was also lower in basin forests than fringe or riverine forests where hydrologic energy is higher, as high standing litter levels reflect long residence of litter in areas of minimal tidal activity.

Climate change may also play a role in changing the relationship between mangroves and NPP resulting from varying effects on temporal and spatial factors. In areas expected to see an increase in temperature patterns, such as the Caribbean islands, the combined effect of reduced freshwater inputs and increased evaporation could significantly increase soil salinity and sulfide concentrations, decreasing litterfall and NPP. Conversely, in areas with expected higher rainfall, higher freshwater and nutrient input could lower the effect of anoxic conditions and enhance litterfall, increasing NPP. There is still a high degree of uncertainly for climate change scenarios, but numerical modeling can be used as a reference to predict changes in a specific mangrove ecosystem's response (Ribeiro et al. 2019).

Predictability

There is consensus within the literature that mangroves are among the most productive ecosystems on earth, with high levels of NPP from their rates of litterfall and above- and belowground biomass (Castañeda-Moya et al. 2013; Jennerjahn and Ittekkot 2002; Ribeiro et al. 2019). Several external factors including seasonal changes, climate, hydrodynamic forces, environmental characteristics, nutrient inputs, climate change, and type of mangrove forest have a significant influence on NPP (Castañeda-Moya et al. 2013; Day et al. 1996; Jennerjahn and Ittekkot 2002; Kamruzzaman et al. 2017; Komiyama et al. 2008; Ribeiro et al. 2019). Because of these external factors, a lot of specific data are needed to estimate NPP for a particular forest; predictability is not high. However, in general, it was found that mangroves occurring in coastal systems with higher temperatures, tidal ranges, and riverine inputs are more productive than mangroves exposed to harsh environments (e.g., low temperatures, seasonal droughts, and hypersalinity) (Ribeiro et al. 2019). Ribeiro et al. (2019) created and employed a numerical model using geophysical and climatic variables to predict mangrove litterfall rates and mangrove NPP, which may be able to be adjusted for other mangrove forests.

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LINK 7: MANGROVE QUALITY/QUANTITY → WATER QUALITY

Description of Relationship

Through processes including sedimentation, microbial activity, and plant assimilation, mangroves have the ability to maintain, and in some cases improve, water quality (Adame et al. 2019; Pawar 2013; Rahman et al. 2013; Schaffelke et al. 2005; Wang et al. 2010; Wolanski et al. 1997; Wu et al. 2008). Mangroves can significantly contribute to the removal of nutrients, including nitrogen and phosphorous, and organic matter from surrounding water (Pawar 2013; Rahman et al. 2013; Wang et al. 2010; Wolanksi et al. 1997; Wu et al. 2008). This has great importance for removing pollutants from water, decreasing turbidity, and preventing harmful algal blooms that cause eutrophication (Satheeshkumar and Khan 2011; Wolanksi et al. 1997). Mangrove systems are also known to be a sink for trace metals (Harbison 1986; MacFarlane et al. 2007), which can possibly reduce human and wildlife exposure to these toxic compounds in estuarine environments. Local environmental conditions, including both biotic and abiotic factors, have site-specific influences on the magnitude of mangrove nutrient exchange and water quality maintenance, complicating the comparison of results between ecosystems (Boyer 2006; Rahman et al. 2013; Satheeshkumar and Khan 2011; Schaffelke et al. 2005; Wang et al. 2010).

Summary of Evidence

Mangrove ecosystems create a suitable environment by removing and transforming pollutants in water through processes such as sedimentation, microbial activity, and plant absorption (Adame et al. 2019; Pawar 2013; Rahman et al. 2013; Schaffelke et al. 2005; Wang et al. 2010; Wolanski et al. 1997; Wu et al. 2008). Specifically, mangroves make a significant contribution to the removal of nutrients and organic matter from surrounding water and help maintain estuarine water quality by stripping nitrogen, phosphorous, and other deoxidizing compounds from effluent. They also export organic carbon, which helps to purify water and reduce turbidity (Pawar 2013; Rahman et al. 2013; Wang et al. 2010; Wolanksi et al. 1997; Wu et al. 2008). With the growth of human populations and commercial industries, coastal waters have been exposed to large amounts of pollution from a variety of anthropogenic sources, and mangrove-facilitated water quality maintenance may become more important (Adame et al. 2019; Pawar 2013; Rahman et al. 2013; Satheeshkumar and Khan 2011). The loss or disturbance of mangroves may have serious downstream effects for coastal water quality resulting from mangroves' lessened capacity to assimilate nutrients and to consolidate sediments (Satheeshkumar and Khan 2011; Schaffelke et al. 2005).

The root and soil properties of mangroves play a large role in the uptake of nutrients such as nitrogen and phosphorous. Mangroves not only absorb nitrate for their growth, but also enhance the efficiency of both the nitrification and denitrification processes. Oxygen is transported to mangrove roots, creating an aerobic rhizosphere around the roots which promotes nitrification. Further, mangrove root exudates, or secretions of organic material into the surrounding soil, provide carbon sources for the process of denitrification. While soil adsorption is the main mechanism for the removal of phosphorous in wetlands, mangroves also uptake phosphorous and alter soil properties around their rhizophore to enhance phosphorous adsorption in the soil by creating an aerobic environment that promotes bacterial synthesis of polyphosphates (Wu et al. 2008). Collectively, these processes allow mangroves to create a suitable environment for removing and transforming pollutants in surrounding water (Pawar 2013; Rahman et al. 2013; Schaffelke et al. 2005; Wang et al. 2010; Wolanski et al. 1997; Wu et al. 2008).

A study that measured changes in water quality across mudflat and mangrove ecosystems in China found that mangroves trap nutrients at rates of 90.5 g nitrogen/m^2/yr, 2.2 total phosphorous/m^2/yr, and 13.7 carbon/m^2/yr. The nitrogen nutrient removal efficiency by mangroves was found to be 92.7% (80.7% by soil and 12.0% by plant), and the phosphorous nutrient removal efficiency was 88.0% (84.2% by soil and 3.8% by plant). The same study found that, on average, about 15% of total nitrogen input into mangrove soils is denitrified, and the maintenance of estuarine water quality by mangroves occurs primarily during flood periods (Wang et al. 2010). Another study examining the denitrification rates of coastal wetlands (including mangroves) during flood periods used modeling to determine that these wetlands can potentially remove up to 70% of incoming nitrate loads during the first 24 hours of a flood. However, this study also determined that not all coastal wetlands denitrify equally, and that there are denitrification hotspots within a catchment basin, characterized by areas with high nitrate concentrations and/or large, intact wetland areas (Adame et al. 2019). Another isolated study was able to correlate loss of mangroves with increased nitrate levels and resulting algal cover on nearby coral reefs, inferring that mangrove loss was a major factor in water quality differences between reefs with and without nearby mangroves (Keyes et al. 2019). However, controls for differences in input pollution at the different sites were not addressed in this study.

Because of their ability to maintain water quality and purify water, mangrove wetland water treatment systems have been considered as an alternative to conventional water treatment methods (Pawar 2013; Wu et al. 2008). Mangrove forests can be used as an additional natural system to increase the efficiency of manmade wastewater treatment systems, as has been tested in Hong Kong (Pawar 2013; Wu et al. 2008). A project that used mangroves to treat municipal wastewater collected from local sewage treatment work in Hong Kong found that mangroves were very effective in purifying wastewater and all effluents treated by the mangrove forest system met standards for nutrient discharge. The study found that 86.65% to 91.83% of total phosphorus and 76.16% to 91.83% of ammonia-nitrogen in wastewater was removed by mangroves, which helped to prevent the algal blooms and eutrophication common prior to the addition of the mangrove treatment system (Wu et al. 2008).

It is also important to note that mangrove plants and sediments are known to be a sink for trace metals such as lead, chromium, and cadmium (Harbison 1986; MacFarlane et al. 2007), which has the potential to reduce human and animal exposure to these metals in estuarine environments. Trace metals can be toxic (Tchounwou et al. 2012), so storage of these metals has the potential to affect public health. However, mangrove soils are not only a sink for these pollutants, but can also be a source when biogeochemical conditions result in release of metals stored in sediments (de Lacerda et al. 2022; Harbison 1986). There is some uncertainty as to how changing estuarine conditions that could occur with climate change may impact the ability of mangrove sediments to retain these metals (de Lacerda et al. 2022).

Strength of Evidence

Moderate. Mangroves' ability to absorb or uptake polluting compounds from surrounding water and the external factors that influence their ability to do so are well-documented and consistent within peer-reviewed scientific literature. Studies were limited in geographic scope and only included site-specific investigations, but used well-documented and accepted methods. Existing methods in studies could not quantify any average or expected values for mangrove water quality maintenance, and the applicability of the findings of these studies is low as a result of the influence of local environmental conditions on the magnitude of mangrove water quality maintenance. Most studies assessed water quality of specific mangrove ecosystems without the use of comparators that would allow a determination of the direct impact of mangroves have on water quality. While the processes by which mangroves can influence water quality are well-documented and clear, what is less clear is the overall impact that a particular mangrove site has on water quality as a whole. As indicated by Adame et al. (2019), the effects of coastal wetlands (including mangroves) on water quality is likely not consistent throughout a landscape, and it may be more useful to examine the combined impacts of mangroves at a wetland or catchment scale to truly see whether measurable or meaningful water quality benefits are being provided. Thus, while mangrove systems have the ability to influence pollutant levels, whether that benefit has meaningful impact on water quality in nearby water bodies is incredibly site-specific and influenced by numerous other factors.

Other Factors

Studies on mangrove maintenance of water quality have indicated that local environmental conditions, both biotic and abiotic, have site-specific influences on the magnitude of water purification by mangroves (Boyer 2006; Rahman et al. 2013; Satheeshkumar and Khan 2011; Schaffelke et al. 2005; Wang et al. 2010). Many studies indicate that coastal water quality is deteriorating as a result of industrial pollution and mangroves are facing threats from anthropogenic stressors, which may reduce their potential to maintain water quality (Pawar 2013; Rahman et al. 2013; Satheeshkumar and Khan 2011; Schaffelke et al. 2005). Other factors that determined variance in water quality in mangrove ecosystems included differences in land use, freshwater input, geomorphology, and sedimentary geology (Boyer 2006).

Temporal differences in water quality were most frequently identified in the literature (Pawar 2013; Rahman et al. 2013; Satheeshkumar and Khan 2011; Wang et al. 2010). In a Bangladesh mangrove ecosystem, water quality parameters were acceptable during the rainy season, but values were moderate to high for the winter and summer seasons. This study found that the highest level of total suspended sediment and ion contents in water occurred in the summer when there is less freshwater flow to flush out the system (Rahman et al. 2013). Similarly, in a mangrove estuary in China, total dissolved nitrogen, total dissolved phosphorous, chemical oxygen demand, and dissolved organic carbon contents were significantly higher in flood periods than in ebb periods (Wang et al. 2010). A study in India found that the highest turbidity levels occurred during the premonsoon period in high-tide water because high turbidity is attributed to waves and turbulence caused by tides and winds, which facilitate the mixing of sediment with the overlying water column. This study also found that the highest levels of phosphate and nitrate were recorded in low-tide water (Pawar 2013).

Mangroves' ability to maintain or improve water quality in a meaningful way is highly dependent on the amount and type of pollutants flowing across a mangrove system. If water flowing into a mangrove system is polluted enough, it may actually damage or degrade the mangroves and in turn decrease their ability to filter out pollutants (Pawar 2013). Additionally, mangroves are limited in the amount of pollutants that they can absorb and/or remove from an estuarine system. If pollution inputs are high enough and/or coming from multiple sources, removal by mangroves may not be sufficient to make a measurable change in water quality in the estuary.

Predictability

There is consensus within the literature that mangroves play a role in maintaining water quality through the removal of nutrients, such as nitrogen and phosphorous, and organic matter from surrounding water (Pawar 2013; Rahman et al. 2013; Schaffelke et al. 2005; Wang et al. 2010; Wolanski et al. 1997; Wu et al. 2008). Studies also indicate that local environmental conditions have a site-specific influence on the magnitude of mangrove nutrient exchange and maintenance of water quality, complicating the comparison of results between ecosystems and the applicability of existing studies of mangrove water quality maintenance (Boyer 2006; Rahman et al. 2013; Satheeshkumar and Khan 2011; Schaffelke et al. 2005; Wang et al. 2010).

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LINK 8: MANGROVE QUALITY/QUANTITY → WAVE ATTENUATION

Description of Relationship

Mangroves can effectively reduce wave energy and attenuate waves because of their network of roots, trunks, and branches. Vegetation drag is the main mechanism of wave energy dissipation. A few key features of mangrove systems influence wave attenuation rates, including mangrove species, tree density, habitat width, forest structure, tree age, and tree height. Understanding wave reflection, wave shoaling, wave breaking, and bottom friction are also essential to accurately estimating wave attenuation by mangroves.

Summary of Evidence

How Mangroves Attenuate Waves

Mangrove forests dissipate incoming wave energy, mostly as a result of wave-trunk interactions and wave breaking. Mangroves can promote wave attenuation by inducing drag force, friction, wave breaking, and wave reflection from prop-roots, epiphytic organisms, shallow nearshore profiles, and cliffed edges (Bao 2011). Vegetation drag is the main mechanism of wave energy dissipation under both average and storm conditions, with additional wave dissipation caused by waves breaking under storm conditions (Lee et al. 2021). Mangroves are able to dissipate wave energy because of the dense network of trunks, branches, and aboveground roots. This increases bed roughness, causing more friction and dissipating more wave energy (Bao 2011). Denser mangrove forests attenuate waves more effectively (Hashim et al. 2013)

Examples of Mangroves Attenuating Waves

In Vietnam, one study found that wave height reduction in a high-density forest of six-year-old trees was significant as a result of drag force from the trees and that wave height decays exponentially with distance from the mangrove front (Bao 2011). Another study in Vietnam found wave height reduction by mangroves was 5 to 7.5 times larger than that by sandy beds only (Hashim et al. 2013). From a study on the Colombian coast, the percentage of wave height reduction was more than 60% for mangroves with cross-shore widths of more than 500 m (Sánchez-Núñez et al. 2020). After a tsunami in Vietnam, the tsunami wave flow pressure was significantly reduced when mangrove forests were 100 m wide (Bao 2011). Generalized total wave attenuation rates increased from 0.002 m^{-1} in sparsely *Avicennia* and *Sonneratia* forest fringes to 0.012 m^{-1} in dense *Rhizophora* species in the back of the forest (Horstman et al. 2014).

Features of Mangroves that Influence Their Ability to Attenuate Waves

Mangrove density and forest width were found to be positively correlated to the percentage of wave height reduction during a storm event (Lee et al. 2021). High mangrove tree density and overground roots in a mangrove forest have higher drag forces on incoming waves than a sandy surface or a mudflat (Bao 2011). Compared to trunks and canopies, mangrove roots contribute to a larger percentage of wave height reduction (Lee et al. 2021). A mangrove forest with a length of about two times the wave length in a storm (about 200 m) can provide approximately 80% wave height reduction (Horstman et al. 2014). Another feature of mangrove-influenced wave attenuation is oyster colonies that commonly grow on mangrove roots. In a protected coastal lagoon in Colombia, the presence of *Crassostrea rhizophorae* oysters attached to prop roots influenced wave attenuation and were responsible for the inversely correlated relationship with water depth and incident wave height (Sánchez-Núñez et al. 2020). The magnitude of the energy absorbed depends on mangrove structure (e.g., density, stem and root diameter, and shore slope). Wave height reduction depends on initial wave height, cross-shore distances, and mangrove forest structures. Height of waves traveling through mangroves decays exponentially and is significantly related to distance traveled (Bao 2011). Wave energy attenuation rate is affected by incident wave height, epiphytic oyster presence, mangrove vegetation density, tidal inundation, and wave reflection from cliffs (Sánchez-Núñez et al. 2020).

Total wave attenuation rates integrate effects of shoaling and energy losses caused by various biophysical interactions within mangrove ecosystems (Horstman et al. 2014). Mean tidal range, volumetric vegetation density, and presence of cliffs at the mangrove edge explain global wave attenuation data in mangrove environments. Overall, wave attenuation rates by vegetation and bottom friction are underestimated from global scale data when wave shoaling is not considered (Sánchez-Núñez et al. 2020). The variability in previously and currently obtained wave attenuation data underlines the susceptibility of mangroves attenuating capacity to variations in both hydrodynamic forcing and vegetation characteristics. More research has to be done on hydrodynamic conditions and vegetation characteristics to understand vegetation induced wave attenuation in mangroves (Horstman et al. 2014).

Strength of Evidence

Moderate. Evidence was overall consistent; however, the confounding factors are understudied. Different aspects of wave attenuation were described in each paper. A thorough meta-analysis is needed to summarize this information.

Other Factors

To analyze wave attenuation by mangroves, scientists must consider other wave transformation processes (such as wave reflection, wave shoaling, wave breaking, and bottom friction) to properly estimate dissipation by vegetation drag force (Sánchez-Núñez et al. 2020). Water depth, and mangrove frontal area, and wave height are dominant variables driving wave attenuation for short waves (Maza et al. 2019). Wave dissipation by drag force did not explain higher wave attenuation patterns for taller waves when the inundation depth was in the zone of oyster presence (Sánchez-Núñez et al. 2020).

In Colombia, it was found that, at lower depths, high volumetric vegetation density generated high superficial rugose areas that were exposed to waves. The low inundation depths in the Caribbean also generate relatively narrow mangrove forest bands that interact with waves, and bottom friction effects are stronger at shallow depths. In a protected coastal lagoon, an inverse relationship between incident wave height and wave energy attenuation at low inundation depths that lack epiphytic oysters was explained by higher orbital velocities associated with higher waves that lead to lower drag forces (Sánchez-Núñez et al. 2020). There can also be an effect of speciation—*Rhizophora*, *Avicennia*, and *Bruguiera* species were found to have a higher median wave reduction rate than other species in disturbed mangrove sites in Singapore (Lee et al. 2021).

For fringe mangroves, seaward slope also influences the incident wave conditions, leading to an enhancement of wave height as a result of shoaling when waves do not break along the slope. An increase in wave steepness induces the highest drag forces in the direction of wave propagation along the first meters of the forest in accordance with increase in wave height and nonlinearity (Maza et al. 2019).

Predictability

The literature is consistent in the fact that mangroves can effectively attenuate short waves and dissipate wave energy and the methods in which mangroves do so. However, many factors must be considered to effectively estimate wave attenuation rates. Estimating wave attenuation often requires advanced modeling and/or field measurement approaches.

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LINK 9: MANGROVE QUALITY/QUANTITY → STORM SURGE ATTENUATION

Description of Relationship

Storm surges occur when high winds and low atmospheric pressure raise water levels at the coast, causing high volumes of seawater to surge onto the land. Storm surges can result in injury to both people and infrastructure in low-lying coastal areas (Liu et al. 2013; McIvor et al. 2012). Mangroves can directly affect surface roughness and contribute to water storage, allowing them to attenuate storm surges and effectively reduce tides, restrict surge inundation, and decrease peak surge heights and water levels (Chen et al. 2012; Dasgupta et al. 2019; Liu et al. 2013; McIvor et al. 2012; Montgomery et al. 2018, 2019; Temmerman et al. 2023; Zhang et al. 2012). This relationship is mainly studied through numerical modeling because of constraints on observation and data collection during storm surge events (Dasgupta et al. 2019; Liu et al. 2013; McIvor et al. 2012). The ability of mangroves to effectively attenuate storm surges is dependent on characteristics of the mangrove forest, physical characteristics and topography of the area, and characteristics of the storm (Blankespoor et al. 2016; Dasgupta et al. 2019; McIvor et al. 2012; Montgomery et al. 2018, 2019; Temmerman et al. 2023).

Summary of Evidence

Storm surges pose a large threat to low-lying coastal areas and their inhabitants and can result in extensive flooding, damage to property, and loss of life (Liu et al. 2013; McIvor et al. 2012). The largest storm surges are typically caused by tropical cyclones (McIvor et al. 2012).

There are two main mechanisms of storm surge attenuation by mangroves: (1) the friction effect and (2) the water storage effect (Chen et al. 2012; Dasgupta et al. 2019; Liu et al. 2013; McIvor et al. 2012; Montgomery at al., 2018, 2019; Temmerman et al. 2023; Zhang et al. 2012). The *friction effect* is defined as the effect of friction and drag forces of mangrove vegetation on incoming storm surges and water flows. As storm surges and waves propagate from open water through coastal mangroves, the friction between the water motion and the dense wetland vegetation and sediment surface reduces wave heights and storm surge levels (Temmerman et al. 2023). Mangroves can thus directly affect surface roughness, height of surface wind waves, and the speed of the wind directly over the water surface within areas where the vegetation reaches above the water level and is able to impose a drag force to limit fluid exchange across the forest (McIvor et al. 2012; Montgomery et al. 2018, 2019). The water storage effect of mangroves on storm surges is less frequently mentioned within the literature, but describes the ability of mangrove forests to store water within the forests through lateral flooding and absorption (Montgomery et al. 2019; Temmerman et al. 2023).

Evidence for the relationship between mangroves and storm surge attenuation comes from both direct observation of water level heights or damage caused by storm surge and from well-validated numerical models that simulate storm surge behavior in the presence or absence of mangroves (Dasgupta et al. 2019; Liu et al. 2013; McIvor et al. 2012). Limited observation data are available on surge reduction rates through mangroves because of the difficulties associated with measuring water levels during storm surges; thus, numerical models and simulations verified using networks of data recorders are often used to study this relationship and the external factors that affect it (Dasgupta et al. 2019; Liu et al. 2013; McIvor et al. 2012).

Observational data that support this relationship are described within the literature. As the storm surge from Hurricane Charley passed through the Ten Thousand Islands National Wildlife Refuge in southwest Florida, the peak water level reduction of the storm surge was 9.4 cm/km through an area that included both mangrove and salt marsh. The peak storm surge water level decrease through an area of just mangroves was measured to be 15.8 cm/km. After the storm surge from Hurricane Wilma passed through the mangrove forest along the Shark River in the Everglades National Park in southwest Florida, peak water levels were reduced by 4.2cm/km, as measured across three recording stations set back from the river by 50 to 80 m. Between the seaward recording stations located 4.1 and 9.9 km from the river mouth, there was a slight increase in water level, indicating an increase in storm surge levels resulting from the presence of coastal mangroves (McIvor et al. 2012). Mangroves can rescue land from inundation, but can also cause inundation because the amplitude of storm surge increases at the front of mangroves forests as a result of mangroves blocking surge water and leading it toward those zones (Rahdarian and Niksokhan 2017; Zhang et al. 2012). Similarly, after Hurricane Wilma, the surge amplitude decreased at a rate of 40–50 cm/km across the mangrove forests and 20 cm/km across areas with a mix of mangrove islands and open water. However, amplitudes of storm surges at the front of the mangrove zone increased by about 10% to 30% because of the mangroves' blockage of surge water (Zhang et al. 2012). After Cyclone Gonu in 2007, 90 km^2 was recused from inundation and 22 km^2 was inundated as a result of the presence of mangroves and their interactions with the storm surge (Rahdarian and Niksokhan 2017). In New Zealand, a combination of observations and numerical simulations found that amplitude of storm surge was reduced at a rate of 40–50 cm/km through mangrove forests and roughly 20 cm/km through patchy regions consisting of a combination of mangrove islands and open water (Montgomery et al. 2018).

Numerical modeling helps simulate the relationship between mangroves and storm surge attenuation. If well-validated against field observations, numerical modeling offers a complementary approach to understanding the factors affecting storm surge water levels. The Eulerian-Lagrangian Circulation model was used to model the surge from Hurricane Andrew on the East Coast of Florida, and use of the model suggested that land cover types, in particular those having large areas of mangrove cover, have significant effects on flood levels and extent (McIvor et al. 2012).

Similarly, the Coastal and Estuarine Storm Tide model simulated the passage of Hurricane Wilma over the Gulf Coast of South Florida and found that the best match between using the simulation and observed data was seen with when the Manning's roughness coefficient, a function of vegetation and flow, in the model was fine-tuned to best match that of a coastal mangrove landscape. The inundation areas predicted by the model were 4,220 km^2 without mangroves and 2,450 km^2 with mangroves, suggesting that mangroves have a large effect on attenuating the inundation extent of storm surges. Using this model, it was found that storm surge reduction rates from Hurricane Wilma were between 20 and 50 cm/km through mangrove areas. The model also shows that while the peak water level was reduced as the storm surge passed through the mangroves, there was a 10% to 30% increase in water levels in front of the mangrove zone compared to simulations without mangroves, because mangroves act as an obstruction to the flow of water, causing water to build up in front of them (McIvor et al. 2012).

In the Bay of Bengal, a hydrodynamic model was run to simulate the surge of Cyclone Sidr. Results showed significant reduction in water flow velocity (29% to 92%) and a modest reduction in surge height (4 to 16.5 cm) as a result of the presence of mangroves (Dasgupta et al. 2019). Numerical simulations showed that the minimum and maximum storm tide reduction rate by mangroves in Iran were 5.32% and 34.88%, respectively (Rahdarian and Niksokhan 2017). Modeling also found that a 6-to-30 km wide mangrove forest in southern Florida attenuated storm surges from Hurricane Wilma and protected inland wetlands by reducing the inundation area by 1800 km^2 and restricting surge inundation inside the mangrove zone. The modeling predicted that Hurricane Wilma would have extended 70% further inland from surge inundation without the mangrove zone (Zhang et al. 2012).

Strength of Evidence

High. Evidence for the relationship between mangrove quality/quantity and storm surge attenuation is well-documented in multiple types of peer-reviewed evidence including site-specific studies and review papers. Sources that document this relationship use limited observational data and more commonly use numerical modeling. This relationship is mainly documented in mangrove forests in southwest Florida on the Gulf of Mexico, but evidence exists for a wide variety of geographic locations. In studies that use observational data, it may be unclear what the contribution of mangroves was to the reduction in storm surge as it is impossible to control for other factors that may also affect water level changes. Predictions of changes and external factors in the relationship between mangroves and storm surge attenuation can only be estimated using complex, site-specific models. Methods used within the literature are well-documented and mostly accepted, except for some concerns are raised about the use of 2-D modeling and Manning's coefficient not being able to capture the complexity of mangrove forests; however, the data extracted from these 2-D models is verified using historical measurements and is consistent with other sources. While modeling has intrinsic errors and uncertainties, if the model is well-validated against field observations, it may offer a complementary approach to understanding the relationship between mangroves and storm surges.

Other Factors

The ability of mangroves to effectively attenuate storm surges is dependent on characteristics of the mangrove forest, physical characteristics and topography of the area, and characteristics of the storm (Blankespoor et al. 2016; Dasgupta et al. 2019; McIvor et al. 2012; Montgomery et al. 2018, 2019; Temmerman et al. 2023). There is limited quantitative data available on these external factors and where data exist, they are generally derived from numerical models rather than observations (McIvor et al. 2012).

Characteristics of mangrove forests that may impact the effectiveness of storm surge attenuation include forest width, tree density, and structural complexity (roots, stems, branches, and foliage) of the dominant species (Blankespoor et al. 2016; Dasgupta et al. 2019; McIvor et al. 2012; Montgomery et al. 2018, 2019). Numerous modeling and mathematical studies have shown that, during cyclones, mangrove forests can attenuate surge height and water flow velocity because of the surface roughness created by the matrix of mangrove tree roots, trunks, and leaves obstructing the flow of water through the forest and creating bed resistance. Thus, mangrove forests can more effectively attenuate storm surges by having more complex and dense structures to increase drag (Dasgupta et al. 2019; McIvor et al. 2012). Numerical modeling studies reveal that resistance to water flowing through mangrove forests varies by mangrove species, density of trees, and water depth. One model found that, irrespective of water depth, the mangrove species *S. apetala* causes maximum obstruction and storm surge attenuation, followed by *A. officinalis* and *H. fomes* (Dasgupta et al. 2019). Other studies show that short mangroves (<4 m) attenuate storm surge more effectively than tall mangroves when water depth is low (<4 m) (Chen et al. 2021). Surge amplitudes decrease faster in areas with more mangroves, but the zonation of mangroves is important to determine this rate. Effects of widths of mangrove zones on reducing surge amplitude are nonlinear, with large reduction rates (15% to 30%) for initial width increments and small rates (<5%) for subsequent width increments. In South Florida, *Rhizophora mangle* trees were found to be more effective in dissipating the energy of low surges because of their dense stilt roots. Narrower mangrove zones can effectively attenuate a tsunami wave with the same amplitude as a surge wave and with a period shorter than a surge wave (Zhang et al. 2012). In general, mangroves are found to be effective at attenuating storms surges if forests are sufficiently wide/dense, relative to the surge decay length scale, to restrict water exchange during a storm (Montgomery et al. 2019).

The physical characteristics and topography of a mangrove area also play a large role in the effectiveness of mangrove storm surge attenuation. One of these characteristics is near-shore bathymetry, as coastal shelves with large shallow water areas produce larger surges than steep offshore slopes and may affect the ability of mangroves to effectively attenuate surges. Similarly, the geometry of the coastline affects this relationship because more concave coasts concentrate the surge into a smaller area, resulting in higher water levels, but when the coast is more convex, water is able to flow sideways and the surge height is reduced. The presence of inland channels interconnecting water bodies also significantly impacts the ability of mangroves to attenuate storm surges because channels allow the surge to flow more easily and quickly through the landscape and thus further inland (McIvor et al. 2012). The degree of channelization within a mangrove area and therefore the capacity of mangroves to reduce flooding may depend on the elevation of the vegetation. Mangrove forests in relatively low, frequently inundated elevations are subjected to tidal currents that promote channelization, which in turn reduces their capacity to mitigate storm surges, but higher-elevation mangrove forests are inundated only at the peak tide when currents are minimized and the sediment regime is depositional, causing no channelization to occur and the mangrove forest's capacity to attenuate storm surge to be maximized (Montgomery et al. 2018). In a numerical modeling study of storm surge after Hurricane Wilma, it was found that the decay rate of peak storm surge height was approximately 18cm/km across areas with a mixture of mangroves and open water, but 24 cm/km through dense mangroves (Chen et al. 2021). A similar study found that surge height decreased at a rate of 23 cm/km through an area with a mixture of mangrove islands and open water, while in areas with less open water, surge height reduction rates ranged from 40 to 48 cm/km (McIvor et al. 2012). In New Zealand, it was found that the presence of channels decreased the efficacy of mangrove flood attenuation from 9.4 to 4.2 cm/km (Montgomery et al. 2018). Empirical data and modeling studies have demonstrated considerable storm surge height reduction by large (at least 10 km wide), continuous mangrove areas with few or small channels (Temmerman et al. 2023). Smaller or discontinuous mangroves do not provide significant storm surge height reduction, and mangrove areas are most effective for storm surge attenuation when they are located further inland along narrow sections of funnel-shaped estuarine channels (Temmerman et al. 2023).

The speed, direction, and intensity of a hurricane or storm can have an effect on how well mangroves can reduce the storm surge and flooding (Liu et al. 2013; McIvor et al. 2012; Temmerman et al. 2023).

Hurricanes with large geographical extents generate higher peak water levels and greater flooded volumes, which may impact the effectiveness of mangrove storm surge attenuation. Surges created by hurricanes with faster forward speeds create higher surges but lower flood volumes, and surges with lower forward speeds produce more flooding but lower peak water levels (McIvor et al. 2012). Likewise, storm surges associated with hurricanes with a fast forward speed may be reduced more by mangroves than surges created by hurricanes with a slower forward speed (McIvor et al. 2012; Temmerman et al. 2023).

Storm track also has major effect on the characteristics of a storm surge because of the interaction between the cyclone and landscape features, which may affect the buildup of water (McIvor et al. 2012). Storm surge magnitudes and flooding areas are reduced by the mangrove zone more for fast-moving hurricanes than slow-moving hurricanes. Forests cannot fully attenuate storm surges from category 5 hurricanes (such has Hurricane Wilma) with slow forward speeds (~5 mph). Increasing hurricane intensity and hurricane size lower the effect of mangroves on attenuating storm surge and reducing the flooding area. Mangrove reduction effect is most sensitive to changes in hurricane forward speed—a decrease in forward speed can result in decreased in flood area reduction by mangroves. Mangroves have the biggest effect on reducing coastal flooding when hurricanes make landfall with approach angles of 67.5°, where the reduced flooding area percentage was 37.7%. Mangrove zones play a more effective role in reducing flooding areas from hurricanes that travel east to west (less than or equal to 90°) (Liu et al. 2013).

Aside from these three main external factors affecting mangroves' ability to effectively attenuate storm surges , global climate change may result in increased storm surge flooding in some areas through intensification of the cyclones driving storm surges and also from sea level rise (McIvor et al. 2012; Montgomery et al. 2018). These cyclones and storm surges also affect mangroves themselves, as some trees may be defoliated or uprooted and extreme events with very high water levels and wind speeds may severely impact or destroy mangrove areas (McIvor et al. 2012). Extensive impact may render mangroves less effective at reducing storm surge heights (Blankespoor et al. 2016; McIvor et al. 2012). Natural recovery from extreme events can take many years to decades, but restoration projects may speed up mangrove recovery (McIvor et al. 2012; Temmerman et al. 2023).

Predictability

The literature is consistent in identifying a relationship between mangrove quality/quantity and storm surge attenuation in low-lying coastal areas. Other factors such as the characteristics of the storm (e.g., forward moving speed, size, and direction), characteristics of the mangrove forest (e.g., density, species, width of forest), and physical characteristics and topography of the area may impact the magnitude by which mangroves can attenuate storm surges, but the literature suggests that the relationship between mangrove-facilitated storm surge attenuation exists regardless of these factors, just to a potentially lesser extent.

The rate of reduction of storm surges through mangrove areas appears to range between 5 and 15 cm/km and can reach up to 50 cm/km, but constant attenuation rates imply a linear reduction in water level with distance into mangrove area that is not accurate and should be regarded with caution (McIvor et al. 2012). To calculate specific rates of storm surge attenuation resulting from a particular mangrove forest, studies use predictive numerical models. Several models were identified in the literature that can be used to predict the extent of this relationship in certain contexts, including the Coastal and Estuarine Storm Tide and Eulerian-Lagrangian Circulation models. Numerical surge-wave models that incorporate flow-wave-vegetation interactions can be used to assess contribution of various other factors (e.g., local coastal geographic features, storm characteristics, and vegetation characteristics) to the reduction of surge, wave, and inundation by vegetation. While the models can be adjusted to represent specific mangrove conditions, they inherently simplify the system to an extent (Sheng and Zou 2017).

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LINK 10: MANGROVE QUALITY/QUANTITY → WIND BUFFER

Description of Relationship

Existing evidence indicates that mangroves can possibly act as a wind buffer by reducing surface wind speeds and thus reduce the generation and intensity of wind waves. However, there is relatively little evidence to support this claim (Das and Crépin 2013; del Valle et al. 2019; Gracia et al. 2018; Marois and Mitsch 2015; McIvor et al. 2012; Spalding et al. 2014).

Summary of Evidence

Vegetation and topography of mangrove forests can reduce wind speed (Das and Crépin 2013). Mangroves can directly affect the speed of wind directly over the water surface in areas where their vegetation reaches above the water level, reducing wind-related damage from large storms by directly attenuating the energy of wind that passes through their dense canopies and reducing the regeneration or propagation of wind waves that contribute to storm surge and floods (del Valle et al. 2019; Gracia et al. 2018; Marois and Mitsch 2015; McIvor et al. 2012; Spalding et al. 2014). However, because wind waves generally originate outside of mangrove areas, mangroves can only prevent wind waves from increasing in size through wind attenuation or reduce the waves themselves by acting as a physical obstacle (McIvor et al. 2012).

While some studies have quantified the effect of mangroves as a wind buffer, a review of the coastal protection benefits provided by mangroves indicates that further research on the capability of mangroves to reduce wind energy is needed (Marois and Mitsch 2015). Similarly, it may not be possible to directly measure the ability of mangroves to act as a wind buffer because studying the effects of vegetation-reduced wind speeds on storm surge heights is impossible to isolate; reduced wind speeds would never occur independently of other effects such as increased drag on the water flow from vegetation (McIvor et al. 2012). One study in the Odisha region of India that modeled mangroves' effect on wind velocity estimated that mangroves can attenuate wind, especially when they exist in large, continuous patches, but the modeling may be flawed as a result of lack of data in the model on the surrounding landscape (Das and Crépin 2013). In South China, measurements were used to find that mean wind speeds up to 5 m/s were reduced by more than 85% by the mangrove forests, and mean wind speed greater than 15 m/s were reduced by between 58.9% and 63.6% by mangrove forests (McIvor et al. 2012). Globally, it was estimated that energy lost when wind and waves pass through mangrove roots and branches can range between 15% and 65% (Gracia et al. 2018).

Strength of Evidence

Low. Though the evidence was consistent in saying that mangroves can act as a wind buffer, there was little explanation as to the mechanisms and limited studies of this effect. Further, existing modeling may be flawed and unable to represent this potentially isolated ability.

Other Factors

The spatial dimensions of the forest (i.e., how far it reaches inland from the shore) is considered one of the most important determinants of protective capabilities with regards to tsunamis and cyclones. Other confounding effects of the relationship include continental slope, distance inland, and elevation (Marois and Mitsch 2015). Species of mangrove may also play a role in the ability of mangroves to reduce wind speeds. In South China, it was found that greater reductions in wind speed were seen near a *Kandelia* mangrove forest as compared to a *Sonneratia* mangrove forest. Denser foliage of mangrove canopies during the warm season also reduced wind speeds further (McIvor et al. 2012). Higher wind speeds lessened the ability of mangroves to attenuate wind speeds in South China and, in severe storms, mangroves may be damaged or torn up by high winds and waves, reducing their ability to act as wind buffers (Spalding et al. 2014).

Predictability

Because of the lack of specificity in the sources, the predictability for this link is low. Many papers discussing the protective value of mangroves do not describe wind buffer or wind protection, but rather discuss protection from storm surge. Gracia et al. (2018) estimates that mangroves may be able to reduce wind and wave energy passing through mangrove roots and branches by between 15% and 65%, but do not specify the effects of mangroves as a wind buffer alone. Similarly, modeling to predict mangroves' ability to act as a wind buffer may be flawed because it is impossible to isolate the effects of wind buffering (Das and Crépin 2013; McIvor et al. 2012).

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LINK 12: MANGROVE QUALITY/QUANTITY → AESTHETICS

Description of Relationship

Anecdotally, mangroves are publicly valued for their aesthetics, but there is little evidence to support this. Limited evidence comes from survey data (Rahman et al. 2018; Mundher et al. 2022), and some additional indication may come from the public's appreciation of forest aesthetics more generally (Nelson et al. 2001) and inferences about how that applies to mangrove forests.

Summary of Evidence

Aesthetics are known to play a key role in people-landscape interactions and in perceptions of a place. "Scenic resource management" has entered into land management decisions (Gobster 1999); however, no cases of mangrove scenic management were identified in the literature.

The appearance of mangroves can be affected by hurricanes and other storms. In some cases, changes to appearance are short term (e.g., temporary defoliation), but in others, aesthetics can be altered on a longer time scale (e.g., tree death). High winds during hurricanes cause significant damage to mangrove canopies (Smith et al. 1994; Doyle et al. 1995). Winds impact the visual qualities of mangroves, causing snapped stems, branch damage, and defoliation. In a study of Hurricane Andrew's effects along the Southwest coast of Florida, canopy disturbance had a positive exponential correlation with increasing wind speed

(Doyle et al. 1995). Hurricanes can also lead to mangrove tree death, whether as a result of total detachment from the substrate or from defoliation, partial uprooting, or changes in environmental conditions that exceed the tolerance of each species (Herrera-Silveira et al. 2022).

Survey studies have found that mangroves are valued for their aesthetic properties (Rahman et al. 2018; Mundher et al. 2022), but evidence is limited and mostly restricted to South and Southeast Asia. Mangrove aesthetics in Malaysia's Permanent Forest Reserve (PFR) were rated in a particular study as one of the most valued aspects of the forest. Tree aesthetics provide motivation for forest preservation as well as functionality, rated in the PFR as third most important, after protection and research/education (Rahman et al. 2018). Mangroves in the Sundarbans (India/Bangladesh) are highly valued for their aesthetic enjoyment, ranked with high importance by 68% of households in one study (Mundher et al. 2022).

While there is little to no research specifying what people value specifically aesthetically about mangrove forests, there is evidence for forests more generally. Among deciduous canopies, trees with thick canopies are seen as more beautiful, alive, and pleasant than trees with weaker leaf and branch canopies (Nelson et al. 2001). It could reasonably be inferred that hurricane impacts on mangrove canopies as well as defoliation might decrease a mangrove habitat's perceived aesthetic value.

Despite multiple sources discussing the aesthetic value of mangrove habitats, in some cases mangroves are actually perceived as unattractive or as providing an aesthetic disservice. While viewed positively by some, others use terminology such as "smelly," "ugly," or "overlooked" to describe mangroves, indicating that not all people think they add positive aesthetic value (Dahdouh-Guebas et al. 2020). Additionally, some find that mangroves inhibit aesthetics by blocking water views. For example, in 2022 a city ordinance was proposed in Miami to outlaw mangrove planting in city parks to protect water views (Staletovich 2022), and there is evidence to show that illegal mangrove harvesting has occurred in places where water views are blocked by mangroves (Graeme et al. 2008).

Strength of Evidence

Low. The evidence for this link is very limited and mostly based on extrapolations. While people discuss the aesthetic value of mangroves anecdotally, it has not been studied in depth and there is conflicting evidence about mangrove forest aesthetic services and disservices. Evidence that was found was not specific to the focal region.

Other Factors

The location of mangroves can affect the significance of mangrove forest aesthetics. Aesthetic value is not relevant for mangrove forests located in remote locations rarely seen by humans.

The baseline status of mangrove forests is also worth considering. If a forest is degraded prior to a hurricane, resulting impact from any particular storm may have less impact on aesthetics than the destruction of a previously pristine forest.

There are diverse species of mangroves, all with different appearances. Red, black, and white mangroves are among the most abundant species in North America. Red mangroves have a shrub-like appearance and grow close to shore, with tangled, reddish exposed roots. Black mangroves grow at slightly higher elevations and possess horizontal roots and pneumatophores, root-like projections protruding from the soil. White mangroves grow at the highest elevation and have a more tree-like appearance, reaching heights of 50 ft in North America (Florida Museum of Natural History 2019). If a hurricane affects the aesthetics of certain species more than others, the degradation of particular species could have varying impacts on aesthetic value.

The type of storm impact to mangrove forests can vary greatly, and thus can have a wide impact on aesthetic value. Shorter-term impacts on aesthetics may not have as significant an impact as more long-term degradation or loss of forest. For example, if a forest is defoliated in a hurricane but is able to replace its leaves within a year, the aesthetic damage is less long-lasting as compared to the death of an entire mangrove stand, which could take many years to fully regrow.

Predictability

Because of the limited and inconsistent information available about this link, the relationship between mangrove quality/quantity and aesthetics is not predictable. While there is some evidence directly addressing mangrove aesthetics, most information had to be inferred.

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LINK 15: NET PRIMARY PRODUCTION → WILDLIFE POPULATIONS

Description of Relationship

Mangrove forests are among the most productive and carbon-rich ecosystems in the world (Ouyang and Guo 2020). One component of mangrove net primary production (NPP), aboveground mangrove tissues falling to the sediment to form litter and be transformed into detritus, provides food for some species of marine benthos, zooplankton, and nekton during all or part of their life cycles (Carugati et al. 2018; Nagelkerken et al. 2008; Ouyang and Guo 2020; Tse et al. 2008). Grapsid and sesarmid crabs are the main consumers of leaf litter in mangrove forests (Carugati et al. 2018; Lee 1995; Nagelkerken et al. 2008; Ouyang and Guo 2020). A less-understood and more debated function of mangrove NPP in affecting wildlife populations is the ability of mangrove forests to export a portion of the productivity to the surrounding aquatic environment for consumption by wildlife; this requires more research and may be dependent on a combination of environmental factors (Lee 1995; Nagelkerken et al. 2008; Ouyang and Guo 2020).

Summary of Evidence

NPP of mangrove forest systems can support wildlife populations primarily by generating food resources, such as leaf litter (Carugati et al. 2018; Nagelkerken, et al. 2008; Ouyang and Guo 2020; Tse et al. 2008). Studies that have found higher densities of juvenile prawns, other crustaceans, and fish in mangrove forest areas as compared to adjacent nearshore habitats have attributed this phenomenon in part to mangrove forests' productivity in comparison to alternative inshore habitats (Nagelkerken et al. 2008).

Mangrove forests are among the most productive ecosystems in the world, with one study ranking them second only to coral reefs in NPP (Castañeda-Moya et al. 2013; Jennerjahn and Ittekkot 2002; Ouyang and Guo 2020; Ribeiro et al. 2019). Higher NPP from producers (i.e., mangroves) allows for more energy to be available to consumers at all levels of the food chain and higher productivity within the ecosystem. NPP of mangrove forests is very important ecologically as it provides energy that enters coastal systems and food webs, which can be made available for use by all other consumers within the ecosystem (Schowalter 2006). Given this, mangrove NPP is generally supportive of wildlife populations. However, beyond that general conclusion, the literature on specific relationships between mangrove NPP and wildlife populations is relatively sparse.

Aboveground mangrove tissues, such as leaves, become litter when they fall to the sediment and are transformed into detritus (Carugati et al. 2018; Nagelkerken, et al. 2008; Ouyang and Guo 2020). Mangrove detritus is a food source for some species of marine benthos, zooplankton, and nekton during all or part of their life cycles (Carugati et al. 2018; Nagelkerken, et al. 2008; Ouyang and Guo 2020; Tse et al. 2008). In particular, sesarmid and grapsid crabs, the crab *Ucides cordatus*, and the gastropod *Terebralia palustris* are key consumers of fallen litter within mangrove forests (Carugati et al. 2018; Lee 1995; Nagelkerken et al. 2008; Ouyang and Guo 2020). Sesarmid crabs generally show the highest degree of dependency on mangrove carbon in comparison to other faunal taxa (Nagelkerken et al. 2008). Leaf litter is the main food source for crabs in mangrove forests; crabs can process up to 57% of the annual mangrove forest litter production (Ouyang and Guo 2020).

Another potential way mangrove NPP affects wildlife populations is through the outwelling hypothesis that claims the high productivity of mangroves is partially exported to the aquatic environment, providing an important food source for secondary consumers and thereby supporting adjacent wildlife populations (Lee 1995; Nagelkerken et al. 2008; Ouyang and Guo 2020). Some research claims that mangrove litterfall may be exported to adjacent coastal waters to support fauna under macrotidal settings (Ouyang and Guo 2020). Recent research has claimed this relationship is much less significant than expected and the hypothesis should be revised because there is little solid evidence for a significant amount of mangrove-derived carbon in adjacent food webs, and earlier estimates may be biased. The original outwelling hypothesis for mangroves was extrapolated from findings from temperate salt marshes, and more research is needed to determine if, when, and under what conditions mangroves can be net exporters of carbon and whether this supports wildlife populations (Lee 1995; Nagelkerken et al. 2008).

Strength of Evidence

Fair. All sources used were peer-reviewed scientific literature, but relatively little evidence was found in the literature about the relationship between mangrove NPP and wildlife populations. The literature was consistent in identifying mangrove leaf litter as an important food source for some wildlife species, particularly grapsid and sesarmid crabs, but was inconsistent in discussing the potential of mangrove forests to export productivity to adjacent waters and ecosystems (the outwelling hypothesis). Sources suggest that more research is needed to draw conclusions about this relationship and how it can apply to mangrove forests' relationships with wildlife.

Other Factors

Because evidence on the relationship between mangrove NPP and wildlife populations is limited and inconsistent within the literature, there is little information about the external factors that influence the relationship. In discussing the potential of mangrove forest ecosystems to export productivity to surrounding waters and adjacent ecosystems, one source noted that the contribution of mangrove-derived organic matter in adjacent systems may vary according to the environmental setting and geomorphology of the system, with contributions being more important in riverine-estuarine systems than in lagoon or island settings (Nagelkerken et al. 2008).

Predictability

Because of the limited and inconsistent information available about this link, the relationship between mangrove NPP and wildlife populations is not predictable. Despite the food source mangrove litter provides to several mangrove-dwelling wildlife species, it comprises just one food source of many available in mangrove forests. It is difficult to draw any conclusions about the effects of mangrove NPP on wildlife populations, nor have any numeric estimates of this relationship been made within existing literature. Information about external influences on this relationship is extremely limited.

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LINK 17: WATER QUALITY → WILDLIFE POPULATIONS

Description of Relationship

Through processes including sedimentation, microbial activity, and plant assimilation, mangroves have the ability to maintain, and in some cases improve, water quality (see Link 7). This relationship may allow mangrove forests to better maintain wildlife populations, but evidence is very limited. Mangroves may be able to do this by filtering out excess nutrients that cause harmful algal blooms with the potential to kill or harm wildlife (Adhavan 2015; Fire and Van Dolah 2012; Rivera-Monroy et al. 1995). Mangrove systems' ability to store trace metals may also have impacts on accumulation of those metals in certain wildlife species (de Lacerda et al. 2022). The effects that mangroves have on turbidity may also play a role in affecting wildlife populations, but evidence is sparse and inconsistent (Nagelkerken et al. 2008; Schaffelke et al. 2005).

Summary of Evidence

Mangrove ecosystems may have the ability to affect their surrounding environment by removing and transforming pollutants in water through processes such as sedimentation, filtration, microbial activity, and plant absorption (see Link 7). By maintaining or improving water quality, mangroves may be able to create more suitable habitats that can support a wide variety of marine species, but direct evidence of this relationship is very limited in the literature.

One way that mangroves may be able to support wildlife populations by influencing water quality is through the uptake of nutrients, such as nitrogen and phosphorous, that could otherwise lead to algal blooms (Rivera-Monroy et al. 1995; Wu et al. 2008). Algal blooms in coastal water can occur when environmental conditions promote the rapid growth of algae, and bloom severity depends in part upon the nutrient enrichment level of the water (Adhavan 2015). Harmful algal blooms are correlated with morbidity and mortality of marine wildlife because they can release toxins, block sunlight from penetrating the water's surface, and create anoxic zones that strip dissolved oxygen from the surrounding water (Fire and Van Dolah 2012). These have been documented affecting species of fish, seabirds, mammals (e.g., manatees, dolphins, seals), reptiles, elasmobranchs, and shellfish. By assimilating excess nutrients from water and through denitrification processes, mangroves could potentially reduce the harmful effects of algal blooms on marine wildlife and prevent morbidity or mortality, but there is no direct evidence of this relationship and it is solely based on extrapolations.

Mangrove systems are also known to act as a sink for trace metals (de Lacerda et al. 2022; Harbison 1986; MacFarlane et al. 2007), which in turn has the possibility to reduce both human and animal exposure to these toxic compounds (see Link 7). However, depending on biogeochemical conditions, mangrove sediments can release stored trace metals into surrounding estuary waters that could accumulate in wildlife species. de Lacerda et al. (2022) review instances where changing biogeochemical conditions (e.g., drought periods) in mangrove areas have been linked to increased mercury levels in fish and shellfish.

Also, the turbidity of the water surrounding mangroves may be a factor that attracts many species to use mangrove habitats. The literature that discusses the wildlife habitat potential of mangroves claims that species, especially juvenile fishes, prefer turbid waters of mangrove ecosystems to hide from larger predators (Nagelkerken et al. 2008). While some species prefer the relatively turbid waters within mangrove habitats, there is also literature that describes mangroves' ability to reduce turbidity (e.g., Schaffelke et al. 2005). Turbidity levels have been shown to impact marine wildlife by influencing trophic interactions in estuaries (Lunt and Smee 2014), and these interactions may shift species compositions (Lunt and Smee 2019). Therefore, if mangroves do affect water turbidity, they may in turn affect nearby wildlife populations. However, this relationship is also based solely on extrapolations.

Strength of Evidence

Low. The evidence for the relationship between mangroves' effects on water quality and wildlife populations is very limited, and evidence had to be extrapolated to explain a possible relationship for this link. Information about algal blooms was consistent, but there were direct contradictions in the information about turbidity (i.e., one set of literature suggests mangroves should reduce turbidity of water, but another set claims wildlife is attracted to mangroves for their turbid waters). There was no information about the influence of external factors, and applicability is very low.

Other Factors

Given the limited availability of evidence within the literature, there were no descriptions of external factors that influence this relationship.

Predictability

Because of the lack of literature evidence of mangroves' ability to affect wildlife populations through their influence on water quality, there is no predictability in this relationship. There are also no measurements or estimates of previous instances of the effects of this relationship, nor are there any models or tools that can predict this relationship.

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LINK 18 AND LINK 19*: SEDIMENT TRAPPING/ SHORELINE CHANGE (EROSION/ACCRETION) → WATER QUALITY

*Links 18 and 19 were assessed together because of overlapping evidence

Description of Relationship

Mangroves can reduce the amount of suspended sediments in the water column by trapping, binding, and stabilizing sediments. They can thus reduce the turbidity of coastal waters, which may have an effect on overall water quality (Chen et al. 2018; Duke and Wolanski 2001; Kitheka et al. 2003; Schaffelke et al. 2005). Evidence for the ability of mangroves to trap sediments is high, but there is relatively little evidence about the direct effect trapping sediments has on water quality, and information had to be extrapolated. The extent to which mangroves can trap sediments and thus affect water quality depends on factors such as the trapping capacity of mangrove trees, vegetation density and biomass, intertidal position, geomorphological setting, and tidal cycles (Chen et al. 2018; Duke and Wolanski 2001; Kitheka et al. 2003).

Summary of Evidence

Mangroves have the ability to trap, bind, and stabilize sediments suspended in coastal waters and brought in with tides through direct contact with their vegetative structures and through the indirect effects mangrove vegetation have on hydrodynamic forces (see Links 4 and 20)

(Chen et al. 2018; Duke and Wolanski 2001; Kitheka et al. 2003; Schaffelke et al. 2005). An Australian study found that where sufficient amounts of sediments were trapped and held within an estuarine mangrove forest, coastal waters were relatively free of suspended material (Duke and Wolanski 2001). Similarly, in Kenya, it was found that a moderately degraded mangrove forest had a sediment trapping efficiency of 65% and a highly degraded mangrove forest had an efficiency of 27%, as compared to a highly vegetated site in Australia with a trapping efficiency of 80% (Kitheka et al. 2003).

This ability to trap sediments, reduce erosion, and promote accretion can allow mangroves to reduce Total suspended sediment, one of the major components of turbidity (Chen et al. 2018; Duke and Wolanski 2001; Kitheka et al. 2003; Sadar 2017; Schaffelke et al. 2005). Some studies have also noted a direct link between mangroves' ability to trap sediments and reduced turbidity of coastal waters, but this relationship is not quantified (Duke and Wolanski 2001; Schaffelke et al. 2005). The amount of dispersed suspended sediments in water, which determines turbidity, is an important indicator of water quality. High levels of suspended sediment, and thus high turbidity, often create direct and indirect negative effects within the water column that reduce water quality (Sadar 2017).

Strength of Evidence

Fair. The evidence for the relationship between mangroves' effects on sediment trapping and shoreline change and thus water quality is very limited, and evidence had to be extrapolated to explain a possible relationship for this link. The literature is consistent in identifying the sediment trapping mechanism of mangroves and how mangroves can affect shoreline change, and some evidence ties this to decreased suspended sediment concentrations or decreased turbidity. Because the direct relationship between mangrove sediment trapping/shoreline change and water quality is not well-supported within the literature, it cannot be generalized and it is unclear how external factors affect this relationship.

Other Factors

Several other factors may affect the extent to which mangroves can trap sediments and thus affect water quality. Links 4 and 20 provide more detail on these other factors, but they include the trapping capacity of mangrove trees, vegetation density and biomass, intertidal position, geomorphological setting, and tidal cycles (Chen et al. 2018; Duke and Wolanski 2001; Kitheka et al. 2003).

The sediment-trapping capacity efficiency, and thus the potential effect on turbidity in coastal waters, of degraded mangrove wetlands is low compared to pristine, heavily vegetated mangrove forests (Chen et al. 2018; Kitheka et al. 2003). Studies have found higher suspended sediment content and turbidity in mangrove forests during flood phases of the tidal cycle than ebb phases (Chen et al. 2018; Kitheka et al. 2003). Further, there is increased turbidity in mangrove forests directly after storm events, but turbidity levels generally recover fairly quickly (Schaffelke et al. 2005). Total suspended sediment content also varies between different areas in a single mangrove forest (i.e., front, middle, back) because of differences in hydrodynamic forces and differing effects of tidal inundation (Chen et al. 2018; Kitheka et al. 2003).

Predictability

Because of the lack of evidence in the literature of mangroves' ability to affect water quality through their influence on sediment trapping and shoreline change, there is no predictability in this relationship. While evidence strongly suggests that mangroves trap sediments and reduce suspended sediment contents in coastal waters, there is no indication of how it can be predicted.

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LINK 20: SEDIMENT TRAPPING → SHORELINE CHANGE (EROSION/ACCRETION)

Description of Relationship

The complex aerial root structure of mangrove trees allows them to trap sediments and function as land builders, inducing shoreline change in the form of both accretion and reduced erosion. As hydrodynamic forces such as tidal currents and flow around mangroves introduce sediment into the area, mangroves trap suspended sediment, allowing the sediment to accrete (Kathiresan 2003). Further, the vegetation and root structures of mangrove trees prevent erosion by reducing wind and water velocity at the shoreline and increasing soil shear strength, respectively (Pennings et al. 2021). The species of mangroves tree and the strength of hydrodynamic forces in the area may affect mangroves' ability to affect shoreline change (Granek and Ruttenberg 2007; Pennings et al. 2021). This link is very closely related to Link 26 (wave attenuation → shoreline change) and some evidence overlaps between these entries.

Summary of Evidence

Mangroves play an important role in maintaining coasts and affecting shoreline changes through both accretion and erosion control. Both hydrodynamic forces and the structure of mangrove tree roots promote sediment trapping, affecting shoreline changes. Specifically, the dense structure of mangrove vegetation and root systems help to generate drag force that dissipates wave action along the coast (Granek and Ruttenberg 2007; Swiadek 1997). Sediment within the water column therefore is trapped by mangrove trunks, root systems, and pneumatophores and deposited into coastal soil, facilitating sediment deposition and accretion in the surrounding area (Furukawa and Wolanski 1996; Sánchez-Núñez et al. 2019; Swiadek 1997; Thampanya et al. 2006; Van Santen et al. 2007). The complex structure of mangrove roots further helps to reduce water velocity of incoming waves at the coast and increase soil shear strength, preventing erosion from occurring at the shoreline, especially with the occurrence of high wave action during both large and small storms (Granek and Ruttenberg 2007; Pennings et al. 2021; Winterwerp et al. 2005).

Various studies have examined the positive effects of mangrove cover on erosion prevention in response to tropical storms and hurricanes. In Texas, it was found that plots with higher mangrove cover significantly reduced both vertical and horizontal erosion on the coast following Hurricane Harvey in comparison to plots with little to no mangrove cover (Armitage et al. 2019; Pennings et al. 2021). Even a site with a low percentage of mangrove cover (11%) provided a high amount of shoreline protection; however, the greatest protective effects were realized in sites with at least 50% mangrove cover (Pennings et al. 2021).

A study conducted at a mangrove habitat in Belize during both Tropical Storms Wilma and Gamma found that mangroves provided substantial coastal protection against storm impacts and coastal erosion (Granek and Ruttenberg 2007). In South Florida, another study demonstrated the ability of coastal mangroves to trap sediment and control erosion during Hurricane Andrew and hypothesized that there will be significant erosion and habitat change after many mangroves were uprooted by the storm (Swiadek 1997). Several studies conducted in Thailand identified the protective ability of mangroves against coastal erosion and toward accretion (Sánchez-Núñez et al. 2019; Thampanya et al. 2006; Winterwerp et al. 2005). In Thailand, mangrove-vegetated shores reduced erosion rates and retained sediments in areas with high wave energy and experienced accretion in areas with low wave energy in comparison to sites with no mangrove cover (Thampanya et al. 2006).

The link between mangrove trees' ability to trap sediments and reduce erosion or promote accretion may have positive impacts on coastal protection and other coastal ecosystems. Erosion control from mangroves is estimated to have a value of US$3679 ha^{-1} yr^{-1} in Thailand and US$693 ha^{-1} yr^{-1} in the Sinú River deltaic system of Colombia (Sánchez-Núñez et al. 2019). There is speculation that the recent transition from marshes to mangroves in the US Gulf Coast may improve the shoreline protection services of wetlands, but this claim needs more quantitative evidence to support it (Armitage et al. 2019).

Strength of Evidence

Moderate. The mechanisms that facilitate the link between mangrove sediment trapping and shoreline change (accretion/erosion) as well as the effects on mangrove sediment trapping on shoreline change are well-studied and consistent. While methods within the literature were well-documented and accepted, most studies were focused in Southeastern Asia and outside the Gulf of Mexico/Caribbean region. Results would need to be further replicated in different environments to assess the impacts of other factors on the link.

Other Factors

The species of mangrove and strength of hydrodynamic forces may affect the ability of mangroves to impact shoreline change. Studies have identified both morphology and vegetation structure of different species of mangrove trees to affect the intensity of sedimentation. Specifically, the root structure and structural complexity of a mangrove tree affects the extent to which the mangrove can attenuate wave flow and promote sedimentation because complex aerial roots increase the surface area of the mangrove and facilitate sedimentation (Kathiresan 2003; Pennings et al. 2021). Trees that form complex root systems such as *Rhizophora* spp. have the largest impact on shoreline change and are more able to reduce erosion or promote accretion than single trees such as *Ceriops* spp. (Furukawa and Wolanski 1996; Sánchez-Núñez et al. 2019). Therefore, zones containing different species of mangroves have varying efficiency of sediment trapping due to varying root structure, and also the difference in tidal inundations/waterflow velocity areas the mangroves experience in zones they tend to grow in. At low tide, coastal zones with predominately *Avicennia–Rhizophora* forests can trap 30% of total suspended sediment received at high tide, and zones with only *Avicennia* or only *Rhizophora* can trap only 25% and 20% of suspended sediment, respectively. This is attributed to differences in root structure complexity (Kathiresan 2003).

The strength of hydrodynamic forces such as drag forces, storms, storm surge, and wave energy also impacts the ability and extent to which mangroves can trap sediment to facilitate accretion or prevent erosion. In areas with larger drag forces and higher flow velocity, mangroves' ability to dissipate waves decreases and they are less prone to sediment retention and more prone to erosion. Further, in lower-energy environments, mangroves promote sedimentation of particles with low settling rates such as clay, silt, and allochthonous organic matter. However, in more energetic environments, these particles are lost and mangrove soils can erode, losing their ability to trap sediments (Armitage et al. 2019; Sánchez-Núñez et al. 2019).

Predictability

The literature is consistent in the fact that mangroves possess the ability to trap sediments, facilitating accretion and reducing erosion on the shoreline because of their vegetative structure and ability to temper hydrodynamic forces along the coast. Despite being consistent in their results, many of the studies relied on site-specific conclusions and further quantitative evidence is needed to generalize the conclusions. Also, the extent to which mangroves possess the ability to trap sediments and facilitate accretion/reduce erosion may be dependent on the species and hydrodynamic forces in the mangrove area.

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LINK 22: SEDIMENT TRAPPING → SOIL ELEVATION

Description of Relationship

Several different types of surface and subsurface processes influence soil elevation in mangrove forests (Cahoon and Lynch 1997; Hayden and Granek 2015; Krauss et al. 2013; Lovelock et al. 2015; McIvor et al. 2013; Whelan et al. 2009). Sediment trapping is a surface process that can occur as a result of the interactions between the complex root structures of mangroves and hydrodynamic forces, and constitutes one of many processes that can affect soil elevation in mangrove forests (Hayden and Granek 2015; Krauss et al. 2003, 2013; Lovelock et al. 2015; McIvor et al. 2013; McKee 2011). While sediment trapping by mangroves can allow for vertical accretion atop the soil surface, several other processes and external factors must also be accounted for to determine whether there will be a net gain or loss in soil elevation (Cahoon and Lynch 1997; Hayden and Granek 2015; Krauss et al. 2013; Lovelock et al. 2015; McIvor et al. 2013; Whelan et al. 2005, 2009).

Summary of Evidence

Soil elevation in this context is the position of the mangrove soil surface in the vertical plane (Krauss et al. 2013). For coastal mangrove trees to survive and maintain the stability of their forest habitat, the rate of soil elevation rise in mangrove forests must occur at a faster rate than sea level rise (Cahoon and Lynch 1997; Krauss et al. 2013; Lovelock et al. 2015; McKee et al. 2007; South Florida/Caribbean Network 2021; Sidik et al. 2016). Although sea level rises globally at an average rate of 3.2 ± 0.4 mm yr^{-1}, soil elevation only has to rise faster than the rate of relative or local sea level rise, 1.9 mm yr^{-1} in the Caribbean, or risk becoming submerged (Krauss et al. 2013). Mangrove-facilitated sediment trapping is one path to affect soil elevation and often increases soil elevation through vertical accretion, therefore increasing the capacity of mangroves to maintain elevation relative to sea level rise (Sidik et al. 2016).

Both comprehensive literature reviews and site-specific studies separate the processes that affect soil elevation into two categories: surface and subsurface processes (Cahoon and Lynch 1997; Hayden and Granek 2015; Krauss et al. 2013; Lovelock et al. 2015; McIvor et al. 2013; Whelan et al. 2009). Some sources also identify a distinction between physical and biological processes (Hayden and Granek 2015; Krauss et al. 2013). *Subsurface* processes that contribute to soil elevation are processes that occur below the soil's surface such as growth and decomposition of mangrove roots, shrink-swell of soils, compaction of soils, and deep land movements (Krauss et al. 2013; Lovelock et al. 2015; McIvor et al. 2013; McKee 2011; South Florida/Caribbean Network 2021; Whelan et al. 2005). *Surface* processes are those that occur at or above the soil's surface and include plant litter and woody debris deposition, benthic mat development, erosion, and the focus of this link, sedimentation (Hayden and Granek 2015; Krauss et al. 2013; Lovelock et al. 2015; McIvor et al. 2013; McKee 2011).

Sedimentation is the process by which mangrove trees trap suspended sediments and deposit them into the surrounding forest, contributing to vertical accretion at the soil's surface, and potentially affecting soil elevation (Cahoon and Lynch 1997; Hayden and Granek 2015; Howard et al. 2020; Krauss et al. 2003, 2013; Lovelock et al. 2015; McIvor et al. 2013; McKee, 2011; Sidik et al. 2016; Whelan et al. 2005). The complex structure and density of mangrove aerial roots supports sedimentation by reducing the velocity of surrounding tidal flows, thereby facilitating trapping and retention of suspended sediment and organic material within the forest (Hayden and Granek, 2015; Krauss et al. 2003, 2013; Lovelock et al. 2015; McKee, 2011; Sidik et al. 2016). By increasing sediment trapping within the wetland, mangroves can increase vertical accretion and potentially increase soil elevation (Cahoon and Lynch 1997; Hayden and Granek 2015; Howard et al. 2020; Krauss et al. 2003, 2013; Lovelock et al. 2015; McIvor et al. 2013; McKee, 2011; Sidik et al. 2016; Whelan et al, 2005).

A soil elevation change study within a red mangrove forest in Belize found that all sites with intact mangroves experienced soil elevation gains and all sites without mangroves experienced soil elevation losses (Hayden and Granek 2015). These results are consistent with the idea that mangroves facilitate sediment trapping that can therefore increase soil elevation when they are present, but there could also be several other surface and subsurface biological and physical processes contributing partially or fully to the soil elevation change experienced in this case. A further study in East Java, Indonesia, found sediment deposition by mangrove-facilitated accretion to be the primary process controlling surface elevation change. However, it was noted that this may be different from mangrove forests in the Caribbean where plant root growth and biomass is the major contributor to surface elevation change (Sidik et al. 2006).

Following the results of the two previous studies, the methods typically used to measure change in soil elevation in mangrove forests do not allow for a definitive link between mangrove sediment trapping and soil elevation to be drawn. The current and most widely used method to study elevation change in mangrove habitats is the Surface Elevation Table–Marker Horizon (SET–MH) system (Krauss et al. 2013; McKee 2011; South Florida/Caribbean Network 2021; Whelan et al. 2009). The SET–MH system provides several precise measurements including elevation change, vertical accretion on the soil surface, and shallow subsidence/expansion from wetland ecosystem. It can not only track elevation change, but also identify what component of the elevation change is attributable to vertical accretion, shallow subsidence, or root zone expansion. However, this method cannot definitively isolate and quantify the effects of mangrove-facilitated sediment trapping alone (Krauss et al. 2013).

Strength of Evidence

Moderate. While the variety of evidence types, including both peer-reviewed review papers and site-specific studies, used acceptable methods and found consistent evidence on the processes that affect soil elevation, including mangrove-facilitated sediment trapping within the Gulf of Mexico/Caribbean region, the predictability and applicability is low. The literature consistently found an overwhelming amount of confounding factors that influence soil elevation and no way to isolate or quantify the effects of mangrove-facilitated sediment trapping alone or definitively draw a link between increased sediment trapping and gains in soil elevation (or the opposite effect), even with leading methods.

Other Factors

Even though a link between mangrove-facilitated sediment trapping and soil elevation is identified in the literature, many other surface and subsurface biological and physical processes and external factors affect the ultimate net effect on soil elevation within an ecosystem. There is a need to comprehensively consider all potential processes and factors that can affect soil elevation in order to determine the strength and magnitude of the link between mangrove-facilitated sediment trapping and soil elevation within a particular system (Cahoon and Lynch 1997). Studies have shown that within certain mangrove forests, mangrove-facilitated sediment trapping may interact with other surface or subsurface processes or factors to ultimately determine the effect on soil elevation (Cahoon and Lynch 1997; McKee 2011). Measures of vertical accretion and soil elevation change in mangrove forests of Rookery Bay, Florida, United States, found that both surface—including sediment trapping—and subsurface processes play important roles in influencing soil elevation change (Cahoon and Lynch 1997). A study conducted in Belize and southwest Florida, United States, drew a similar conclusion—that surface and subsurface processes affected soil elevation changes, and even found it is possible for a forest to experience positive vertical accretion through sediment trapping, but there was overall soil elevation loss in the ecosystem because of the interactions between surface and subsurface processes in determining soil elevation change (McKee 2011).

Not only do variations in internal ecosystem processes affect soil elevation, but external factors may also play a confounding role in determining effects on soil elevation. Some of these factors include the types of sediments available within an ecosystem, the geographic location of the mangrove forest, the species of mangrove tree and its functional root type, the type of mangrove forest (i.e., overwash, basin, fringe, or others), hydrodynamic forces, and storms/hurricanes (Cahoon and Lynch 1997; Hayden and Granek 2015; Krauss et al. 2013; McIvor et al. 2013; South Florida/Caribbean Network 2021; Whelan et al. 2009).

More specifically, the geographic location and availability of different types of sediment plays an important role in whether or not mangroves can facilitate sediment trapping to contribute to soil elevation change. A study on soil elevation change in mangrove forests of Moreton Bay, Queensland, Australia, found variation in sediment availability and sea level can influence gains in soil surface elevation of mangrove forests (Lovelock et al. 2015). Similarly, a study comparing soil elevation between mangrove forests of Indonesia and the Caribbean found the role of mangrove-facilitated sediment deposition to be dependent on environmental features and soil properties of the site (Sidik et al. 2006). Fundamental differences were found in mangrove forests underlain by peat deposits and those receiving mineral sediment inputs, such as muddy coastal environments (Cahoon and Lynch 1997; McKee et al. 2007).

Predictability

Because of the numerous confounding factors and processes influencing soil elevation change, the link between mangrove-facilitated sediment trapping and soil elevation has low predictability. While evidence does exist that mangrove-facilitated sediment trapping can contribute to soil elevation changes in certain environments, the relationship is not straightforward, and even when an ecosystem experiences positive vertical accretion from mangrove-facilitated sediment trapping, an overall loss of soil elevation in the ecosystem is still possible as a result of the strong influence of other factors and processes (McKee 2011). Further, the SET–MH method used to measure the impact of three types of components in soil elevation change is not specific enough to definitively demonstrate or quantify an isolated link between soil elevation and mangrove sediment trapping (Krauss et al. 2013).

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LINK 26: WAVE ATTENUATION → SHORELINE CHANGE (ACCRETION/EROSION)

Description of Relationship

Mangroves play an important role in providing coastal protection by attenuating wave height and energy, acting as a natural barrier to incoming waves and tidal flows. Wave attenuation by mangroves facilitates the accretion of sediments and reduces the erosive effects of incoming waves, which may affect shoreline changes (Bao 2011; Doughty et al. 2017; Gedan et al. 2010; Hong Phuoc and Massel 2006; Horstman et al. 2014; Kamil et al. 2021; Le Nguyen and Vo Luong 2019; Pennings et al. 2021; Sánchez-Núñez et al. 2019; Van Santen et al. 2007). This service is highly context-dependent, influenced by wave parameters, mangrove characteristics, and other external factors (Besset et al. 2019; Doughty et al. 2017; Gedan et al. 2010; Hashim and Catherine 2013; Kamil et al. 2021; Nguyen et al. 2015).

Summary of Evidence

Wave attenuation, or the reduction in incoming wave height/energy, by mangroves occurs as a result of the physical vegetative structures in coastal mangrove forests. The complex, rigid network of stems, branches, and aerial roots in mangrove forests impose resistance by increasing drag force, which, in combination with the effect of bottom friction, work in the opposite direction of incoming waves, causing them to attenuate and dissipate (Gedan et al. 2010; Hong Phuoc and Massel 2006; Horstman et al. 2014; Kamil et al. 2021; Othman 1994; Van Santen et al. 2007). Mangrove-induced wave attenuation allows mangroves to play a critical role as a shoreline buffer and stabilizer in two ways: (1) by affecting shoreline change through indirect sediment accretion via hydrodynamic processes and (2) by directly reducing erosion by dissipating incoming waves (Bao 2011; Gedan et al. 2010; Hong Phuoc and Massel 2006; Horstman et al. 2014; Winterwerp et al. 2005). Cumulatively, these mechanisms promote sediment deposition and inhibit erosion, contributing to lasting shoreline stability and accretion (Gedan et al. 2010). Impact to the mangrove system from deforestation or disturbance can result in potentially irreversible coastal erosion as a result of the loss of wave attenuation benefits, suggesting that mangrove plant structure, rather than physical variables correlated with mangrove forest development, attenuate waves and prevent erosion (Besset et al. 2019; Gedan et al. 2010; Nguyen et al. 2015; Othman 1994).

The first process of mangrove wave attenuation facilitating sediment deposition occurs when the strong drag forces of mangrove vegetative structures such as aerial roots and trunks dissipate the energy of incoming waves and reduce wave velocity to the extent that suspended sediments carried in with the waves are deposited (Besset et al. 2019; Gedan et al. 2010; Sánchez-Núñez et al. 2019, Swiadek 1997). Further, because of the dissipation of wave energy by mangroves in this process, the deposited sediments do not get resuspended or carried back out of the forest (Besset et al. 2019; Gedan et al. 2010; Sánchez-Núñez et al. 2019, Swiadek 1997; Van Santen et al. 2007). Thus, wave attenuation in mangroves has been found to facilitate enhanced sediment deposition, leading to accretion and stabilization on shorelines through increased soil strength and erosion prevention (Doughty et al. 2017; Hong Phuoc and Massel 2006; Horstman et al. 2014; Le Nguyen and Vo Luong, 2019; Nguyen et al. 2015; Van Santen et al. 2007)

Mangrove-facilitated wave attenuation also reduces the impacts of waves and currents on coastal erosion, protecting the sediments deposited in the latter process against erosion and protecting sediments even when new sediment delivery/accretion is low (Bao 2011; Besset et al. 2019; Doughty et al. 2017; Gedan et al. 2010; Hashim and Catherine, 2003; Hong Phuoc and Massel 2006; Kamil et al. 2021; Le Nguyen and Vo Luong 2019; Nguyen et al. 2015; Othman, 1994; Pennings et al. 2021; Sánchez-Núñez et al. 2019; Van Santen et al. 2007). Wave action is one of the main factors governing erosion in mangrove forests (Hong Phuoc and Massel 2006; Horstman et al. 2014). The dense and rigid network of mangrove stems, branches, and aerial roots is responsible for an increase of roughness and drag force that results in reduction of currents and attenuation of waves (Doughty et al. 2017; Sánchez-Núñez et al. 2019; Van Santen et al. 2007). By attenuating wave height and energy, mangroves provide coastal protection and act as a natural barrier to incoming waves, thereby reducing erosion and stabilizing the shoreline (Bao 2011; Besset et al. 2019; Gedan et al. 2010; Hashim and Catherine 2003; Hong Phuoc and Massel 2006; Kamil et al. 2021; Nguyen et al. 2015; Pennings et al. 2021; Othman 1994).

A study in Australia observed sustained sediment deposition in mangrove fringe, in contrast to an alternation of accretion and erosion in an adjacent bare mudflat, that was explained by the bare mudflat's inability to prevent erosion because of its lack of vegetative structures (Van Santen et al. 2007). In Texas, vertical and horizontal erosion rates were greatest in sites with 0% mangrove cover in comparison to sites with some mangrove cover, but even a low percent cover of mangroves (11%) provided a high amount of shoreline protection compared to the absence of mangroves; this was attributed in part to mangroves' ability to dissipate waves (Pennings et al. 2021) In east Central Florida, modeled erosion prevention was significantly higher (470% increase) in scenarios with mangrove vegetation than with salt marsh vegetation, and mangroves prevented losses of 0.044 ± 0.036 m^2 of land as a result of the increased ability of mangroves to protect coastlines by attenuating waves, reducing erosion, and promoting sediment deposition (Doughty et al. 2017). The relationship between mangrove wave attenuation and shoreline change has thus been demonstrated through a variety of theoretical, laboratory, and field monitoring studies; however, some gaps still remain as a result of conflicting information, and there may be potential flaws in some studies' methods (Besset et al. 2019; Gedan et al. 2011; Nguyen et al. 2015).

Strength of Evidence

Moderate. Evidence for the relationship between mangrove-facilitated wave-attenuation and shoreline change is well-documented in multiple types of peer-reviewed evidence types, including site-specific studies, review papers, and meta-analyses. Studies employ a wide variety of methods including modeling, field studies, and laboratory experiments, but both Nguyen et al. (2015) and Besset et al. (2019) raise some concerns about the methodology of other studies for being too simplistic and not accounting for all confounding factors. The literature is consistent in the mechanisms behind the effects of wave attenuation by mangroves on shoreline change, as well as mangroves' ability to attenuate waves and affect shoreline under a narrow set of conditions (high vegetation density and low wave energy) in a variety of geographic locations, including the Caribbean/Gulf of Mexico region. Similarly, the literature consistently identifies an influence of mangrove characteristics, wave parameters, and external factors on this relationship, but there is some variability in the magnitude and direction of the effects of these factors, making this relationship highly context-dependent, relying on several other factors that must be considered to determine the wave-attenuating capacity of mangroves in a specific site, and if they can affect shoreline change.

Other Factors

Under conditions of high volumetric densities of mangroves and low wave energy, there is great consensus that mangroves promote higher wave attenuation, which is then a fundamental driver of sediment retention, erosion mitigation, and increasing shoreline stability (Gedan et al. 2010; Nguyen et al. 2015; Sánchez-Núñez et al. 2019; Swiadek 1997). However, outside of these conditions, the ability of mangrove-facilitated wave attenuation to affect shoreline change is highly variable and there is conflicting evidence on the magnitude and mechanisms of effects of varying other factors (Gedan et al. 2010). The amount of wave attenuation, and therefore shoreline change, by mangroves is affected by three categories of factors: mangrove characteristics, wave parameters, and external factors (Besset et al. 2019; Doughty et al. 2017; Gedan et al. 2010; Hashim and Catherine 2013; Kamil et al. 2021; Nguyen et al. 2015).

Mangrove characteristics that influence this relationship include mangrove density, species, tree age, tree structure, and the forest width. Dense mangrove forests are better able to attenuate waves through the obstruction of waves by more intricate root networks with less space between trees, leading to less erosion and more accretion on the shoreline (Hashim and Catherine 2003; Horstman et al. 2014; Kamil et al. 2019; Othman 1994; Sánchez-Núñez et al. 2019). Due to the differences in root type and complexity across species, the species of mangrove influences the relationship between wave attenuation and shoreline change (Hashim and Catherine 2003; Hong Phuoc and Massel 2006; Horstman et al. 2014; Kamil et al. 2019; Nguyen et al. 2015). Tree age, which indicates height, trunk and root diameters; stem density; and resistance to wave impact, also affects wave attenuation: older, more developed trees can exert larger drag force on incoming waves (Hashim and Catherine, 2003; Hong Phuoc and Massel 2006; Sánchez-Núñez et al. 2019). Because mangrove forests require sufficient width to fully attenuate waves, the forest width is important for mangrove wave attenuation to affect shoreline change, but the optimum mangrove forest width for coastal protection depends on area characteristics (Hashim and Catherine 2003; Kamil et al. 2019; Nguyen et al. 2015).

Wave parameters such as wave energy, wave height, and storm events also significantly impact mangrove wave attenuation and its relationship to shoreline change. There is general consensus that mangroves attenuate waves and stabilize the coastline in areas of low wave energy (Gedan et al. 2010; Nguyen et al. 2015; Sánchez-Núñez et al. 2019; Swiadek 1997). High-energy waves are believed to reduce mangroves' ability to attenuate waves and can increase erosion, reduce accretion through sedimentation, and even uproot mangrove trees (Gedan et al. 2010; Horstman et al. 2014; Kamil et al. 2019; Sánchez-Núñez et al. 2019). Wave height also has been measured to have an effect on attenuation-induced sedimentation, with sediment deposition rates rapidly reducing with increases in mean observed wave heights (Horstman et al. 2014; Kamil et al. 2019). Similarly, storm events and increases in storm frequency that increase wave energy and height will increase the likelihood of severe flooding and erosion events, which will lead to higher erosion rates and reduce mangroves' erosion protection capacity (Doughty et al. 2017; Gedan et al. 2010).

Finally, external factors may also influence the relationship between the ability of mangroves to facilitate wave attenuation and shoreline change. Differences in coastal bathymetry may impact the ability of mangroves to attenuate waves because it is a primary control of wave energy (Gedan et al. 2010; Kamil et al. 2019; Pennings et al. 2021). Water depth may also impact this relationship, but there is much conflicting evidence of the magnitude and direction of this factor (Kamil et al. 2019; Hong Phuoc and Massel 2006). Anthropogenic encroachment and disturbance may also greatly impact mangroves' ability to attenuate waves and affect shoreline change. Mangroves are highly sensitive to human pressures and the feedback effects of mangrove habitat destruction, which may lead to a breakdown of the buffering effect of mangrove forests on wave energy and in promoting sediment trapping, potentially accelerating erosion (Besset et al. 2019; Doughty et al. 2017). The presence of prevailing, sustained, large-scale regional erosion, potentially resulting from anthropogenic reduction of sediment supply, may prohibit mangroves from their land-building and coastal protection roles (Besset et al. 2019; Gedan et al. 2010). Further, continued sea level rise resulting from anthropogenic climate change may lead to higher erosion rates and reduce wetland erosion protection capacity (Doughty et al. 2017).

Predictability

The literature is consistent in suggesting that mangroves provide context-dependent wave attenuation, which affects shoreline change through increased accretion by sedimentation or reduced erosion. The most consistent, and therefore predictable, relationship exists under conditions of high volumetric densities of mangroves and low wave energy, where mangroves promote higher wave attenuation. This process is a fundamental driver of sediment retention, erosion mitigation, and increasing shoreline stability (Gedan et al. 2010; Nguyen et al. 2015; Sánchez-Núñez et al. 2019; Swiadek 1997). Outside of these narrow conditions, the ability of mangroves to effectively attenuate waves and affect shoreline change is highly dependent on mangrove characteristics, wave parameters, and external factors, of which many have conflicting magnitudes and directions of effects within the literature, making the predictability of this relationship low (Besset et al. 2019; Doughty et al. 2017; Gedan et al. 2010; Hashim and Catherine 2013; Kamil et al. 2021; Nguyen et al. 2015).

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LINK 27: STORM SURGE ATTENUATION → FLOOD HEIGHT/EXTENT

Description of Relationship

By attenuating storm surges and their associated peak water level height and waves, mangroves can reduce coastal flooding height and extent during events such as storms and hurricanes (Dasgupta et al. 2019; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019; Torres-Ortega et al. 2019; Spalding et al. 2014). Mangroves provide this service by acting as a buffer on the coast, limiting water exchange across the forest and providing water storage within the forest so that flood height and extent is limited (Dasgupta et al. 2019; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019; Torres-Ortega et al. 2019; Spalding et al. 2014). The extent to which mangroves can reduce flood height and area depends on factors such as storm and mangrove forest characteristics (Dasgupta et al. 2019; Krauss et al. 2009; Liu et al. 2013; McIvor et al. 2012; Menéndez et al. 2020; Montgomery et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021; Spalding et al. 2014).

Summary of Evidence

Because of their ability to attenuate storm surges and associated peak water levels and waves, mangrove forests contribute to reduction of coastal flood risk in low-elevation coastal zones (Dasgupta et al. 2019; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019; Torres-Ortega et al. 2019; Spalding et al. 2014). Storm surges occur when high winds and low atmospheric pressure raise water levels at the coast, typically during storm and hurricane events, causing seawater to flood onto the land (McIvor et al. 2012). Mangroves often serve as a first line of defense against flooding because their vegetative structures (i.e., roots, trunks, branches, and canopies) pose physical resistance to the inland flow of oncoming surge, attenuating the associated high water levels and waves (Menéndez et al. 2020; Montgomery et al. 2019; Narayan et al. 2019).

Because surge height and velocity determine the height and extent of coastal flooding, there is consensus in the literature that mangroves' ability to attenuate storm surge allows them to attenuate coastal flooding, but there is little described about the precise mechanisms of this process, aside from the reduced water flow and velocity resulting from surge attenuation (Dasgupta et al. 2019; Spalding et al. 2014). As a surge moves through a mangrove forest, mangroves can effectively attenuate water levels by limiting fluid exchange across the forest and providing water storage, reducing inundation extent and height (Dasgupta et al. 2019; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019; Torres-Ortega et al. 2019; Spalding et al. 2014). A 500 m wide mangrove forest can decrease wave heights by 50% to 100%, but even relatively small reductions in water levels can greatly reduce the extent of flooding in low-lying areas behind mangroves. The greater the storm surge attenuation, the greater the flood reduction will be (Liu et al. 2013; Menéndez et al. 2018; Spalding et al. 2014). While flood protection benefits may vary as a result of differences in storm and mangrove forest characteristics, global mangrove presence is estimated to reduce the amount of land flooded annually by 35,000 km^2 (Menéndez et al. 2018, 2020).

The effect of mangroves and their ability to attenuate storm surges on coastal flooding height and extent has been primarily documented using three types of methods: (1) direct observations of water level heights, (2) use of well-validated numerical models that simulate storm surge behavior in the presence or absence of mangroves, and (3) observations of the damage caused and lives lost from storm surges (McIvor et al. 2012; Montgomery et al. 2019). Models validated with historical measurements are most often used to demonstrate the magnitude of effects produced by mangroves because of their ability to predict flooding height and extent without mangrove presence (Liu et al. 2013).

The Coastal and Estuarine Storm Tide (CEST) model was used to model the passage of Hurricane Wilma in Southwest Florida. The inundation areas predicted by the model were 4,220 km^2 without mangroves present and only 2,450 km^2 in the same area with mangrove presence, demonstrating that flooding was restricted when mangroves were included in the model (Montgomery et al. 2019). Modeling also demonstrated that Wilma's flooded area in Florida would have extended 70% further inland without the protection of the 6–30 km zone of mangroves (Soanes et al. 2021). Another study focused on Florida found that during Hurricane Irma, flooding from storm surge would have increased by more than 3,200 ha in the absence of mangroves across the state (Narayan et al. 2019). Krauss et al. (2009) found flood height reduction by mangroves in response to hurricanes on the Gulf Coast of Florida to range between 4.2 to 9.4 cm per km of mangroves; in continuous mangrove forests, flood height reduction by mangroves was 40 to 48 cm per km of mangroves. In Biscayne Bay, Miami, Florida, removal of mangrove vegetation from model scenarios resulted in outputs showing massive flooding with increased total inundation volume and area in the low-lying area behind Biscayne Bay. That modeling study found that nearly 66% of surge and inundation from the ocean was buffered by vegetation and, with vegetation, total inundation volume decreased from 4.79×10^8 to 1.65×10^8 m^3 and total inundation area dropped from 5.28×10^8 m^2 to 1.79×10^8 m^2 (Sheng and Zou 2017).

Strength of Evidence

High. Evidence for the relationship between mangrove-facilitated storm surge attenuation and flood height and extent reduction is well-documented in multiple types of peer-reviewed evidence types, including site-specific studies and review papers. While the evidence of a relationship between mangroves' ability to attenuate storm surges and thus reduce coastal flooding, as well as the effects of other factors, is consistent across the literature, evidence of the mechanisms behind this relationship are not fully explained or well-documented. The relationship between storm surge reduction and flood mitigation is implied as two processes that occur in sequence, but there are no current methods to generalize predictions of how much flood extents will change in response to storm surge attenuation by mangroves. Predictions of changes in flood height and extent can only be estimated using complex, site specific models. Despite this gap, much evidence exists of a strong relationship between mangrove-facilitated storm surge attenuation and flood height/extent reduction, and the two processes occur together. Methods used within the literature are well-documented and mostly accepted, except for some concerns are raised about the use of 2-D modeling and the Manning's coefficient not being able to capture the complexity of mangrove forests, but the data extracted from these 2-D models is verified using historical measurements and is consistent with other sources (Sheng and Zou 2017).

Other Factors

The extent to which mangroves can reduce flood height and area depends on spatial and temporal factors such as storm and mangrove forest characteristics (Dasgupta et al. 2019; Krauss et al. 2009; Liu et al. 2013; McIvor et al. 2012; Menéndez et al. 2020; Montgomery et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021; Spalding et al. 2914;). Beginning with storm characteristics, the capacity of mangroves to reduce storm surge and flood risk is dependent on the size, forward speed, and direction of the storm (Liu et al. 2013; McIvor et al. 2012; Menéndez et al. 2018; Montgomery et al. 2019; Spalding et al. 2014). Mangroves are more effective at reducing water levels and inundation of fast-moving, smaller, and weaker hurricanes than those of slow-moving, large, and strong hurricanes (Liu et al. 2012; McIvor et al; 2012; Spalding et al. 2014). Larger storms tend to generate higher water levels and greater flood areas, and shorter-period storms are unable to transport water through the forest as efficiently as longer-period storms (McIvor et al. 2012; Montgomery et al. 2019; Spalding et al. 2014). Liu et al. (2013) conducted a sensitivity analysis of mangroves' ability to mitigate coastal flooding in response to a variety of hurricane characteristics. It was found that the faster the forward speed of a storm, the greater percent reduction in flooded areas; a forward speed of 2.2 ms^{-1} reduced flooded areas by 27% and a speed of 11.2 ms^{-1} reduced flooded areas by 31.2%. Hurricane approach angle also impacts flood extent because it determines the distance a hurricane travels over mangrove forest area. Approach angles that allow storms to travel further over mangroves decrease flood extent (Liu et al. 2013). With climate change, the intensity and frequency of large storm events are likely to increase and thus the role of mangroves in attenuating storm surge and reducing coastal flooding may change, especially as extreme events may exceed the natural tolerance and capacity of mangroves to attenuate storm surge and mitigate floods (Gijsman et al. 2021; Menéndez et al. 2020).

Differing mangrove forest characteristics may also impact storm surge attenuation and flood extent (Dasgupta et al. 2019; McIvor et al. 2012; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021; Spalding et al. 2014). During storm events, mangroves can attenuate storm surge and thus reduce flood height and extent because of the matrix of mangrove tree roots, trunks, and leaves that obstruct the flow of water through the forest and create bed resistance (Dasgupta et al. 2019; Menéndez et al. 2018; Torres-Ortega et al. 2019; Spalding et al. 2014). This process is then dependent on the existence of a dense mangrove forest made up of species with aerial roots and dense canopies that have greater effects on reducing waves and flooding (Dasgupta et al. 2019; McIvor et al. 2012; Menéndez et al. 2018; Torres-Ortega et al. 2019; Spalding et al. 2014). Further, the width of a mangrove forest is important in reducing coastal flooding, as peak water level decays more rapidly in wider forests than in narrower forests, which can be attributed to additional water storage within the vegetation and the associated water flux through the vegetation (McIvor et al. 2012; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Soanes et al. 2021; Spalding et al. 2014). Increasing the area of mangrove forests can lead to more drag on incoming waves and storm surges, thus reducing the flooding that these waves and surges may cause inland (Torres-Ortega et al. 2019). A 3-D numerical model of storm surges based on the coupled Curvilinear-Hydrodynamics 3D–Simulating Waves Nearshore (CH3D–SWAN) model found that increases in height, density, and/ or width of a vegetative area results in a reduction in inundation volume (McIvor et al. 2012).

Predictability

The literature is consistent in identifying a correlation between mangroves' ability to attenuate storm surge and reduced coastal flooding height and extent in low-lying coastal areas. Other factors such as the characteristics of the storm (e.g., forward moving speed, size, and direction) and characteristics of the mangrove forest (e.g., density, species, width of forest) may affect the magnitude by which mangroves can reduce coastal flooding and extent. However, the literature suggests that the relationship between mangrove-facilitated storm surge attenuation and flood mitigation exists regardless of these factors, just at a potentially lesser extent.

It is difficult to generalize the relationship between mangroves' ability to attenuate storm surge and the amount of resulting flood reduction. Studies use predictive models to calculate specific flood reductions resulting from a particular mangrove forest. Several models were identified in the literature that can be used to predict the extent of this relationship in certain contexts. Numerical surge-wave models that incorporate flow-wave-vegetation interactions can be used to assess contribution of various other factors (e.g., local coastal geographic features, storm characteristics, and vegetation characteristics) to the reduction of surge, wave, and inundation by vegetation. With these models, the Manning's coefficient, a function of vegetation and flow, can be locally adjusted to represent mangroves in a specific location. However, this can be time-dependent and spatially varying because the models only use a constant bottom-friction coefficient. Some of these models include the CEST model; Sea, Lake, and Overland Surge from Hurricane model; Finite-Volume Coastal Ocean Model, and Advanced Circulation model. Vegetation-resolving 3-D numerical models, such as CH3D–SWAN, explicitly represent vegetation effects without needing to readjust the Manning's coefficient, and may be better able to model the vegetation-related physical processes without excessive tuning (Sheng and Zou 2017).

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LINK 28: WILDLIFE POPULATIONS → FISH AND SHELLFISH HARVEST

Description of Relationship

Mangroves are widely recognized for their role in enhancing both small-scale and commercial fish and shellfish harvest by supporting wildlife populations through the provision of food, habitat, and thus, nursery functions (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b). Numerous studies have documented greater abundances of juveniles of harvested fish and shellfish species in mangroves than in other estuarine and inshore habitats in various places around the world, as well as correlations between the extent of mangroves and catch in nearby fisheries (Aburto-Oropreza et al. 2008; Barbier and Strand, 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b). While there is strong evidence of a correlation between mangrove habitats and fish and shellfish harvest, causation cannot be concluded (Carrasquilla-Henao and Juanes 2016; Manson et al. 2005a, b). Factors contributing to this link include environmental factors that affect the potential fishable biomass, human impact drivers that affect the actual fishable biomass, and socioeconomic drivers that affect actual harvest (Barbier and Strand 1998; Hutchison et al. 2014; Manson et al. 2005b).

Summary of Evidence

Mangrove forests support a diversity of marine animals (see Links 5 and 13). It is widely held that mangroves are therefore critical for sustaining production in coastal fisheries through their role as important habitats, resource providers, and nursery areas for marine animals, including fish and shellfish (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b). Mangroves support fisheries that vary in scale, fishing methods, and target species. This includes fisheries within the mangroves themselves that focus on mangrove-resident species such as crabs and mollusks, fisheries in mangrove channels and lagoons, and offshore fisheries for species such as penaeid prawns that use mangroves as a nursery but move out to the continental shelf as adults (Hutchison et al. 2014). Mangroves' support for fishing activity is based on the assumption that the area of mangrove habitat in an estuary translates to secondary production and fishery catch, and thus, mangrove habitat loss or degradation would lead to a reduction in, or total loss of fisheries production (Manson et al. 2005b).

Mangroves are believed to enhance fish and shellfish catch in two main ways: (1) the provision of food, and (2) the provision of shelter, including nursery habitat (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b Relatively few fishery species are mangrove residents for the entirety of their life cycles. Rather, most are transient visitors that use mangrove forests for part of their life cycle, often during their juvenile development stage. This means that mangroves are a nursery ground for many commercially important species (Hutchison et al. 2014; Manson et al. 2005b). Species of interest to the fisheries sector are found at all levels of the food chain in mangroves. This includes detritivores such as mangrove crabs, prawns, and mullet; filter feeding bivalves; planktivorous fish such as herring and anchovy species; and consumers at higher trophic levels such as some mud crabs and many other fish, including snappers and groupers. Thus, fisheries in offshore habitats benefit from stock replacement from mangroves (Hutchison et al. 2014).

Because mangroves are so critical for sustaining production in coastal fisheries, the success of recruitment—animals that enter an adult population and subsequently reproduce—depends on accessibility of mangrove habitat (Manson et al. 2005b). Several studies have documented this by showing either greater abundances of juveniles of harvested fish and shellfish species in mangroves than in other estuarine and inshore habitats in various places around the world, or through correlations between the extent of mangroves and the catch in nearby fisheries (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b).

Mangroves may confer advantages in the growth and survival of juveniles of some species, as compared to other coastal habitats, which in turn would enhance recruitment of adult species and could then increase fish and shellfish harvest. Studies that compare fish abundance in areas adjacent to mangroves to areas without mangroves give an indication of the value of mangroves in affecting fish and shellfish harvest. These studies demonstrate what may happen to faunal communities and fisheries if mangroves are lost: these changes have potential to cause cascading effects at higher trophic levels, with possible consequences for fisheries production for species linked to mangrove habitats. Studies have shown that the biomass of adults of several commercial species were higher where mangroves were adjacent to the adults found in coral reef habitats, as opposed to sites where no mangroves to serve as nursery habitats were nearby many of these species were absent or present at low densities. This correlation has been documented for the rainbow parrotfish *Scarus guacamaia*, which has a high dependency on mangrove habitats and was fished commercially in Belize until the late 1970s. On one reef where all the adjacent mangroves had been cleared in the 1960s, *S. guacamaia* became extinct, whereas on other mangrove-rich reefs they survived at low densities despite heavy fishing (Manson et al. 2005b).

Other studies have also recognized mangroves' ability to support wildlife populations as essential inputs to fisheries globally. In Campeche State, Mexico, mangrove areas were estimated to account for one-third of all Gulf finfish production and one-half of all shrimp production (Barbier and Strand 1998). Although several coastal ecological factors determine the biological productivity of the Gulf fisheries accessed in Campeche, the most important production mechanisms underlying these fisheries was found to be the combination of estuaries and lagoons with coastal mangrove vegetation, which provide the ideal habitat as breeding grounds and nurseries. Similarly, modeling in this study suggested that decline in the mangrove area here would have a proportionate impact on output in the Campeche shrimp fishery (Barbier and Strand 1998).

It has also been estimated that two-thirds of the world's harvest of fish and shellfish are directly linked to estuarine mangrove habitat. Proportions of mangrove-related species in fisheries around the world include 80% in Florida, 60% in Fiji and India, and nearly 100% for prawn catch in Southeast Asian countries (Hutchison et al. 2014; Manson et al. 2005b). In Queensland, Australia, a study used modeling to demonstrate that for mangrove-related species (banana prawns, mud crabs, and barramundi), mangrove area accounted for most of the variation in coastal fisheries production, suggesting a strong, positive correlation between mangrove area and catch (Manson et al. 2005a). In the Gulf of California, fisheries landings are positively related to the local abundance of mangroves and, in particular, to the productive area in mangrove–water fringe that is used as a nursery and/or feeding grounds by many commercial species. Mangrove-related fish and crab species account for 32% of the small-scale fisheries catch in this region, but this is believed to be an undervaluation (Aburto-Oropreza et al. 2008).

A meta-analysis of the mangrove-fisheries linkage at a global level systematically reviewed 23 publications containing 51 studies and found strong evidence for the mangrove-fishery linkage and that mangrove area was a good predictor of fishery catch overall (Carrasquilla-Henao and Juanes 2016). Despite the evidence in favor of a linkage between mangrove supported fish and shellfish harvest, one of the major criticisms of this evidence is that correlation does not imply causation, and more data is needed to establish a causal relationship. (Carrasquilla-Henao and Juanes 2016; Manson et al. 2005a, b).

Strength of Evidence

High. Evidence for the relationship between mangrove-supported wildlife populations and fish and shellfish harvest is well-documented in many types of peer-reviewed scientific literature, including review papers and meta-analyses. This relationship has been observed and documented in a variety of geographic locations, including the Gulf of Mexico and Caribbean. Evidence was very consistent that there is a strong correlation between mangroves' ability to support wildlife populations and thus fish and shellfish harvest. Studies identified similar relationships between mangrove food and habitat provision that increase fish production and recruitment, which can be harvested if demand exists, to explain this relationship. This relationship has been primarily documented in studies that found greater abundances of juveniles of harvested fish and shellfish species in mangroves than in other estuarine and inshore habitats and through correlations between the extent of mangroves and the catch in nearby fisheries. The literature suggests that the mechanisms behind a mangrove-fishery linkage are generalizable and would suggest an applicable link, but there is a lack of causal evidence that the literature notes is a barrier to establishing a causal linkage between mangrove-supported wildlife populations and fish and shellfish harvest. Measuring the exact relationship has proved difficult.

Other Factors

The external factors affecting the relationship between mangroves' support of wildlife population and fish and shellfish catch can be grouped into three categories: (1) environmental factors that affect the potential fishable biomass, (2) human impact drivers that affect the actual fishable biomass, and (3) socioeconomic drivers that affect actual harvest (Barbier and Strand 1998; Hutchison et al. 2014; Manson et al. 2005b). Potential fishable biomass stems from the productivity and availability of fish, which is strongly linked to the area of mangroves, characteristics of the mangrove forest, and the services they can provide to wildlife populations (Hutchison et al. 2014). This is influenced by factors such as mangrove productivity and biomass, nutrient input, freshwater input, complexity of mangrove area, length of margin or area of mangrove forest, climate, ecological setting, and biogeographical setting (Hutchison et al. 2014; Manson et al. 2005b). On a species level, the level of a particular species' dependency on mangrove habitat and thus the impact of a mangrove-fishery linkage varies depending on the species of interest, the life history of the species, and the proportion of the life history spent in the mangroves (Manson et al. 2005b).

Actual fishable biomass refers to the direct and indirect effect of humans on mangrove-associated fish stocks through harvesting fish or altering the environment (Hutchison et al. 2014). Overfishing can greatly reduce fish productivity and potential future fish and shellfish harvest: as long as harvest effort levels continue to rise, harvests will fall even if mangrove areas are fully protected (Barbier and Strand 1998; Hutchison et al. 2014). Science-based fishery policies that protect from overfishing (and are enforced) will influence the level of actual fishable biomass. Similarly, impacts to mangroves from degradation and clearance directly impact primary productivity within the mangrove area, influencing fish production and potentially reducing harvest. Other human-impact drivers that affect the actual fishable biomass include mangrove condition, water condition, fishery impacts, and mangrove conservation (Hutchison et al. 2014).

Lastly, fished biomass refers to the demand-driven amount of fish and shellfish actually being harvested. That demand can be understood and modeled in relation to coastal population sizes, the influence of markets, of economic drivers, and cultural traditions (Hutchison et al. 2014). Other socioeconomic drivers of mangrove fishery harvest include proximity to people, economic conditions, cultural conditions, alternative livelihoods, and fisheries management.

Predictability

The literature is consistent in identifying a correlation between mangrove-supported wildlife populations and fish and shellfish harvest. There is an abundance of evidence documenting greater abundances of juveniles of harvested fish and shellfish species in mangroves than in other estuarine and inshore habitats in various places around the world, as well as correlations between the extent of mangroves and the catch in nearby fisheries (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b). Studies have found 30- nearly 100% of species in various fisheries are mangrove-related (Hutchison et al. 2014). The evidence also suggests that the generalizable role of mangroves in the provision of food, habitat, and thus, nursery functions provides direct and indirect support to harvest of fish and shellfish (Aburto-Oropreza et al. 2008; Barbier and Strand 1998; Carrasquilla-Henao and Juanes 2016; Hutchison et al. 2014; Manson et al. 2005a, b). Some studies were able to apply modeling to predict this relationship (Barbier and Strand 1998; Hutchison et al. 2014; Manson et al. 2005a). The combination of this evidence and the influence of external factors supports that when demand exists for harvest of mangrove-dependent species of fish and shellfish (either during some or all of their lifecycle or as food sources), mangroves' support for wildlife species enhances harvest.

While existing studies indicate a strong correlation between mangroves and fish and shellfish harvest, studies also indicate there is inadequate data to establish a causal relationship (Carrasquilla-Henao and Juanes 2016; Manson et al. 2005a, b). If adequate data are available and are used in conjunction with an understanding of the processes linking coastal habitats to fish populations, it should be possible to predict changes to fisheries catch when changes in mangroves occur. Further, since different species respond in different ways to changes in mangrove structure and function, it is clear that species need to be investigated individually (Manson et al. 2005b).

Local Context

According to research done through surveys near Jobos Bay, fishers who report engaging in spearfishing and snorkeling around mangrove roots indicate that when damage to roots occurs after storms it changes the manner in which they fish, as well as the fish they are able to find. Accessibility to these fishing opportunities changes after a large storm. Mangrove damage has also changed shore-based fishing activity—when mangroves die and fall over at shoreline edges, it changes the way people are able to fish at these sites (Jessica Tipton, personal communication).

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LINK 29: WILDLIFE POPULATIONS → RECREATION

Description of Relationship

Mangroves are ecologically important sites for a variety of wildlife, including a diversity of bird, mammal, fish, and reptile species (Canestri and Ruiz 1973). For this reason, among many others, mangrove forests are attractive sites for recreation for both locals and tourists (Ahmad 2009; Canestri and Ruiz 1973; Hakim et al. 2017; Jusoff and bin Hj. Taha 2009; Spalding and Parrett 2019). Wildlife-centered recreation in mangrove areas includes birdwatching, sport or recreational fishing, wildlife observation, boating, photography, and hiking (Ahmad 2009; Carvache-Franco et al. 2020; Hakim et al. 2017; Jusoff and bin Hj. Taha 2009; Marasinghe et al. 2021; Spalding and Parrett 2019). There is evidence that wildlife populations may increase recreation in mangrove areas. There is also interest in understanding whether there was also evidence for the reverse of this relationship: how recreation in mangrove areas might negatively affect wildlife populations. However, there is very limited evidence discussing how unsustainable recreation and tourism in mangrove areas might degrade or pollute mangrove systems, which could affect their ability to support wildlife populations (Hakim et al. 2017; Marasinghe et al. 2021; Spalding and Parrett 2019).

Summary of Evidence

Mangroves support a wide diversity of wildlife due to their productivity and structural complexity, acting as nursery grounds for many fish species, providing refuge to a variety of birds, and housing a diversity of mammals and reptiles (see Links 5 and 13). The concentration of these species in mangrove forests provides an idyllic space for wildlife-centered recreation including birdwatching, photography, sport or recreational fishing, wildlife observation, boating or canoeing, and hiking (Ahmad 2009; Carvache-Franco et al. 2020; Hakim et al. 2017; Jusoff and bin Hj. Taha 2009; Marasinghe et al. 2021; Spalding and Parrett 2019).

There is a growing general preference by people to observe natural areas, which has led to increases in visitation to and recreating in nature-based destinations around the world (Hakim et al. 2017; Marasinghe et al. 2021). For example, in Sri Lanka, more than 2.7 million international tourists visited wildlife tourism destinations; approximately 173,000 of those tourists visited coastal wetlands and marine parks (Marasinghe et al. 2021). Mangroves are also popular for tourism/recreation among local communities, especially in locations where international tourism is limited, such as in Iran and Bangladesh (Ahmad 2009; Hakim et al. 2017; Spalding and Parrett 2019).

Many studies have discussed wildlife-centered recreation as a feature and benefit of mangrove areas. The mangrove forest of Larut Matang, on the northern coast of the Parak State of Malaysia, is a well-known location for birdwatching, with a rich habitat for migratory and local forest birds that supports more than 58 species (Ahmad 2009. One study found that in this mangrove area, fishing is the most popular recreational activity (52.1% of sample) (Ahmad 2017). In this same area, 9.3% of those sampled participated in wildlife observation from the presence of birds and other terrestrial animals that depend on the mangrove forest (Ahmad 2017). A study in East Java demonstrated the use of mangrove areas as nature-based tourism and recreation sites. That study notes that the significance of the biological, ecosystem service, and aesthetic appeals of mangrove ecosystems in the context of tourism/recreation is not fully understood or appreciated, but mangroves have unique bio-ecological features that make them great sites for ecotourism and recreational use (Hakim et al. 2017).

A global analysis of mangroves as sites for wildlife-based recreation and tourism found that the scale and geographic extent of mangrove tourism and recreation includes almost 4,000 attractions in 93 countries, with two-thirds of attractions found in the Americas and Caribbean. The largest number of wildlife-based mangrove recreation attractions in the study are in North America, dominated by the United States (largely Florida). The most widespread recreational activity recorded in the analysis was boating, which includes canoeing and kayaking, and was often centered around wildlife watching. Other popular activities recorded included birdwatching and fishing. Wildlife recreation attractions in mangrove areas globally included observations of species including alligators and crocodiles, birdlife, bioluminescence, fireflies, manatees and dugongs, and monkeys. This analysis also found that it is likely that global mangrove recreation and tourism attracts tens to hundreds of millions of visitors annually, and the most popular individual sites may attract hundreds of thousands of visitors per year (Spalding and Parrett 2019).

There is evidence that wildlife populations contribute to recreation in mangrove areas, but evidence for the reverse relationship—how recreation activities affect wildlife populations—is very limited. There are mentions in the literature that unsustainable recreation and tourism in mangrove areas can degrade or pollute mangrove systems, which in turn could have negative effects on the wildlife that live there (Hakim et al. 2017; Marasinghe et al. 2021; Spalding and Parrett 2019). The loss or degradation of mangroves can lead to loss of biodiversity and the loss of a wide ecological niche for feeding, breeding, and hatching of fish and marine creatures, as well as migratory species (Hakim et al. 2017). This may have a negative impact on mangrove wildlife-centered recreation, but this link was not made directly in the literature. In East Java, it was found that recreation and tourism led to evidence of mangrove disturbance because visitors vandalized mangrove sites and left trash in the mangrove environments (Hakim et al. 2017). However, the review conducted by Spalding and Parrett (2019) found that unlike tourism impacts associated with other ecosystems such as coral reefs, mangrove visitation appears to have minimal impact, aside from some locations reporting potentially unsustainable activities such as over-fishing.

Strength of Evidence

Moderate. Evidence for a relationship between wildlife and recreation in mangrove areas is well-documented and consistent within peer-reviewed scientific literature, but lacks causal linkages. The evidence included information from a variety of geographic locations, with most evidence being concentrated in South and Southeast Asia, including a global review paper. The literature was consistent in identifying the types of recreation centered around wildlife observation in mangrove forests. While the literature indicates a relationship between wildlife and recreation in mangrove areas, the relationship is not necessarily causal and there may be some uncertainty in deciphering if wildlife is a cause of some recreation activities, or just a benefit observed by tourists and recreationists. Some popular recreation activities (e.g., birdwatching, fishing) are directly related to wildlife populations and are casually related so that if wildlife populations were to decrease or increase, the amount of recreation could reasonably be assumed to increase or decrease. However, for many of the recreation activities that occur in mangrove areas (e.g., hiking, canoeing, photography), it is unclear from the literature if the existence of wildlife is a driver of recreation activities, or if wildlife presence and observation is simply a nice feature of recreation within mangrove areas but does not directly drive the occurrence of those activities. Within current literature, it is also unclear to what extent wildlife presence affects recreation, i.e., how much could wildlife decrease before recreation is negatively affected. The literature on the reverse relationship—effect of recreation activities on wildlife in mangroves—was generally inconsistent and uncertain.

Other Factors

The relationship between mangrove-supported wildlife and successful recreation may be affected by factors such as mangrove site accessibility, local community involvement, the quality of mangrove ecosystems, and the availability of mangrove tourism and recreation programs (Ahmad 2009; Hakim et al. 2017). The dense vegetation and root structure and muddy environment of mangroves may be a barrier for visitors exploring and recreating in mangroves (Hakim et al. 2017). Policies that conserve and protect mangroves have been found to benefit recreation activities because they promote biodiverse natural systems that people recreate in more frequently (Ahmad 2009).

Predictability

The literature is consistent in identifying the link between mangrove wildlife and recreation.

However, Spalding and Parrett (2019) explicitly note that it is difficult to establish a direct link between mangrove wildlife populations and some forms of recreation that occur in mangrove areas. The relative importance of mangroves and associated wildlife in relation to other features of interest varies considerably between attractions. There are many locations where mangroves are known to be the sole or core attraction, so it is likely that mangroves are attracting tens to hundreds of millions of visits per year worldwide. However, it is unclear whether the wildlife supported by mangroves are also a driver of recreationists and tourists for recreation activities that do not directly involve wildlife (e.g., boating, hiking, photography). For example, Everglades National Park typically hosts one million visitors per year, but includes many habitats and a broad range of activities, so it is not possible with current data to know the role of mangroves and wildlife in driving such numbers (Spalding and Parrett 2019). While mangroves or the wildlife they support may not be a primary driver for destination and recreation, they offer a popular attraction that can influence destination choice and recreational activities, and their popularity appears to be growing (Marasinghe et al. 2021; Spalding and Parrett 2019).

The effects of recreation on wildlife are also uncertain and have low predictability because they are understudied. There is some conflicting information about whether tourism and recreation pose negative effects to mangroves and the wildlife they support (Hakim et al. 2017; Marasinghe et al. 2021; Spalding and Parrett 2019). It may be reasonably inferred, however, that if tourism and recreation occur at unsustainable levels and severely degrade mangrove systems, those systems may be unable to support the wildlife that attracts recreationists, therefore negatively impacting the amount of recreation occurring in a particular mangrove area. However, this relationship is inferred and is not directly documented in any sources.

Local Context

Kayak tour operators near Rookery Bay report that mangrove habitat for wildlife is essential to their business. People attending tours say they expect to see wildlife.

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LINK 31: WILDLIFE POPULATIONS → THREATENED AND ENDANGERED SPECIES PERSISTENCE

Description of Relationship

Mangrove forests play a crucial role in providing habitat to a wide variety of flora and fauna as a result of their complex vegetation structures and sheltered habitats that are rich in food resources and offer safe foraging and breeding grounds. Mangrove habitats host a variety of threatened and endangered species, and the characteristics of mangrove forest ecosystems, such as through facilitating high levels of biodiversity that may have cascading trophic impacts on endangered species, may help these species persist. While little causal evidence exists for this relationship, the literature suggests that the loss of mangrove habitat area and the resources they provide may result in an elevated risk of extinction for a variety of mangrove-dependent species.

Summary of Evidence

Mangroves are ecologically important to a variety of flora and fauna because their structural complexity and productivity creates ideal foraging, nursery, nesting, and refuge grounds (see Links 5 and 13). Some of these species are threatened or endangered, and the habitat and resources provided by mangrove forests may help them persist. Similarly, the loss of mangrove habitat or degradation of their provisional services may result in threat of extinction for the vast biodiversity of mangrove-dependent species (Gopal and Chauhan 2006; Holguin et al. 2006; Kathiresan 2010; Polidoro et al. 2010).

Much of the research related to this link is concentrated in the Sundarbans Mangrove Ecosystem, shared between Bangladesh and India and comprising the world's largest contiguous coastal wetland. The biodiversity of the Sundarbans includes about 350 species of vascular plants, 250 fishes, and 300 birds, as well as numerous species of phytoplankton, fungi, bacteria, zooplankton, benthic invertebrates, mollusks, reptiles, amphibians, and mammals, many of which are threatened and endangered (Gopal and Chauhan 2006). These threatened and endangered species include 17 flora species; 10 reptile species, including six species of nearly extinct or threatened tortoise and turtle species and three species of endangered lizards and monitors; three bird species, including the rare grey-headed fish eagle and Pallas's fish eagle; and eight mammal species (Gopal and Chauhan 2006). Similarly, preliminary data in the Bangladeshi Sundarbans indicates a relatively high density of the endangered wild tiger (*Panthera tigris*) as compared to alluvial floodplains in the Terai region of Nepal, thus suggesting the forest has a high value for the conservation of the Sundarbans tiger population. This high density is attributed to the large amount of prey biomass available in the Sundarbans mangrove ecosystem (Barlow et al. 2011). While the literature does not directly address the relationship between mangrove wildlife populations and threatened and endangered species persistence, it does note that any negative impacts on mangrove forests (e.g., unsustainable human activity, climate change, sea level rise) will affect the biotic composition of mangrove forests through both direct effects and indirectly through food chain modifications caused by changing amounts of detritus available in mangrove ecosystems (Gopal and Chauhan 2006; Kathiresan 2010). That is, any impacts on mangroves and the species that inhabit them may have direct or indirect impacts that interfere with the persistence of threatened and endangered species.

In the US Virgin Islands, a study focused on the effects of Hurricanes Irma and Maria on mangrove-dependent species after the hurricanes uprooted red mangrove trees and stripped their prop roots of attached marine life, some of which are listed as threatened under the US Endangered Species Act. Prior to the storms, the mangroves supported diverse prop root communities with a variety of sponges, tunicates, anemones, and seaweeds, as well as numerous fish, including snappers, grunts, and angelfish. Following the two hurricanes, there was extensive impact to the prop root communities, reduced abundance of fish species, and loss of shade from mangrove trees in the mangrove-adjacent waters. Recovery of this ecosystem and its associated species depends on red mangrove propagules re-establishing and producing prop roots to support rich marine life, along with a reestablished mangrove canopy to provide the shade that was critical to the biodiversity present before the storms. Recovery of this ecosystem will allow for the restoration of four threatened coral species and support the endangered hawksbill sea turtles through the return of sponges, a key component of their diet (Rogers 2019).

Other studies identify individual threatened and endangered species that depend on mangrove habitats, and thus may be affected by ecosystem degradation or indirect effects of changes in wildlife populations. The endangered Illidge's ant-blue butterfly (*Acrodipsas illidgei*) inhabits mangrove forests in southeastern Queensland, Australia (Breitfuss and Dale 2004). The goliath grouper (*Epinephelus itajara*) is a mangrove-dependent reef fish critically endangered throughout its distribution area of tropical and subtropical eastern and western Atlantic Ocean (Frias-Torres and Luo 2009). A US distinct population segment of smalltooth sawfish (*Pritis pectinata*) is listed as endangered under the US Endangered Species Act, and is dependent on critical mangrove nursery habitats in the Charlotte Harbor Estuary and Ten Thousand Islands/Everglades of Southwest Florida (Norton et al. 2011). In northeastern Brazil, endangered Antillean manatees showed a positive relationship with mangrove estuaries, and manatee density was significantly higher in marine protected areas with preserved mangrove estuaries than in nonprotected areas (Alves et al. 2013).

While these studies do not directly address the link between mangrove wildlife populations and threatened and endangered species persistence, mangroves are considered critical threatened and endangered species habitats. The loss or degradation of mangroves, and their associated wildlife, would therefore likely produce negative effects. If special management and conservation needs are not addressed, the functional elimination of mangrove habitat and nurseries through habitat destruction could push populations to a tipping point where suitable habitat and nursery areas become a population recovery limiting factor (Norton et al. 2011). Similarly, by supporting individuals of these threatened and endangered species, mangrove forests help to sustain genetic diversity within their populations that will aid in the ability for species to adapt to changes in the ecosystem and persist.

Strength of Evidence

Moderate. While the literature consistently identifies the relationship between mangrove habitat, the resources they provide, and their associated biodiversity with threatened and endangered species persistence, the relationship is not specific. Even though the literature does not directly address the relationship between mangrove wildlife populations and threatened and endangered species persistence, it does note that any negative impacts on mangrove forests will affect the biotic composition of mangrove forests through both direct or indirect impacts that interfere with the persistence of threatened and endangered species. This relationship is therefore more general and cannot be extrapolated to predict responses to changes in specific wildlife populations on specific threatened or endangered species in mangrove forests. Evidence for this relationship is found in peer-reviewed scientific literature of site-specific studies, but not review papers or meta-analyses, and was concentrated in Southeast Asia.

Other Factors

The relationship between mangrove-associated wildlife and threatened and endangered species persistence may generally be affected by any loss or degradation of the mangrove habitat. Disturbances such as human exploitation of forests, mangrove forest clearing, altered freshwater flows into mangrove forests, climate change, and sea level rise may reduce mangrove habitat, altering the biotic composition of the ecosystem and reducing the persistence of threatened and endangered species (Gopal and Chauhan 2006; Holguin et al. 2006; Kathiresan 2010; Polidoro et al. 2010). Each individual species and population is unique and will therefore react differently to changes in wildlife populations. Studies specific to each species of interest are required to determine the impacts of changes in mangrove-associated wildlife on that species' persistence.

Predictability

While the literature does not indicate any models or tools to predict this relationship, the general relationship between mangrove-associated wildlife populations and threatened and endangered species persistence is present in the literature. However, since each individual species and population is unique and will react differently to changes in wildlife populations, predictability is low for this link. Models can be built for individual species to predict both their population size and distribution given changes in habitat availability, but no generalized predictions can be made.

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LINK 32: SHORELINE CHANGE → PROPERTY PROTECTION

Description of Relationship

The influence mangroves have on shoreline change can allow them to act as a natural barrier to protect coastal property and infrastructure against hazards such as extreme weather events, erosion from waves and tides, and sea level rise. Mangroves have the ability to modify coastlines through the attenuation of waves and their erosive effects, capturing sediments, and building soils through accretion (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; Narayan et al. 2019; Spalding et al. 2014; UNEP 2014). While the mechanisms behind these mangrove-facilitated processes and how they relate to shoreline change are well-documented, there is little evidence on the specific effects and extent to which they can affect property protection from coastal hazards. The relationship between mangrove-affected shoreline change and property protection is not well-documented, but it is highly dependent on both the location of property relative to mangroves and to the coast and climate change (Dunn et al. 2000; Gracia et al. 2008; McIvor et al. 2013; Spalding et al. 2014).

Summary of Evidence

One of the many ecosystem services provided by mangroves is the ability to protect shorelines against coastal risks such as wave damage and erosion, large storms, and sea level rise (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; Narayan et al. 2019; Spalding et al. 2014; UNEP 2014). Mangroves are able to provide this protection because of their ability to influence shoreline change through (1) reducing erosion caused by wave action and tides and (2) enhancing accretion by trapping sediments (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; McIvor et al. 2012, 2013; Narayan et al. 2016; Spalding et al. 2014; UNEP 2014). This protection afforded by mangroves' influence on shoreline change may apply to property and infrastructure in the coastal zone, as mangroves are often the first line of defense for coastal communities, but direct evidence of this relationship is limited (Bell and Lovelock 2013; Narayan et al. 2019). Further, if mangrove-facilitated coastal protection through reduced erosion and increased accretion can apply to property, this ability would be highly dependent on the location of property relative to mangroves and to the coast as well as climate change (Dunn et al. 2000; Gracia et al. 2008; McIvor et al. 2013; Spalding et al. 2014).

Wave attenuation as facilitated by mangroves' vegetative structures can decrease the incoming flow of water's ability to erode the coastline. If not prevented, erosion can cause the shoreline to retreat inland, damaging nearby coastal property by allowing waves, erosion, and storm effects to reach further inland (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; McIvor et al. 2012; Narayan et al. 2016; Spalding et al. 2014; UNEP 2014). Similarly, the attenuation of waves by mangrove forests leads to accretion by encouraging sediment deposition in mangrove forests and on the coastline (Bell and Lovelock 2013; Gracia et al. 2018; McIvor et al. 2013; Spalding et al. 2014; Temmerman et al. 2013; UNEP 2014). By actively building up the shoreline surface as ecosystem engineers, mangroves may be able to keep pace with sea level rise and prevent the retreat of the shoreline inland, potentially averting the associated property risks (Bell and Lovelock 2013; Borsje et al. 2011; Gracia et al. 2018; McIvor et al. 2013; Narayan et al. 2019; Spalding et al. 2014; Temmerman et al. 2013; UNEP 2014).

Mangroves providing protection benefits to the shoreline as a result of their effects on shoreline change have been documented across a wide variety of geographic locations, but without making direct links to or quantifying the effects of property protection specifically. In Guyana, the Gulf of Thailand, and Java, where mangrove forests have been destroyed for development of aquaculture and agriculture, coastal erosion has increased significantly, reaching rates of up to –3 m per year, and posing threats to property protection (Gracia et al. 2018). The loss of land to coastal erosion not prevented by mangroves may affect local economies by damaging infrastructure built for protection from coastal hazards such as flooding, storm surges and waves, and tsunamis (Gilman et al. 2008). In Surat Thani Province, Thailand, the value of 20 years of mangrove protection and stabilization services was found to be US$12,263 ha^{-1} (Barbier 2016). Similarly, erosion control from mangroves is estimated to have a value of US$3679 ha^{-1} yr^{-1} in Thailand and US$693 ha^{-1} yr^{-1} in the Sinú River deltaic system of Colombia (Sánchez-Núñez et al. 2019). While these economic valuations demonstrate an importance of mangrove services, it is not specified if the values used mangrove-facilitated property protection in their calculations.

Strength of Evidence

Fair. The literature is consistent in identifying the mechanisms through which mangroves can influence shoreline change (i.e., wave attenuation, reduced erosion, and increased accretion), but evidence that points to whether that influence on shoreline change actually influences property protection is very limited across a variety of evidence types, including peer-reviewed review papers, meta-analyses, and technical reports. Further, no specific evidence was found on what the magnitude or extent of mangroves' effect on shoreline change is on property protection, as studies focus on quantifying effects of mangrove-facilitated coastal protection or reduced erosion in general. If mangrove-facilitated shoreline change and protection is to translate into actual property protection, the relationship will be highly dependent on both the location of property relative to mangroves and to the coast and the effects of climate change, making the generalizability of these findings low (Dunn et al. 2000; Gracia et al. 2008; McIvor et al. 2013; Spalding et al. 2014).

Other Factors

Property location relative to the coast and nearby mangrove forests as well as changing climatic conditions are major factors that can determine whether mangroves will be able to protect property from erosion-caused damage (Dunn et al. 2000; Gracia et al. 2008; McIvor et al. 2013; Spalding et al. 2014). Aside from these factors, mangrove forest characteristics such as tree density, forest width, diameter of vegetative structures, dominant species, sediment input, and hydrodynamics affect the extent to which mangroves can affect shoreline change. In theory, these factors could also influence the magnitude of property protection afforded through mangrove-facilitated shoreline change if such a relationship exists (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; Spalding et al. 2014; Temmerman et al. 2013; UNEP 2014).

Property and infrastructure would have to be located close enough to the coast and landward from coastal mangroves to reap any protective benefits from mangrove-facilitated shoreline change. The property must also be in a location where the property would be threatened by erosion were the mangroves not present. There has been a global increase in coastal development, and most of the world's megacities are located in the coastal zone, which may put more property at risk of coastal erosion (Gracia et al. 2008).

Climate change that influences wave patterns or sea level rise may also put properties that previously were not exposed to shoreline change risks at risk, and the presence of mangroves may be able to mitigate that risk (Dunn et al. 2000; Gracia et al. 2018; Spalding et al. 2014). Globally, sea levels are rising as a result of climate change. As sea levels rise, the impacts of waves, storm surges, and erosion will reach further inland, increasing rates of coastal property damages and losses (Dunn et al. 2000; Gracia et al. 2018; Spalding et al. 2014). Episodic erosive events like hurricanes, which are increasing in frequency and intensity with climate change, can drastically and rapidly increase shoreline retreat inland, posing further threats to property protection (Dunn et al. 2000). Under current climate change scenarios in areas with low coastlines, almost 30% of residences within 200m of the sea may be severely affected by erosion-related property losses over the next 50 years (Gracia et al. 2018). With increasing amounts and an increasing value of coastal property at risk of shoreline erosion, the presence of mangroves may be able to reduce the amount of damage done to these properties through their positive impacts on reducing erosion and increasing accretion.

Predictability

The literature is consistent in suggesting that mangroves provide effects on shoreline change through wave attenuation, erosion reduction, and encouragement of sediment accretion, which allows mangroves to protect shorelines from wave damage, erosion, and sea level rise (Barbier 2016; Bell and Lovelock 2013; Gracia et al. 2018; McIvor et al. 2012; Narayan et al. 2019; Spalding et al. 2014; Temmerman et al. 2013; UNEP 2014). The shoreline protection benefits mangroves provide are, however, not well-studied, documented, or quantified in terms of how they apply to property protection, and the protection provided is highly dependent on the specific geographic context of the mangroves relative to coastal property that may be affected by shoreline change. Trends in accelerated sea level rise and changes in wave/storm patterns resulting from climate change may be increasing the amount of properties vulnerable to shoreline erosion and retreat. The presence of mangroves may be able to mitigate that risk, but it is still highly dependent on local factors (Dunn et al. 2000; Gracia et al. 2018; Spalding et al. 2014). Studies have suggested that modeling, measurement, monitoring, and use of biological indicators may aid in determining if desired levels of risk reduction can be achieved by a certain mangrove forest in a certain area, but no specific models or tools were identified (Gracia et al. 2018; Spalding et al. 2014).

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LINK 33: FLOOD HEIGHT/EXTENT → LOCAL BUSINESSES

Description of Relationship

There is evidence that shows by reducing water levels and wave energy that causes coastal flooding, mangroves can mitigate flood-related damages to coastal property and infrastructure. While there is little existing evidence of this protective benefit of mangroves applying to local businesses, it is reasonable to assume that local businesses are also located within potential flood zones and may reap similar benefits to other infrastructure. The ability of local businesses to mitigate flood impacts and recover from potential damages is affected by several external factors, including characteristics of the local business, access to aid post-flood, and ability to prepare for the flood.

Summary of Evidence

The ability of mangroves to reduce flood height and extent in coastal areas, and thus reduce flood-related damages to coastal property and infrastructure is well-documented within the literature (see Link 34). Globally, mangroves reduce property damage from coastal flooding by US$65 billion per year, but the property protection value of mangroves varies across regions and countries as a result of differences in the location/density of coastal property, mangrove forest and storm characteristics, the impacts of climate change, and mangrove habitat loss or degradation (see Link 34). While not specified in the literature, this likely includes avoided damages of local businesses by flood events.

Flooding can have devastating impacts on businesses, especially on those who may be unprepared and vulnerable to the range of both direct and indirect impacts of floods (Sun et al. 2022; Wedawatta et al. 2014). In 2019, natural catastrophes, including flooding, were the third-largest business risks for small and midsize companies (Allianz 2019). The impacts of flooding on businesses include both direct and indirect impacts such as property damages, temporary business closures, travel difficulties, damaged or lost stock/equipment, loss of production or trade, supply chain issues, loss of electricity or water, staff unavailability, and physical and psychological impacts on owners and employees (Sun et al. 2022; Wedawatta et al. 2014). For example, flooding in Annapolis, Maryland, was seen to affect local economic activity by reducing consumer visits to the downtown area by up to 24% (Hino et al. 2019). These impacts may be fatal to some business; approximately 25% of small businesses never reopen following natural disasters (Davlasheridze and Geylani 2017).

By averting or reducing flooding, mangroves may be able to reduce these negative impacts on local businesses. A healthy and well-managed mangrove ecosystem can act as a buffer against flood hazards and reduces the exposure of local businesses, people, and productive assets to floods (Karanja and Saito 2018). The indirect benefits from averted flooding, such as avoided business interruption, are estimated from insurance claims to be 139% larger than direct damages to property (Allianz 2019). In the Tana Delta, Kenya, the net value of mangroves for flood reduction was estimated to be between US$238 and US$311 ha/yr. While these estimates do not account for loss only avoided in the business sector, this loss is included in the estimate (Karanja and Saito 2018).

Strength of Evidence

Fair. While there is strong evidence on the protective benefits of mangroves for property/ infrastructure and the impacts of floods on local business, there is very limited existing information about the link from mangroves to local business. Existing evidence comes from peer-reviewed scientific literature. Despite there being limited information about the direct link between mangrove-associated flood reduction and local business protection, there is strong evidence of the protective benefits of mangroves that can be reasonably extrapolated to local businesses.

Other Factors

Several other factors impact the relationship between mangrove-facilitated reduction in flood height/extent and impacts on local businesses. Evidence suggests that small and medium-sized businesses are most likely to be unprepared and vulnerable to the range of impacts from coastal flooding (Davlasheridze and Geylani 2017; Marshall et al. 2015; Sun et al. 2022; Wedawatta et al. 2014). This is typically because of their lack of preparation for flood events, inability to quickly adapt to extreme circumstances in the short term, and lack of resources following flood events (Davlasheridze and Geylani 2017; Sun et al. 2022). Similarly, women-owned, minority-owned, and veteran-owned businesses appear more likely to not survive a natural disaster, such as flood events. Businesses that are older, larger in size, with owners who had greater industry experience and/or prior experience navigating natural disasters are more likely to survive and recover from flood events (Marshall et al. 2015; Sun et al. 2022).

Access to aid, such as loans and insurance coverage, following a flood may also impact the ability of a business to recover (Davlasheridze and Geylani 2017; McNamara 2013; Sun et al. 2022). That said, insurance may be very costly or difficult for local businesses to obtain in areas with prevalent flood risk (McNamara 2013).

Early warning systems may also help local businesses reduce impacts of flooding (McNamara 2023; Sun et al. 2022). Following the devastating flash floods in Fiji in 2012, the local business community indicated that the failure of the government to provide early and widely broadcasted warnings of incoming floods reduced their ability to prepare (McNamara 2013).

Local factors such as susceptibility to natural disasters that cause flooding or local infrastructure may also impact flood impacts on local businesses and their ability to recover (McNamara 2023; Sun et al. 2022). Similarly, businesses in neighboring counties unaffected by floods, but that assist in recovery, could experience significant increases in the activity following disasters due to social networks and spatial relationships (Sun et al. 2022)

Predictability

Because there is limited information on this direct link, predictability based on evidence is low. However, since there is a strong relationship between mangrove-facilitated flood mitigation and protection of property located landward of mangroves in coastal areas, it can be reasonably assumed that local businesses could also be protected from flood impacts in and around mangrove areas. It is difficult to generalize a monetary value of these benefits because of differing local contexts in terms flood extent and what types of businesses are affected.

Local Context

While flooding of local businesses was the primary focus of workshop conversations, there were indications that storm effects to mangroves can indirectly affect local businesses in other ways. For example, in Jobos Bay, workshop participants discussed how local fishermen who run businesses could be impacted through changes to fish nursery habitat and thus local availability of fish. Similarly, local restaurants are affected if they exclusively contract with those local fishermen. Both reserves reported that mangrove degradation might negatively affect local artisanal honey businesses that rely on mangrove habitat to support their bees.

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LINK 34: FLOOD HEIGHT/EXTENT → PROPERTY PROTECTION (EROSION AND FLOODING)

Description of Relationship

Storm surges and associated flooding pose major threats to coastal property and infrastructure (McIvor et al. 2012). By reducing water levels and wave energy that cause coastal flooding, mangroves can reduce flood-related damages to coastal property and infrastructure (McIvor et al. 2012; Narayan et al. 2019; Torres-Ortega et al. 2019). Several case studies and economic valuations of the protective benefits against flooding by mangroves have demonstrated a strong relationship between mangroves' ability to mitigate flooding and property protection from storm and flood events in coastal areas. Factors such as climate change, habitat destruction, property location relative to mangroves and the coast, and characteristics of the storm and protective mangrove forest may influence the extent to which mangroves can protect property (Gijsman et al. 2021; McIvor et al. 2012; Menéndez et al. 2018, 2020; Narayan et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021).

Summary of Evidence

Coastal flood risks are increasing rapidly as a result of climate change, coastal development, population growth, and habitat loss (Gijsman et al. 2021; McIvor et al. 2012; Menéndez et al. 2020; Narayan et al. 2019). Global climate change is causing sea level rise, which can lead to the intensification and increased frequency of storms and hurricanes, therefore causing an increase in storm surges and coastal flooding and posing a threat to property and infrastructure in coastal areas (McIvor et al. 2012). In terms of property loss or damage, storm surges and their associated flooding may be the most destructive natural hazard of geophysical origin on the coast; it can cost billions to repair property damages from coastal flooding (McIvor et al. 2012, Narayan et al. 2019). States like Florida on the US Gulf Coast are particularly vulnerable to storm surges as a result of high frequency of hurricanes, subsidence, and rising sea levels (Narayan et al. 2019). Along with an increase in flood events, rapid coastal population growth and urbanization is also increasing vulnerability to and consequences of flood events as a result of increased property density and destruction of mangroves for development in some cases, especially in the tropics (Gijsman et al. 2021; Menéndez et al. 2020).

Mangroves can act as a first line of defense for coastal communities against flood events (Narayan et al. 2019). The vegetative structures of mangrove forests obstruct and slow the flow of water as storm surges move inland, reducing water levels, inundation, and thus storm surge and flood-related damages to infrastructure and property (McIvor et al. 2012; Narayan et al. 2019; Torres-Ortega et al. 2019). Following destructive storm events, studies have conducted evaluations of damages to property in sites with and without mangrove cover and have consistently found that mangrove presence reduced property damage costs (Akber et al. 2018; McIvor et al. 2012; Narayan et al. 2019). In Orissa, India, following a cyclone with a 9 m storm surge, average damage per house and other adverse effects was valued lowest (US$33.31) and coincided with the lowest level of inundation in a mangrove-protected village, compared to higher damage per house in a village protected by an embankment (US$153.74) and a village with no protection (US$44.02) (McIvor et al. 2012). Similarly, following Cyclone Sidr in Bangladesh, total quantifiable loss in property damage from the cyclone in a village sheltered by a mangrove forest was less than half the cost of total quantifiable loss in an unsheltered village . This study also found that on a scale from 1 to 11, from least to most damaged, the mean damage of houses following the cyclone was only 6.16 for the mangrove-protected area and 10.53 for the unprotected area (Akber et al. 2018).

Aside from determining the protective benefits of mangroves for property from historical case studies of coastal natural disasters, process-based numerical modeling that accounts for local variation in characteristics of storms, mangrove habitat, topography, and bathymetry, and sophisticated economic valuation methods, such as the avoided cost method, can quantify the extent to which mangroves protect property (Menéndez et al. 2018, 2020). Using these methods and property insurance information, Narayan et al. (2019) quantified the protective value of mangrove-flood reduction in Florida and found that mangroves in Collier County reduced annual flood risk by 25.5% to properties behind them, providing an average benefit of US$540 per hectare of mangroves per year across these properties. In response to Hurricane Irma, mangroves averted US$1.5 billion in storm damages statewide, and every hectare of mangroves with properties behind them provided an average of US$7500 in risk reduction benefits (Narayan et al. 2019). A modeling study in Jamaica found that damages to residential and industrial property would increase by more than US$32.6 million annually if current mangroves were lost, and one hectare of mangroves provides on average more than US$2500/yr of direct flood reduction benefits from tropical cyclones (Torres-Ortega et al. 2019). A similar evaluation in the Philippines found that without mangrove presence, flooding and damage to people, property, and infrastructure would increase annually by around 25%, and an additional 25.65% (76 km) of state and local roads would be affected by floods (Menéndez et al. 2018).

While property protection benefits may vary based on local conditions, Menéndez et al. (2020) estimated that mangroves reduce property damage globally by more than US$65 billion annually by protecting against floods. If current mangroves were lost, 9% more property would be damaged each year, which may be much higher in certain areas based on local conditions, and property losses caused by 100-year flood events would increase by US$270 billion. This study also found that the nations realizing the greatest economic benefits from mangrove flood mitigation property protection are the United States, China, India, and Mexico. These most-protected areas are typically more developed and principally benefit from mangroves based on the high value and density of coastal assets that are protected (Menéndez et al. 2020). The economic benefits provided from property protection due to mangrove-facilitated flood reduction are also typically greater than restoration costs, as benefits increase as more mangroves are restored and even small-scale mangrove restoration initiatives can help reduce the flood risk to homes and infrastructure up to 475 m inland (Beck et al. 2022; Gijsman et al. 2021; Menéndez et al. 2018; Narayan et al. 2019; Soanes et al. 2021).

Strength of Evidence

High. Evidence for the relationship between mangroves' ability to mitigate flood height and extent and property protection is well-documented and consistent within several types of peer-reviewed scientific literature and technical reports. The literature consistently recognizes a strong relationship between mangroves' reduction in flood height/extent and property protection across a variety of different conditions and geographic locations, including in the Gulf of Mexico and Caribbean, and also consistently places a high value on their protective abilities. Consistent findings across a variety of settings within the literature suggests that there is a high applicability for this relationship. Even though some other factors that influence this relationship must be considered, the magnitude and direction of their effects are well-studied and can be applied in different environments. The methods used within most studies were well-documented and accepted; however, critiques have been made about using insurance data for monetary estimates of property protection, as done by Narayan et al. (2019). While this is an individual modeling study about specific mangroves in an area and may not be transferable, it does show one method for estimating the value of mangroves in property protection from coastal flooding.

Other Factors

While the evidence strongly suggests that mangroves' ability to mitigate flood height and extent produces benefits for property protection, factors such as characteristics of both storm and protective mangrove forest, climate change, the property location relative to mangroves and the coast, and habitat destruction may influence the extent to which mangroves can protect property (Gijsman et al. 2021; McIvor et al. 2012; Menéndez et al. 2018, 2020; Narayan et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021). Menéndez et al. (2020) found that, globally, the percent risk reduction benefit provided by mangroves trends toward greater benefits with more intense storm events However, this may not always be the case, as storm events that are too intense can degrade or uproot mangroves and thus reduce their protective capacity (Gijsman et al. 2021).

Climate change is increasing sea level rise and the intensity and frequency of large storm events, leading to an increase in storm surge flooding and vulnerability of local communities, infrastructure, and the natural environment (Gijsman et al. 2021; McIvor et al. 2012; Menéndez et al. 2020; Narayan et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021). When the impacts of extreme events or changes in environmental conditions exceed mangroves' natural tolerance, mangroves may reach a critical threshold where they become so degraded that they can no longer provide property protection (Gijsman et al. 2021). Mangroves recovering from storm events also have reduced services, and an increase in frequency of storms could decrease the amount of time that mangroves have to recover between storms, reducing their protective capacity (Gracia et al. 2018).

The location of property or infrastructure relative to mangroves is crucial to mangroves' ability to provide flood protection. Since mangroves increase surge levels immediately in front of their coastal forests but reduce water levels and inundation behind the forest, any property or infrastructure built in front (seaward) of mangroves may in fact have increased flooding and flood loss. This was observed and quantified following Hurricane Irma in Florida when some properties in front of mangrove forests experienced increased flood damages. However, these same areas of mangroves also reduced losses during this storm by US$88 million for properties behind them, demonstrating that the effects of mangrove forests on flooding are not positive everywhere and are largely dependent on development choices (Narayan et al. 2019).

Predictability

The literature is consistent in identifying a strong relationship between mangrove-facilitated flood mitigation and protection of property located landward of mangroves in coastal areas. Globally, mangroves reduce property damage from coastal flooding by US$65 billion per year, but the property protection value of mangroves varies across regions and countries because of differences in the location/density of coastal property, mangrove forest and storm characteristics, the impacts of climate change, and mangrove habitat loss or degradation (Gijsman et al. 2021; McIvor et al. 2012; Menéndez et al. 2018, 2020; Narayan et al. 2019; Torres-Ortega et al. 2019; Soanes et al. 2021). Economic valuations across a variety of geographic locations have valued mangrove's protective service for property against flood risks at between US$540–$7,500 per hectare of mangroves annually, with a global average valuation of US$4,000 per hectare in annual flood protection benefits (Menéndez et al. 2020; Narayan et al. 2019; Torres-Ortega et al. 2019).

A combination of process-based numerical modeling that can account for local variation in external factors and economic valuation methods can be used to quantify the extent to which mangroves protect property in different specific locations (Menéndez et al. 2018, 2020). The avoided damage economic valuation method was most frequently used and identified as the most robust way to value the protective capacity of mangroves because it can be applied over large areas and is more accurate (Menéndez et al. 2018). This method uses process-based modeling of flood losses under scenarios with and without mangrove protection and uses the difference in losses between the two scenarios to represent the averted damages (i.e., benefits) provided by current mangroves (Narayan et al. 2019).

Local Context

The Jobos Bay workshop group reported observations that certain low-lying neighborhoods around the bay were protected by mangroves from Hurricane Maria. Houses behind mangrove areas did not appear as damaged as houses in areas where mangroves had been cut or removed. Similarly, Rookery Bay workshop participants shared the story of a particular property on Pine Island Sound that was protected by surrounding mangroves during Hurricane Charlie—the home was damaged but survived the storm. Other neighboring properties that had removed their mangroves were destroyed.

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LINK 35: WIND BUFFER → PROPERTY PROTECTION

Description of Relationship

Evidence of mangroves acting as a wind buffer, thus reducing the regeneration and propagation of wind waves atop storm surges that lead to flooding, is limited (Das and Crépin 2013; del Valle et al. 2019; Gracia et al. 2018; Marois and Mitsch 2015; McIvor et al. 2012; Spalding et al. 2014). If this relationship exists, there may also be evidence it can protect coastal property leeward of mangroves through reduced wind waves, storm surge, and inundation, but this relationship has relatively little evidence and may be difficult to model in isolation (Das and Crépin 2013; del Valle et al. 2019; Gracia et al. 2018; Marois and Mitsch 2015; McIvor et al. 2012; Spalding et al. 2014).

Summary of Evidence

Limited evidence of mangroves' ability to act as wind buffer through directly affecting the speed of wind directly over the water surface within areas where the vegetation reaches above the water level exists (Das and Crépin 2013; del Valle et al. 2019; Gracia et al. 2018; Marois and Mitsch 2015; McIvor et al. 2012; Spalding et al. 2014). Some studies indicate by acting as a wind buffer, mangroves can mitigate effects of the wind on the water surface, such as increased wind waves, storm surges, and flooding, and therefore, protect coastal property and infrastructure, but little quantitative evidence is provided for this claim (Das and Crépin 2013; del Valle et al. 2019; McIvor et al. 2012; Spalding et al. 2014).

One study that applied a theoretical model to examine whether mangroves attenuated damage from cyclonic winds during the 1999 cyclone in the Odisha region of India found that mangroves are able to act as a wind buffer and provide substantial protection to properties, including property even relatively far from mangroves and the coast, but only if mangroves exist in large, continuous patches. This study estimated the wind protection benefits of mangroves to properties located leeward of mangroves to be approximately US$177 per hectare of mangrove at 1999 prices (Das and Crépin 2013). Despite this evidence, there may have been flaws in the modeling used, because the study did not have access to or use detailed data on the surrounding landscape and assumed constant wind speeds. Further, the study calculated aggregate damage from both storm surge and wind damage and was unable to isolate the effects of wind buffering on property protection (McIvor et al. 2012).

Strength of Evidence

Low. There is very little evidence to support this link. Though the evidence that does exist was consistent in saying that mangroves can act as a wind buffer, there was little evidence of this translating to property protection. Further, methods using modeling may be flawed and unable to represent the isolated ability of mangroves to act as a wind buffer.

Other Factors

Property would have to be located on the leeward side of mangroves for the trees to afford any wind protection. One modeling study estimated that narrow patches of mangroves provide limited protection of villages and could even worsen storm damages. However, large, continuous patches of mangroves were able to protect coastal property. The same study's models show that there was stronger wind protection by mangroves for villages close to landfall or within high impact zone of the storm, with weaker protection for villages in low impact zone (Das and Crépin 2013). These other factors are based on modeling and require further research to assess their broader applicability.

Predictability

Due to the lack of evidence in the literature of mangroves' ability to act as a wind buffer conferring property protection, there is limited predictability in this relationship. Das and Crépin (2013) used theoretical modeling to predict mangroves' ability to act as a wind buffer, but this model may be flawed because it is impossible to isolate the effects of wind buffering and it did not use sufficient data on wind speeds or the surrounding environment (Das and Crépin 2013; McIvor et al. 2012). Predictions of this relationship require complicated numerical modeling (Das and Crépin 2013).

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LINK 37: AESTHETICS → PROPERTY VALUE

Description of Relationship

There is a lack of evidence clearly indicating that mangrove aesthetics influence property value. To make inferences about the relationship, studies were identified that discuss price premiums for property attributes like proximity to green space or unobstructed views of waterbodies (which mangroves can inhibit).

Summary of Evidence

No evidence was found that directly links property values to mangrove habitat. However, there are multiple cases of the hedonic method being used to attribute property price premiums to natural features such as lakes or trees. In simple terms, this method uses a statistical model to develop a relationship between housing price data and property features, such as distance to waterbody, waterfront access, or percent tree canopy (Lansford and Jones 1995). It is then possible to estimate how housing prices might respond to variations in those property features. Using the hedonic method, it would be possible to estimate house price premiums supplied by the aesthetic features of a mangrove forest. Examples of research using the hedonic method can be found for estimating the influence of aesthetics from lake and river views (Kulshreshtha and Gillies 1993; Lansford and Jones 1995) and greenways (Nicholls and Crompton 2005).

Despite the lack of research specifically addressing the relationship between mangrove aesthetics and property value, inferences can be made from broader studies of green spaces and hedonic pricing. One such study found that residential properties with trees in Georgia, United States, led to a 3.5% to 4.5% increase in sales prices (Anderson and Cordell 1988), while a study of urban green spaces in the United Kingdom revealed that properties located in close proximity to public green spaces can have up to a 49% increase in sale price, although this increase was only significant in half of the housing types studied (McCord et al. 2014). It is difficult to directly apply these studies of urban and forested properties to a mangrove context because of the various other factors involved in the pricing of residential properties. One major factor complicating this relationship is the high value placed on water views, which can be obstructed by mangroves. Homes with water views are found to have significantly higher property values, as on Lake Erie, where having a lake view can increase home value by 56% (Seiler et al. 2001). In Washington State, United States, high-quality ocean views can increase property prices by almost 60%, while even low-quality partial views add roughly 8% (Benson et al. 1998). The price premium placed on water views has led to the clearing and destruction of mangroves for illegal construction in Puerto Rico. For example, within a protected reserve where tree removal by nearby residents is banned, more than 3,600 mangrove trees were illegally cut to build homes, pools, and docks, prompting public scrutiny and launching a criminal investigation by Puerto Rico's Department of Justice (Coto 2022). Similar cases of mangrove clearing have occurred in Wharekawa Harbor, New Zealand, in an attempt to create unobstructed water views (Graeme et al. 2008). In Miami, Florida, a city-proposed ordinance sought to prohibit planting new mangroves or tall foliage to protect water views (Staletovich 2022); however, this ordinance was never passed. It is clear that, in some cases, mangroves appear to hold less value to the public than unobstructed water views.

Strength of Evidence

Low. There was generally very little information available that describes the relationship between mangrove aesthetics and property values. Extrapolations can be made from research describing how things like vegetation and water view aesthetics affect home prices, but inconsistencies between sources make it difficult to define the relationship between mangrove aesthetics and home prices. There were also inconsistencies in the limited evidence, with some evidence indicating mangroves would increase home value and other evidence indicating that they would in fact decrease home value.

Other Factors

It is difficult to definitively state the connection between mangrove aesthetics and property value because of the multitude of factors that affect property prices. Popular real estate website Zillow provides potential buyers information on a multitude of factors: property lot size, structure, the number of rooms, bedrooms, and bathrooms, the year built, and more, demonstrating the complexity of factors considered in the pricing of property (Wentland et al. 2020). These extenuating factors often influence property value far more than the presence or quality of mangroves/foliage nearby, thus making it difficult to quantify mangroves' direct impact.

The quality of the appearance of mangroves may also potentially impact property values. Broad, leafy canopies have been found to carry more aesthetic value based on survey data (Nelson et al. 2001). It can thus be inferred that the quality of leaves and density of the mangrove canopy in proximity to the property could have a positive correlation with property value.

Ultimately, property values are largely dependent on homeowner preferences. If an owner desires the aesthetic of foliage, then mangroves may correlate to a higher property value. However, homeowners who do not value the appearance of mangroves, or who prefer unobstructed water views over greenery, will likely place a lower value on properties with mangroves nearby.

Predictability

Because of the limited and inconsistent information available about this link, the relationship between mangrove aesthetics and property value is not predictable. There is no evidence directly linking mangrove aesthetics to property value, so all information had to be inferred. Despite this evidence, the subjective nature of property pricing and personal preference mean that there is no reliable way to predict exactly how changes to mangrove forests will affect property value.

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LINK 38: FISH AND SHELLFISH HARVEST → ECONOMIC ACTIVITY (RECREATION AND TOURISM)

Description of Relationship

Mangroves are home to and provide nursery functions for a variety of fish and shellfish species, many of which are recreationally important (Walton et al. 2006). Recreation and tourism related to both private and chartered recreational fishing in mangroves and adjacent areas that contain mangrove-dependent species may be economically important because of the revenue they generate and jobs they create (Adams and Murchie 2015; Bennett and Reynolds 1993; Enchelmaier et al. 2020; Huang et al. 2020; Seary et al. 2021; Walton et al. 2006). There is evidence of improved fish abundance and richness in mangrove areas following restoration and reforestation as well as increased estimates of the economic value of mangrove-dependent fish species and associated tourism, but the evidence does not specifically link changes in fishing activity in and around mangrove areas with the economic value of that recreation (Adams and Murchie 2015; Enchelmaier et al. 2020; Walton et al. 2006). Other studies have discussed causal links between restoration of other coastal ecosystems, such as oyster reefs and seagrass wetlands, and increased recreational fishing and tourism which may have applications to mangrove systems (Carlton et al. 2016; Huang et al. 2020).

Summary of Evidence

Mangroves are widely recognized for their role in enhancing fish and shellfish harvest by supporting wildlife populations through the provision of food, habitat, and nursery functions (see Link 28). Fish and shellfish harvest are important recreational features of mangroves which generate substantial economic value and contribution to local economies (Adams and Murchie 2015; Huang et al. 2020). Mangrove-associated fishing can contribute greatly to the livelihoods of coastal communities, and recreational fishing activities can generate income and create jobs (Seary et al. 2021).

Many species of recreationally important fish are dependent on mangroves for part or the entirety of their life cycles. Therefore, the ability of mangroves to provide fish and shellfish for harvest may affect economic output from recreation and tourism within and around a mangrove area. For example, the recreational fish species common snook (*Centropomus undecimalis*) and Atlantic tarpon (*Megalops atlanticus*) depend on mangroves for one or more of their life stages; two other recreational species, bonefish (*Albula vulpes*) and barramundi (*Lates calcarifer*), are commonly found in mangrove areas. Each of these species support recreational fisheries, with annual economic impacts of hundreds of millions of dollars on both the state and regional scale and a large constituency of users. In Florida, the annual impact of the recreational common snook fishery in 2000 was estimated to be US$1.56 billion. The common snook is also important for recreational fishing in Texas and Central and South America, but no economic estimates exist for these locations. The annual economic impact of the recreational tarpon fishery exceeds US$100 million in Charlotte Harbor Estuary in

Southwest Florida and exceeds US$19 million in the St. Lucie estuary in Southeast Florida. Tarpon are also an important component of the recreational flats fishery, with an annual economic impact that exceeds US$465 million in the Florida Keys, US$55 million in Belize, and US$990 million in the Florida Everglades, and are important to recreational fisheries in Cuba, Costa Rica, Nicaragua, and Puerto Rico. Recreational bonefish have an economic impact that exceeds US$141 million in the Bahamas, are part of the recreational flats fishery that has an annual economic impact exceeding US$465 million in the Florida Keys, and have an unmeasured economic impact in Cuba, Mexico, and Turks and Caicos (Adams and Murchie 2015). The loss and degradation of mangrove habitats can negatively impact the fisheries that rely on these species and can result in reduced economic benefits from recreation and tourism (Adams and Murchie 2015; Islam and Bhuiyan 2018).

A study on restored mangrove-fringed pools in Bill Baggs Cape Florida State Park shows progress toward recovering fish abundance and richness in and around mangrove areas following ecosystem restoration. Specifically, in that location a higher catch per unit effort has been recorded for small forage fish such as hardhead silverside and mangrove gambusia, which may have ecologically important implications as they are a source of food for larger recreationally fished species (Enchelmaier et al. 2020). In the Philippines, socioeconomic impacts of a community-led mangrove reforestation project were examined, but it is difficult to parse out the exact relationship between mangrove fish and shellfish harvest and economic activity from recreation and tourism. Combined revenues from mangrove fisheries, tourism, and timber result in an annual benefit of US$315 ha^{-1} yr^{-1}, and 73% of fishers thought that mangroves directly increased fish catch. Revenues from tourism in the Buswang Eco-Park in the Philippines and additional services provided from replanted mangroves average US$41 ha^{-1} yr^{-1}; more than half of visitors were willing to pay twice as much in entry fees following mangrove restoration, although the study did not identify if the increase in revenue resulted from an increase in recreational fish and shellfish harvesting and tourism (Walton et al. 2006).

Other studies have evaluated the economic impacts of increased fish and shellfish harvest resulting from habitat restoration in non-mangrove coastal areas and found strong relationships between ecosystem restoration and economic benefits from recreation and tourism. One study examined the economic impacts of the restoration of Half Moon Reef oyster habitat in Matagorda Bay, Texas, which resulted in a substantial increase in marine biodiversity and productivity. Following reef restoration, there was an increase in recreational fishing trips to Matagorda Bay as a result of the Half Moon Reef restoration project for both private boat (non-guided) fishing trips and charter (guided) fishing trips. The increased recreational fishing led to the creation of 12 jobs, US$465,000 in annual labor income, an additional US$691,000 to Texas' gross domestic product, and US$1.273 million in economic activity. Similarly, charter fishing is estimated to increase annually by 14.9% total after the restoration, owing 10.5% growth directly to the restoration project (Carlton et al. 2016).

In Australia, recreational fishing is an important pastime, with an estimated 830,000 participants who make upward of 6 million fishing trips in the state of Victoria alone, supporting 16,257 direct jobs and generating AU$2.6 billion in direct output. A study in this context examined welfare gains across recreational fishing locations in Australia with varying percent cover of seagrass. Aggregate economic benefits from recreational fishing and tourism varied based on percent seagrass cover, ranging from near-zero in areas of low seagrass cover to up to AU$6.2 million per year with a 10% increase in seagrass coverage, and AU$22 million per year with a 30% increase in seagrass (Huang et al. 2020). While the results of these two studies do not apply directly to mangrove systems, they may provide some insight into how an increase in fish and shellfish populations in coastal ecosystems can bolster recreation and tourism and their associated economic activity.

Strength of Evidence

Moderate. Evidence for a relationship between mangrove-related fish and shellfish harvest and economic activity derived from recreation and tourism is documented and consistent in peer-reviewed literature, but lacks causal linkages. The evidence included information from a variety of geographic locations. The literature was consistent in identifying economic benefits from both private and chartered or guided recreational fishing and associated tourism, but the relationship is not necessarily causal and the literature did not discuss many external factors that influenced this relationship. Because causal information was scarce, causal information had to be extrapolated from studies that focused on economic benefits from the restoration of other coastal ecosystems (i.e., oyster reefs and seagrasses), so applicability of this information may be limited.

Other Factors

While the literature regarding the causal link between mangrove-related fish and shellfish harvest and economic activity derived from recreation and tourism was sparse, some external factors were described to potentially influence this link. The state of the mangrove forest and its ability to support fish populations was the main factor that affected recreational fishing and tourism. Overexploitation and habitat loss or degradation are anthropogenic impacts that reduce a mangrove forest's ability to support fish and shellfish populations for recreational harvesting, although the literature did not specify the extent to which a mangrove habitat has to be degraded or how much fish populations have to reduce for effects to be seen in tourism and recreation (Adams and Murchie 2015; Bennet and Reynolds 1993). A study in Malaysia found that mangrove tourism supports about 500 jobs and a tourist industry valued at US$3.7 million per year, and if mangroves were to be damaged there, all of the fisheries and many of the tourism benefits would be lost (Bennet and Reynolds 1993). Further, unsustainable tourism may hurt mangroves and their ability to serve as sites for recreational fishing in the future. Unsustainable tourism practices may result in habitat destruction, noise pollution, and contaminant pollution which could reduce the potential of mangrove sites to serve as tourism and recreational fishing sites (Islam and Bhuiyan 2018).

Other external factors may influence this relationship that were not mentioned within the literature. One example is the proximity of mangrove sites to other tourism attractions and the attractiveness of the site (i.e., if the mangrove site is not an attractive tourism site, economic benefits from recreational fishing and tourism may be small). Similarly, the economic benefits of recreation and tourism related to mangrove fish and shellfish harvest may be limited if there is not an existing tourism industry in the area.

Predictability

The literature included limited information about the predictability of the relationship between mangrove fish and shellfish harvest and economic activity derived from recreation and tourism. Much of the information regarding a causal link was extrapolated from literature describing similar coastal ecosystems (oyster reefs and seagrass) and may provide little predictability for mangrove systems. Within the literature, there was evidence of economic benefits from mangrove recreation and tourism and increased fish abundance and richness in mangrove areas following restoration, but it is unclear how much of the benefits are directly from fish and shellfish-related recreation and tourism, so that information also provides little predictability for this relationship. For the four species of recreationally important fish described by Adams and Murchie (2015), the predictability of a relationship between fish and shellfish harvest and economic activity from recreation and tourism may be clearer. Overall, most of the data and literature found was not specific to the causal link between fish and shellfish harvest and the economic value of recreation and tourism in mangrove areas, so this link may need further research for clearer predictability (Adams and Murchie 2015; Enchelmaier et al. 2020; Walton et al. 2006).

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LINK 39: FISH AND SHELLFISH HARVEST → FOOD

Description of Relationship

Mangroves are widely recognized for their role in enhancing both small-scale and commercial fish and shellfish harvest by providing nursery functions and habitat for a diversity of fish and shellfish species. Much of the fish and shellfish harvested within mangrove areas is important for the food security and nutritional needs of coastal communities, with particular importance in less economically developed countries where subsistence fish and shellfish harvest occurs. Large-scale commercial fishing also contributes exported seafood to inland communities. There is a large gap in literature regarding the amount and importance of subsistence fishing that occurs within and near mangroves because of barriers to data collection, which may lead to an underestimate of the value of fish and shellfish harvest for food provision in coastal mangrove areas.

Summary of Evidence

Mangrove forests support a diversity of marine animals (see Links 5 and 13). It is therefore widely understood that mangroves are critical for sustaining production in coastal fisheries through their role as important habitats, resource providers, and nursery areas for marine animals, including fish and shellfish (see Link 28). Mangroves support fisheries varying in scale, fishing methods, and target species, including fisheries within the mangroves themselves for mangrove-resident species such as crabs and mollusks, fisheries in mangrove channels and lagoons, and offshore fisheries for species such as penaeid prawns that use mangroves as nurseries but move out to the continental shelf as adults (see Link 28). Since a large portion of the world's human population lives in coastal or estuarine areas (e.g., 70% of the population of Southeast Asia), there is a great importance of fishery activities as a source of food (Rönnbäck 1999).

One of the widely cited ecosystem services of mangrove ecosystems is food provision because of the fish and shellfish abundance and harvest that occurs within them. Coastal subsistence economies in many developing countries are heavily dependent upon sustainable harvest of fish and shellfish from mangroves. The median fisherman density, as well as the fish and shellfish yield per unit area, is considerably higher in mangrove areas than in other fished systems. Fish standing stock ranges from 4 to 25 g m^{-2} in intertidal mangrove habitats and is much higher in mangrove habitats compared to adjacent coastal habitats. Mangroves in northern Australia contain 4 to 10 times higher fish abundance compared to adjacent seagrass habitats, and fish are 35 times more abundant in Florida mangroves than in adjacent seagrass beds (Rönnbäck 1999).

The range of coastal fisheries resources that depend on mangroves is extensive, and many of these species are important to the food security and livelihoods of coastal communities, especially in less economically developed countries (Bouillon et al. 2009; Macintosh et al. 2011; Rönnbäck 1999; zu Ermgassen et al. 2020; Waycott et al. 2011). Small-scale fisheries are not only an important contributor to the national economies of many developing nations, but are also a critical source of food in many parts of the world. Subsistence fishing within and around mangrove areas contributes to food security because of the source of protein provided by the fish and shellfish harvested. Five out of the 10 countries with the most mangrove fishers (Indonesia, Bangladesh, Nigeria, Thailand, and the Philippines) are also considered to be among those countries most reliant on fish as a source of protein and most vulnerable to malnutrition. It is estimated that in many West and Central African nations more than 50% of small-scale fishers fish at least part-time in or near mangroves, with five (Nigeria, Cameroon, The Gambia, Ivory Coast, and Ghana) ranked among the most reliant on fish and vulnerable to malnutrition (zu Ermgassen et al. 2020).

On the northern Brazilian Coast, communities are heavily reliant on mangrove-associated fish and crab production. Interviews with community members who frequently use mangrove ecosystems for fish and shellfish harvest revealed the following common perspectives about the food provisioning services of mangroves: "*The mangrove preserves life in the village*," "*It is from there, that we get our food*," and "*When there is nothing, we go there*" (Glaser 2003). In small-scale fisheries in Southeast Asia, 63% to 93% of households living near fisheries were involved in fishing, but only a small proportion of these included a professional fisher, indicating that most of the catch is for subsistence purposes and is consumed by the fishers' families and communities. In contrast, large-scale industrial fishing is carried out entirely by professional fishers and uses large boats that enable them to operate far from population centers to target specific species. Catch from large-scale fishing is likely to be exported overseas for consumption with little being locally consumed (Hutchison et al. 2015).

Rönnbäck (1999) conducted a review of global seafood production within mangroves that found mangroves support the highly commercially important seafood products of penaeid and palaemonid shrimps. The *Acetes* spp. shrimp are the most important to fisheries and are partially dried to make a fermented paste that forms a key ingredient in Southeast Asian cooking. The global average annual penaeid shrimp production for seafood is 162 kg/ha of mangrove forest, and even discarded catch from shrimp trawling has a potential value if landed and used for human consumption or processed into fish meal. Edible species of oysters, mussels, cockles, and gastropods are also collected extensively within mangrove areas for local consumption, usually by families of local fishermen. In a subtropical mangrove forest in eastern Australia, the total biomass of fish caught for seafood over one year was as high as 5840 kg/ha. In Perak, Malaysia, 39,000 tons of mangrove-dependent fish were landed for consumption as seafood in 1990 (Rönnbäck 1999).

Assessments of subsistence fishing linked to mangrove areas globally are often considered underestimates because of data limitations. A significant portion of total fisheries catch is nonmarketed subsistence harvest that is not included in national fishery statistics. The contribution of subsistence fisheries to total catch supported by mangroves was estimated to be 10% to 20% in Sarawak, 56% in Fiji, and 90% in Kosrae, but these are likely underestimates because of limited data (Rönnbäck 1999). There have been no large-scale efforts to quantify the intensity or number of small-scale or subsistence mangrove-associated fishers and their seafood catch (zu Ermgassen et al. 2020). Information of this kind is difficult to acquire and quantify. Most fisheries within mangrove areas are small-scale because mangrove areas are largely impenetrable to large boats or machinery required for commercial fishing, but small-scale fisheries are frequently underreported in government statistics and the literature. Similarly, much of the catch never enters formal markets, as it is consumed by fishers, their families, and the local community, adding a further barrier to data collection (Hutchison et al. 2015).

Strength of Evidence

Moderate. The relationship between mangrove-associated fish and shellfish harvest and food provision is documented and consistent within the literature. Evidence was found in peer-reviewed scientific studies, reviews, and reports that geographically focused mainly within Southeast Asia. There was little to no reporting of mangrove-associated subsistence fishing in the United States or other more developed countries and more research could be done to further examine the relationship in these other contexts. While there was widespread consistency about the high abundance of fish and shellfish harvested within and around mangrove areas, some of the literature did not make the direct connection of this harvest being used as a source of food, but this can be reasonably inferred. Information was more limited and general about the importance of subsistence and small-scale fish and shellfish harvest as seafood because of limitations to data collection. In general, the literature supports the provisioning service of seafood within mangrove areas.

Other Factors

The literature suggested that the use of fish and shellfish harvest for food has a particularly important use in less–economically developed countries where coastal communities are heavily dependent on the nutrition and protein provided by seafood (Bouillon et al. 2009; Rönnbäck 1999; zu Ermgassen et al. 2020). While other information about external factors influencing the relationship between fish and shellfish harvest in mangrove areas and food provision is sparse within the literature, some factors may be assumed. In coastal areas with low access to and availability of other food sources, people may be more dependent on mangrove-derived fish and shellfish harvest. Similarly, cultural practices and food preferences may play a role in the extent to which mangrove-derived seafood is consumed.

Predictability

While the literature suggests a direct link between fish and shellfish harvest and the provision of food, there is limited information regarding the predictability of this relationship, or models or tools that could be used to predict this relationship in different contexts. Even though the literature does not directly state that most or all fish and shellfish harvest is used as seafood, it may be reasonably inferred.

For small-scale or subsistence fisheries, it can be more difficult to predict the quantity of fish and shellfish that will be harvested as seafood because of limited data, but certain factors can be used to predict a community's dependence on subsistence fisheries. Some of these factors include the availability of other food sources and economic development.

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LINK 43: FOOD → FOOD SECURITY

Description of Relationship

Mangroves are widely recognized for their role in enhancing both small-scale and commercial fish and shellfish harvest by providing nursery functions and habitat for a diversity of fish and shellfish species. Fish and shellfish harvest provide valuable sources of protein and nutrients and can contribute to the incomes and livelihoods of those who sell their catch. Thus, mangrove fisheries contribute to food security in two ways: (1) through the direct consumption of protein and nutrient-rich fish and (2) by contributing indirectly to food security by increasing a fisher's livelihood. While the relationship between fisheries and food security is well-documented within the literature, there is limited information specifically about mangrove fisheries food security.

Summary of Evidence

Food security involves ensuring reliable access to an adequate supply of food (Mohd Razali et al. 2021). In coastal areas, such as those in and around mangrove forests, fish is widely recognized as a cornerstone of food security. Within the literature, there is more information about food security from fishing in general, and not directly related to mangrove-linked fisheries. Ten percent of the world's population depends on the ocean for a readily accessible source of protein, and small-scale fisheries are especially vital for food security. Fisheries are an integral part of ensuring food security worldwide with fish providing 6.7% of total protein consumed by humans (Taylor et al. 2019). In the Pacific Island region, for example, fish provides 50% to 90% of animal protein for coastal communities (Bell et al. 2018). Most of this fish traditionally comes from small-scale coastal fisheries, which directly increase the availability of nourishing food for local, national, and international markets (Bell et al. 2018; Taylor et al. 2019).

Food-producing livelihoods, such as fisheries, have the potential to improve food security and levels of nourishment through (1) direct consumption and (2) indirectly through incomes earned (Bell et al. 2018; Taylor et al. 2019). As for direct consumption, fish provides more than 4.5 billion people with at least 15% of their average per capita intake of animal protein. Subsistence fishing in coastal areas is particularly important for food security, especially in developing countries (Laffoley and Grimsditch 2009; Taylor et al. 2019). Subsistence fisheries are often informal and overlooked from a lack of data, and are therefore less documented within the literature (Taylor et al. 2019). For indirect incomes, fish contribute significantly to the income of more than 10% of the world, increasing food security through livelihoods (Taylor et al. 2019).

Mangrove forests support a diversity of marine animals targeted by fishers, and it is widely held that mangroves are therefore critical for sustaining the production of food in coastal fisheries through their role as important habitats, resource-providers, and nursery areas for marine animals, including fish and shellfish (see Link 39). Mangroves, therefore, can be vital for the food security of coastal communities, particularly in developing countries, providing nurseries and fishing grounds for artisanal fisheries (Albert and Schwarz 2013; FAO 2010; Laffoley and Grimsditch 2009).

An example of this can be seen at two sites in the Solomon Islands where mangrove forests are critical for food security and the livelihoods of coastal communities. At the Langa Langa Lagoon, mangroves provide an important ecosystem for fishing and harvesting shells and crabs that contribute to food security. Mangrove fruit (from the species *Bruguiera gymnorhiza*) is also a traditional food source throughout the lagoon. People in the Maramasike Passage area of the Solomon Islands are also highly dependent on mangroves for subsistence needs. For Maramasike Passage communities, limited access to surrounding coral reef resources means that fish and shellfish harvested from mangroves and associated rivers provide the major source of dietary protein. Mangrove mud shells, mud crabs, fruit, fish, and other shellfish are important food sources, and mangrove mud crabs and mud shells are an important market product (Albert and Schwarz 2013).

Aside from fisheries production as it relates to food security, mangroves can also contribute to food security in other ways. Mangroves can also protect food production systems that lie further inland by buffering against coastal elements such as wind, waves, and flooding that could affect inland agricultural production (FAO 2010). Mangrove plants themselves may also be consumed in coastal communities and contribute to food security (Albert and Schwarz 2013; Rudianto et al. 2022). Mangrove plants are an alternative source of food for coastal communities in addition to rice, corn, and sago, and processing mangrove fruit can make a form of flour that can be used as a raw material and a source of carbohydrates (Rudianto et al. 2022).

Strength of Evidence

Moderate. While there is strong evidence that fishing contributes to food security, there is limited evidence of this relationship occurring in mangrove areas specifically. Because of the nature of subsistence fishing, evidence of this sort is difficult to collect. Therefore, a lack of evidence does not necessarily mean that the relationship does not exist, but rather that there may be a gap in the literature. Existing evidence comes from peer-reviewed scientific literature and scientific reports and is focused in developing countries. This relationship has primarily been examined in developing countries, and further research could shed light on the nature of subsistence fishing and food security in other locations.

Other Factors

The external factors that affect the relationship between mangrove food provision and food security can be broken down into factors that affect (1) the availability of fish and (2) the contribution of fish to food security.

Several factors can affect the availability of fish as a food source in mangrove areas. Climatic hazards such as sea level rise, increasing sea surface temperature, and natural disasters can all impact the availability of fish (Mohd Razali et al. 2021; Taylor et al. 2019). Anthropogenic impacts such as pollution, environmental degradation, and overfishing can also reduce the availability of fish and shellfish that can be harvested (Albert and Schwarz 2013; Rudianto et al. 2022; Taylor et al. 2019). Any factors that degrade mangrove habitats that act as nurseries or support fish and shellfish populations could also impact the availability or accessibility of fish that can be caught and contribute to food security (see Link 39).

The factors that can affect whether fisheries' catch will contribute to food security are not directly addressed within the literature, but may be assumed. The first of these factors is location. An individual or community will likely only rely on mangrove-associated catch for food security if they are in a coastal area with nearby mangroves. This is more common in developing countries (Laffoley and Grimsditch 2009), but there is a small yet growing body of literature on the links between subsistence fishing and food security in countries like the United States (e.g., Quimby et al. 2020; Boucquey and Fly 2021). Another factor that may affect this is regional dietary preferences or traditional and cultural. If these preferences align with mangrove-associated catch, it is more likely that food security will be more reliant on mangrove-associated catch. Access to other foods may also impact the contribution of mangrove-associated catch to food security.

Predictability

Because there is limited information for this link, there is limited information on the predictability of this relationship. The current existing information suggests that in coastal mangrove areas with subsistence or small-scale fisheries, especially within developing countries, it may be reasonable to assume that mangrove-associated fish and shellfish harvest contributes to food security.

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LINK 45: RECREATION → ECONOMIC ACTIVITY (RECREATION AND TOURISM)

Description of Relationship

Mangrove forests support multiple recreational activities such as hiking, boating, fishing, and wildlife watching, which may be a valuable realized or potential source of income and economic benefits. Systematic reviews found it likely that mangrove tourism attracts tens to hundreds of millions of visitors annually and is a multibillion-dollar industry worldwide (Spalding and Parrett 2019). Studies have used willingness-to-pay and contingent valuation methods to estimate the economic value of mangrove-associated tourism and recreation globally, but with results concentrated in Asia, to be between US$1.74 ha^{-1} yr^{-1} and US$507,369 ha^{-1} yr^{-1}, with an average of US$37,927 ha^{-1} yr^{-1}. Despite these figures, other studies have suggested that it is not possible to generate or extrapolate median values for tourism per unit area of mangrove because methods are not standardized and there is such limited data. However, they note that it is reasonable to assume mangrove tourism and recreation is a multibillion-dollar global industry (Salem and Mercer 2019). Increases in economic benefits generated from mangrove-associated recreation and tourism could potentially be achieved with an increase in communication/advertisement of mangrove tourism sites, accessibility of mangrove areas, and the development of coordinated recreational activities or excursions (Avau et al. 2011; Nobi et al. 2021).

Summary of Evidence

Tourism and recreation are major ecosystem services provided by mangrove forests as they attract ecotourists, hikers, wildlife watchers, boaters, and fishermen (see Link 29). Significant economic benefits are associated with the tourism and recreational value of mangrove forests, such as increases in revenue; support of local, regional, or national economies; and employment.

A review of global user-generated content from TripAdvisor identified 3,945 mangrove attractions spanning 93 countries, with a significant concentration in the Americas and Caribbean. However, the study mentioned this is likely to be an underestimate of all attractions because of limitations of the methods. Some of the most popular mangrove sites attract hundreds of thousands of visitors per year and may generate millions of dollars in visitor expenditures, as well garner support from local communities who recreate in mangrove areas. In total, global mangrove tourism likely attracts tens to hundreds of millions of visitors annually and is a multibillion-dollar industry. Despite the widespread use of mangroves for recreation and tourism, a comprehensive review of 253 economic valuations of coastal recreation found only 11 mangrove-specific valuations (4.6%) (Spalding and Parrett 2019).

A different meta-regression analysis of mangrove-associated tourism and recreation that included data from 73 studies primarily concentrated in Asia estimated its economic value to be between US$1.74 ha^{-1} yr^{-1} and US$507,369 ha^{-1} yr^{-1}, with an average of US$37,927 ha^{-1} yr^{-1} (Salem and Mercer 2012). Despite this figure, Spalding and Parrett (2019) suggest that it is not possible to generate median values for tourism per unit area of mangrove, nor is it possible to extrapolate the values here to other sites because of the variability of each site. However, they note that it is still reasonable to assume that mangrove tourism and recreation is a multibillion-dollar industry.

Several other studies estimate the economic value of specific mangrove tourism and recreation sites. In the Potengi estuary mangrove wetlands of northeast Brazil, the full potential of economic benefits of tourism and recreation have not yet been reached, but modeling has determined the potential tourism use to be US$3,500,000 per year. Also in Brazil, the Cananéia mangroves have a potential tourism value of US$33,700,000 per year (Souza and Ramos e Silva, 2011). The estimated total value of recreation and tourism in the Can Gio mangroves in Vietnam is US$104,400,00 per year, US$1,000,000 per year in the Matang Forest in Malaysia, and US$700,00 per year for the Hara Biosphere Reserve in Iran (Spalding and Parrett 2019). Tanner et al. (2019) valued mangrove-based recreation in the Galapagos at US$16,958 ha^{-1} yr^{-1}, contributing a total of US$62 million in revenue generated from 84 locations identified as mangrove-based tourism sites. The annual economic contribution of tourism in the Sundarbans Reserve Forest of Bangladesh is estimated to be US$53 million/yr, with the estimated value of tourism per visit calculated to be US$577 (Nobi et al. 2021).

In the Philippines, socioeconomic impacts of a community-led mangrove reforestation project were examined, but it is difficult to parse out the exact relationship between mangrove fish and shellfish harvest and economic activity from recreation and tourism. Combined revenues from mangrove fisheries, tourism, and timber result in an annual benefit of US$315 ha^{-1} yr^{-1}. Revenues from tourism in the Buswang EcoPark and additional services provided from replanted mangroves average US$41 ha^{-1} yr^{-1}. Additionally, more than half of polled visitors were willing to pay twice as much in entry fees following mangrove restoration (Walton et al. 2006).

Strength of Evidence

Moderate. The relationship between mangrove-associated recreation and economic activity associated with recreation and tourism was well-documented and supported within the literature. Evidence was found from a variety of peer-reviewed scientific literature, including site-specific studies and literature reviews/meta-analyses that sourced information from a variety of geographic locations, mainly concentrated in Southeast Asia. While there was widespread consistency in evidence regarding the ability of mangroves to provide recreation and tourism opportunities and how this produces economic benefits, the evidence was inconsistent in the ability to extrapolate information and the reliability of certain valuation methods. The economic valuation methods were well-documented, but studies also mention potential flaws in the methods and ways to improve them. Overall, it is reasonable to assume that mangrove tourism and recreation host many visitors and produces large economic benefits per year globally, but it is difficult to apply site-specific valuations to specific sites.

Other Factors

The relationship between mangrove recreation and linked economic activity may be affected by external factors. Studies identified areas of improvement for mangrove tourism and recreation sites to increase visitors and the amount of revenue generated through mangrove tourism and recreation, but they did not discuss the expected magnitude of change. Communication and tourism advertising that shows the configuration of the mangrove, its richness, diversity of associated ecosystems, and the easily observable presence of abundant wildlife can be used to promote the development of tourist services in areas within and adjacent to mangrove forests. The development of excursions and specific tourism programs or activities may also be able to attract different types of clients who are looking for more structured or guided recreation and tourism in mangrove areas (Avau et al. 2011). A study in the Sundarbans Reserve Forest of Bangladesh that found that increasing and developing facilities for watching wildlife, hiking trails within the mangrove area, and the availability of information such as forest maps, wildlife precautionary signs, and danger zones could increase the number of tourists that visit the site (Nobi et al. 2021). This factor also relates to access, in that if the site is very remote or hard to get to, it might generate less economic benefit through tourism.

Predictability

While the literature identifies a strong relationship between mangrove recreation and the economic benefits of tourism and recreation, it may be difficult to extrapolate valuation data because of external factors that significantly impact this relationship. A meta-regression analysis of mangrove-associated tourism and recreation that included data from 73 studies primarily concentrated in Asia estimated the economic value of mangrove-associated tourism and recreation to be between US$1.74 ha^{-1} yr^{-1} and US$507,369, with an average of US$37,927 ha^{-1} yr^{-1} (Salem and Mercer 2012). However, Spalding and Parrett (2019) suggest that it is not possible to generate median values for tourism per unit area of mangrove nor is it possible to extrapolate the values to other sites because of the variability of each site. Site specific studies estimate annual impacts of mangrove tourism and recreation to be between US$104,000,000 in Vietnam and US$700,000 in Iran (Spalding and Parrett 2019). Despite extrapolation and applicability to other sites being limited, it is still reasonable to assume that mangrove tourism and recreation is a multibillion-dollar industry. Further, the literature did not indicate the extent or magnitude of causal relationships or how changes in recreation affect economic activity of tourism and recreation, and only conducted valuations of the economic benefits of recreation and tourism.

The literature identified methods used to model or measure economic valuations of mangrove-associated tourism and recreation. The contingent valuation method measures both large discrete and marginal changes in ecosystem goods and services and uses surveys to elicit responses from people about maximum willingness-to-pay or willingness-to-accept for hypothetical changes in environmental quality (Salem and Mercer 2012). Another study did note, however, that this method may not always produce reliable results because the open-ended questions can generate responses with large variability (Diswandi and Saptutyningsih 2019). Another method used to assess recreational value of an ecosystem is the travel cost model, which has often been used to evaluate the losses occurring from beach closures after oil spills (Salem and Mercer 2012). This method would be more equipped to measure causal changes but was less frequently used in the literature. Ideally, a study valuing tourism and recreation ecosystem services would try to measure both the producer surplus and consumer surplus, but data requirements for such methodology may be limited, so market price approaches, or using gross revenues associated with the habitat, are often used (Tanner et al. 2019).

Local Context

In Jobos Bay, the workshop group reported that recreation-linked businesses in a nearby town saw short term negative effects after Hurricane Maria, but this was linked to physical damage to businesses post-storm. The workshop group was not sure that persistent degraded mangroves at Jobos Bay would deter tourists and recreators, and there was a belief that visitors would still come despite visible damage. However, there are indications that tourists might be deterred by water with high turbidity. There are similar indications at Rookery Bay, where kayak tour guides report that visitors have a better time when the water is clearer.

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LINK 51: PROPERTY PROTECTION (EROSION AND FLOODING) → PUBLIC SAFETY (RELATED TO EVACUATIONS)

Description of Relationship

While strong evidence exists for the relationship between mangroves and storm surge attenuation (see Link 9), flood mitigation (see Link 27), and property protection (see Link 34), there is no existing literature on the direct relationship between mangrove property protection from erosion/flooding and public safety related to evacuations, indicating a gap in the literature. Extrapolations based on existing literature indicate that because mangroves can reduce coastal floods and storm surge as well as protect from erosion, we may be able to assume that coastal infrastructure in the potential flood zone is also given some level of protection by mangroves. Some of this coastal infrastructure could include roads that are either evacuation routes themselves or roads leading to evacuation routes, helping to promote public safety through protecting evacuation routes. One of the advantages of using mangroves as a flood protection strategy is they can be expected to naturally respond to increased sea levels or land subsistence and thus don't require expensive maintenance which have to be periodically upgraded to keep up with subsidence (FHWA n.d.b; McIvor et al. 2013; Takagi et al. 2016).

Summary of Evidence

A host of scientific literature supports the relationships between mangroves and storm surge and wave attenuation (see Link 9), flood height/extent mitigation (see Link 27), and property protection from erosion and flooding (see Link 34). These relationships are supported through both direct observations and numerical modeling and are well-documented and well-accepted. Mangroves contribute to coastal defense strategies through their ability to effectively reduce the height of wind and swell waves over short distances (less than 500 m) and their ability to reduce storm surge water levels over greater distances (several kilometers) (McIvor et al. 2013; Narayan et al. 2017; Takagi et al. 2016). Wind and swell waves are reduced in height by between 50% and 100% over 500 m of mangroves, while storm surges are reduced by between 5 cm and 50 cm per kilometer of mangrove (McIvor et al. 2013). Together, these two functions of mangrove forests help to reduce flood height and extent and thus reduce flood risk to coastal communities and properties (McIvor et al. 2013; Narayan et al. 2017; Takagi et al. 2016).

Based on this cumulative information, extrapolations support the hypothesis that because mangroves can reduce coastal floods and storm surge as well as protect from erosion, it can be assumed that coastal infrastructure in the potential flood zone is also given some level of protection by mangroves. Some of this coastal infrastructure may include roads that are either evacuation routes themselves or roads leading to evacuation routes, helping to promote public safety through protecting evacuation routes in case of emergencies (McKenna et al. 2018).

Where human resources and infrastructure are in close proximity to mangroves, mangroves are increasingly seen as part of a wider risk reduction strategy that also often includes seawalls, dikes, levees, and early warning systems, evacuation plans and refuges (Narayan et al. 2017; McIvor et al. 2013). These approaches are often hybrid, combining mangrove forest area with built structures such as dikes. Similarly, the dynamic nature of mangroves may allow them to sustainably protect in the future and survive against sea level rise and land subsidence by increasing soil surface elevation and inland migration (McIvor et al. 2013; FHWA n.d.b; Takagi et al. 2016).

Between 1994 and 2010, the Vietnam Red Cross restored 8,961 ha of mangroves in Vietnam to protect 100 km of dikes by reducing the energy of wind waves acting on the dikes and thus, reduce the risk of waves overtopping. This project also trained 324,700 people in disaster preparedness and led to the protection of 2 million people from typhoons and associated flooding and the avoidance of US$20 million in losses to public infrastructure and private property across two communities. In Orissa, India, mangroves were connected to a reduction in the death toll from 9 m storm surge associated with Cyclone 05B in 1999. Similarly, the villages protected by mangroves suffered the fewest damages to property and the smallest inundation duration. In a village protected by solely an embankment, greater crop damage was experienced because after the embankment was breached, seawater took longer to flow back out of breaches, exposing crops to salt water for longer. However, in a village protected by mangroves, water was able to drain away rapidly, resulting in reduced crop damage (McIvor et al. 2013). While these examples do not directly support the relationship between mangrove property protection and public safety, they demonstrate the role of mangroves in protecting infrastructure and mitigating flood extent. This relationship could be extrapolated to the protection of roads by mangroves, some of which may be used as evacuation routes or lead to evacuation routes.

Other related evidence demonstrates the use of coastal wetlands (not necessarily mangroves) to reduce damage to roads during storm events, which may protect evacuation routes. High-resolution flood and loss models were used to demonstrate how the presence of salt marshes across 12 coastal US states from Maine from North Carolina resulted in avoided direct flood damages totaling US$625 million during Hurricane Sandy, including avoided damage to roadways. These models estimate a 16% average reduction in annual flood losses by salt marshes, with higher reductions in flood losses at lower elevations (Narayan et al. 2017). The US Department of Transportation is also increasingly investigating and implementing the use of wetlands as roadway protection, as wetlands can protect coastal highways from the brunt of storm surges and waves (FHWA n.d.b). In New Jersey, living reef and marsh plantings are being implemented to reduce flooding of coastal roads that often serve as evacuation routes (McKenna et al. 2018). The Maryland Department of Natural Resources created an active living shorelines program in 2008 to install ecosystem-based shoreline protection to infrastructure including roads. In 2012, Louisiana's Coastal Protection and Restoration Authority developed a Coastal Master Plan to provide a system-wide strategy for reducing hurricane flood risk and restoring land along the Louisiana coast, including six projects to create wetlands to protect sections of Louisiana Highways LA-27, LA-82, and LA-182. These wetlands will serve as protective buffers to reduce flooding from hurricanes and storms (FHWA n.d.a). While these examples reference wetlands that do not include mangroves, their results may be extrapolated to mangroves as they have similar wave attenuation and flood mitigation capabilities and would be similarly able to protect coastal roadways that may be used in evacuations.

Strength of Evidence

Low. Within the existing literature, there was no direct evidence of the relationship between mangrove-facilitated property protection from erosion/flooding and public safety related to evacuations. Extrapolations for this relationship can be made from links with strong evidence, including the relationship between mangroves and wave attenuation, storm surge attenuation, and flood mitigation. Extrapolations were also made from literature that focused on the protection offered by other types of wetlands and coastal ecosystems. Evidence for this information came from both scientific literature and gray literature reports by the US Department of Transportation. From this collective knowledge base, it can be assumed that because mangroves can reduce coastal floods and storm surge as well as protect from erosion, coastal infrastructure in the flood zone is also given some level of protection by mangroves. Some of this coastal infrastructure may include roads that are either evacuation routes themselves or roads leading to evacuation routes, helping to promote public safety through protecting evacuation routes. However, these extrapolations indicate a gap in the existing literature as there is no direct evidence of public safety being affected by the protection of property or infrastructure by mangroves. This is an important gap to fill as exposure to coastal hazards is increasing, population density on the coast is increasing where these hazards pose the largest risk, and mangroves may be a cost-effective and sustainable solution (Narayan et al. 2017; Takagi et al. 2016).

Other Factors

Several other factors impact the ability and effectiveness of mangroves to protect property from erosion and flooding from wave damage and storm surge (see Links 9, 27, and 34). Some of these factors include mangrove characteristics (e.g., tree density, forest width, tree diameter, species), storm characteristics (e.g., forward speed, characteristics of waves, angle of approach, intensity), and topography and local area characteristics (e.g., bed slope, bathymetry, tidal conditions) (McIvor et al. 2013; Narayan et al. 2017; Takagi et al. 2017). These factors may similarly affect the ability of mangroves to protect roads, which may be potential evacuation routes, thus affecting public safety.

Another major factor is the location of mangroves relative to evacuation routes. Wetlands, including mangroves, have greatest value where they are most extensive and in front of the asset needing protection (i.e., roads that are evacuation routes or lead to evacuation routes). This is especially important because mangroves can increase water levels in front of them but reduce water levels behind them, meaning that if the mangroves are located landward of evacuation routes, they may lead to increased flooding and a decrease in public safety because of decreased access to these evacuation routes (Narayan et al. 2017). Mangroves should thus be located seaward of evacuation routes to have a positive impact on public safety.

Mangroves may also be best suited to contribute to coastal risk reduction and increased public safety alongside and in combination with other risk reduction measures such as seawalls/dikes, early warning systems, and evacuation plans. While the presence of mangroves can never fully eliminate risk, mangroves can significantly reduce risk and increase public safety when used appropriately with other measures (McIvor et al. 2013).

Predictability

Because there is limited information for this relationship, the predictability is low and no models or tools were identified to predict the direct relationship between mangrove property protection from erosion and flooding and public safety related to evacuations. Related models have been developed to simulate and represent mangroves' wave reduction, storm surge attenuation, and flood mitigation capabilities (McIvor et al. 2013). The WAPROMAN and SWAN models are based on simplified representations of mangroves as a series of cylindrical elements with different densities per unit area at different heights above the ground to help model mangrove wave reduction (McIvor et al. 2013). The Eulerian-Lagrangian Circulation model and Coastal and Estuarine Storm Tide (CEST) models can be used to model storm surge attenuation in mangroves by representing area as spatial grid and incorporating mangroves into the model with a surface roughness coefficient (McIvor et al. 2013). Models such as the CEST model, Sea, Lake, and Overland Surge from Hurricane model, Finite-Volume Coastal Ocean Model, Advanced Circulation model, and Curvilinear-Hydrodynamics 3D–Simulating Waves Nearshore model use 3D modeling or an adjusted surface roughness coefficient to model the reductions of flood height and extent by mangroves (Sheng and Zou 2017). These models may be employed to demonstrate the reduction of wave, storm surge, and flood impacts on roads in potential flood zones that may be used for evacuation routes.

If these models demonstrate that the roads would have a reduced or no impact from erosion or flooding because of mangrove presence, it may be assumed public safety would increase because of improved access to evacuation routes.

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LINK 52: PROPERTY PROTECTION (EROSION AND FLOODING) → PROPERTY VALUE

Description of Relationship

Mangroves can reduce coastal flooding height and extent as well as erosion, leading to protection of coastal property and infrastructure (see Links 27 and 34). Generally, properties located within floodplains have lower property values than their counterparts, but this effect may be negated in coastal areas by the inherent value added by amenities of coastal properties. Hypothetically, if mangroves reduce flood extent, they could in turn reduce the amount of property located within a floodplain, and thus have a positive impact on property value. However, there is no existing evidence linking the effect of mangrove-related flood reduction to changes in coastal property value, and this effect may be irrelevant for coastal properties that have high property values regardless of location in a floodplain. This relationship would depend on characteristics of the property, frequency of flood events, the property market, and both the buyer and seller having access to knowledge of flood risks. Some evidence exists for the potential of natural coastal barriers, such as mangroves, to provide defenses against flooding and erosion that could translate to reductions in property insurance premiums, but this is an emerging field with limited information thus far.

Summary of Evidence

By attenuating storm surges and their associated peak water level height and waves, there is strong existing evidence for the ability of mangroves to reduce coastal flooding and erosion, leading to measurable protective benefits on coastal property and infrastructure (see Links 27 and 34). Coastal flood and erosion risks are rising rapidly as a result of climate change, and if all existing mangroves were destroyed, 9% more property would be flooded annually across the world because of the loss of mangroves' protective services and ability to reduce inundation area (Menéndez et al. 2020; Rajapaksa et al. 2016, 2017).

Economic theory suggests that, other things being equal, properties located within a floodplain, such as those in coastal areas, should suffer a price discount (Beltrán et al. 2018; Rajapaksa et al. 2016, 2017). In an efficient housing market, the price of property located within the floodplain ought to be lower than the price of equivalent property outside because the price discount would serve as a measure of the benefits of a reduction in flood risk (Beltrán et al. 2018; Rajapaksa et al. 2016). A meta-analysis shows actual price discounts of property located in floodplains lie anywhere between –75.5% and +61.0%, with an average estimate for property values in 100-year floodplains pointing to a premium of +3.7% rather than the expected price discount. While the overall effect size for properties affected by inland flooding points to a discount of –5.6%, properties at risk of coastal flooding have a premium of +14.8%, which explains the overall average premium of properties at risk of flooding (Beltrán et al. 2018). The high value of coastal properties, even if they are at risk of flooding, stems from the presence of amenities associated with proximity to the coast, such as beach access or sea views, and how these factors seem to outweigh flood risk for buyers (Beltrán et al. 2018; Rajapaksa et al. 2017). While the direct link between mangrove property protection and property value has not been studied, this information suggests that even if mangroves are able to protect coastal property and reduce erosion and flooding, there may not be a measurable impact on property value for coastal properties because of the premium cost they inherently have thanks to the amenities they offer. More inland properties may experience an increase in property value if protected by mangroves from flooding and erosion.

Some evidence exists for the potential of natural coastal barriers, such as mangroves, to provide defenses against flooding and erosion that could translate to reductions in property insurance premiums. Wetlands, including both mangroves and marshes, have already been considered in insurance industry risk models as a risk-reducing feature, but this is an emerging field with limited information and actual uses thus far. While nature-based features are not well understood or used by the insurance industry yet, if implemented correctly, nature-based features like mangroves could contribute to reducing exposure of nearby property and consequently the losses paid by insurers. Thus, reduction in loss expectancies by insurance companies could be translated into premium reductions for property insurance (Beck et al. 2019).

While there is evidence that mangroves reduce flood heights and there are links between flood risk and property value, there is currently no direct evidence linking mangrove presence to property value. However, there are indications that the presence of mangroves or other coastal systems could possibly influence insurance rates.

Strength of Evidence

Low. While there is no existing direct evidence linking reduced flooding and erosion associated with mangrove presence to property value, there is evidence of mangroves reducing flood height and extent and erosion, as well as information relating flood risk to property value, which allows some extrapolations for the existence of this link. The existing evidence was consistent, but did not address this direct relationship, and there are no methods in the existing literature to test this relationship. Applicability is also low for this link because property value is affected by many external factors and there is no evidence that demonstrates the extent of their influence.

Other Factors

While the relationship between mangrove property protection from erosion and flooding and property value is not directly studied in the literature, sources suggest that this relationship would depend on characteristics of the property, frequency of flood events, the property market, and both the buyer and seller having access to knowledge of flood risks.

The value of a property is determined by a multitude of factors, including the amenities associated with the property's location. Many properties located in the coastal flood zone include inherent amenities, such as beach access or a sea views, which externally affect the value of the property and may outweigh any impact the risk of flooding has on property value (Beltrán et al. 2018; Rajapaksa et al. 2016, 2017). Inland properties may have more noticeable differences in property value resulting from the presence of protective mangroves. Similarly, the existence and nearness of other flood mitigation methods to the property may also impact the property value (Beltrán et al. 2018). Other characteristics of the property, including nearby property values in the neighborhood, the home's condition, and several others, also externally impact the value of properties (Rajapaksa et al. 2017).

The frequency and recency of flood events may also impact the value of a property. Discounts for inland houses within a 100-year floodplain are –2.9% on average and rise to –6.9% immediately after a flood, indicating that recent floods cause homeowners to alter their perceptions of flood risk and its relationship with property value (Beltrán et al. 2018). Some studies find the recovery of property markets to occur within 3–5 years of the flood event, indicating that flood risk mitigation by mangroves may not have a lasting impact on property value in areas with less frequent flooding. Property values in regions with more amenities (e.g., coastal areas) are shown to recover faster (Rajapaksa et al. 2017).

This relationship is also dependent on both the buyer and seller having access to updated, accurate information about flood risk for the property. If property buyers underestimate the cost of flooding, or if they are relatively unaware of flood hazards, there might be little reduction in the value of properties within a floodplain (Atreya et al. 2013; Bartosova et al. 2020). Results in Queensland, Australia, further suggest that property buyers are more responsive to the actual incidence of floods than to the disclosure of information to the public on the risk of floods, indicating that even if people have access to knowledge about flood risk, property values tend to be more reactive and affected by actual flood events (Rajapaksa et al. 2016).

Predictability

Because of limited information on this link, there is limited information on the predictability of this relationship. Extrapolations from existing evidence seem to indicate that mangrove-facilitated property protection would have a larger impact on property value for inland properties, and there may be limited to no impact on the value of coastal properties because of the high value of coastal properties regardless of flood risk. Further, if mangroves are able to reduce insurer payouts by protecting property from erosion and flooding, there may be a decrease in property insurance premiums.

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LINK 53: THREATENED AND ENDANGERED SPECIES PERSISTENCE → RECREATION

Description of Relationship

Mangrove forests are an important site for wildlife-based tourism and recreation because of their support for diverse flora and fauna. Recreational activities such as birdwatching, sport or recreational fishing, wildlife observation, boating, photography, and hiking are popular within mangroves, in part because of their biodiversity, including threatened and endangered plant and wildlife species. There is evidence that wildlife populations, including threatened and endangered species, may be a driving factor for recreation in mangrove areas, but there is a gap in the understanding of the causal relationship between the persistence of these threatened and endangered species and recreational activities. The literature does not clearly address whether these species are directly supporting recreation, and if a change—or how much of a change—in their populations would affect recreation.

Summary of Evidence

Mangrove forests play a crucial role in providing habitat to a wide variety of flora and fauna as a result of their complex vegetation structures, sheltered environments, rich in food resources, and safe foraging and breeding grounds (see Links 5 and 13). Mangroves provide habitat for a variety of threatened and endangered species, and the characteristics of mangrove forest ecosystems may help these species persist (see Link 31). The concentration of these species in mangrove forests provides an ideal space for wildlife-centered recreation including birdwatching, photography, sport or recreational fishing, wildlife observation, boating or canoeing, and hiking, but the literature does not identify a direct causal link between threatened and endangered species persistence and recreation (Ahmad 2009; Carvache-Franco et al. 2020; Hakim et al. 2017; Jusoff and bin Hj. Taha 2009; Marasinghe et al. 2021; Spalding and Parrett 2019).

A global analysis of mangroves as sites for wildlife-based recreation and tourism found that the scale and geographic extent of mangrove tourism and recreation includes almost 4,000 attractions in 93 countries, with two-thirds of attractions found in the Americas and Caribbean. The most widespread recreational activity recorded in the analysis was boating, which includes canoeing and kayaking, and was often centered around wildlife watching. Other popular activities recorded included birdwatching and fishing. Wildlife recreation attractions in mangrove areas globally included observations of species including alligators and crocodiles, birdlife, bioluminescent plankton, fireflies, manatees and dugongs, and monkeys (Spalding and Parrett 2019). While Spalding and Parrett's (2019) global analysis of wildlife-based mangrove recreation did not directly address the relationship between endangered species and recreation, mangrove forests support a wide diversity of threatened and endangered species, many of which are central to wildlife-based recreation in mangrove areas (see Link 31).

In the Yucatan Peninsula, Mexico, some communities use endangered Antillean manatees for tourism purposes, including observation of manatees during boat trips, but there are few organizations that explicitly perform this activity (Robles Herrejón et al. 2020). The Sundarban Mangroves in Bangladesh and India are home many threatened and endangered species, including 17 flora species, 10 reptile species, including six species of nearly extinct or threatened tortoise and turtle species and three species of endangered lizards and monitors, three bird species, including the rare grey-headed fish eagle and Pallas's fish eagle, and eight mammal species (Gopal and Chauhan 2006). This mangrove forest ecosystem provides tourism services to local and international visitors, suggesting a relationship between the presence of threatened and endangered species and recreation within this area (Nobi et al. 2021). In the US Virgin Islands, red mangrove prop roots and canopies support a rich biodiversity of marine life, including four threatened coral species and the endangered hawksbill sea turtles through the reestablishment of sponges, a key component of their diet (Rogers 2019). These species are important to the tourism and recreation associated with coral reefs within the US Virgin Islands, and their loss may result in reduced recreation in this area (Pittman et al. 2018).

While the majority of these studies do not directly address the link between threatened and endangered species persistence and recreation, they indicate a relationship between the presence of wildlife and recreation within mangrove areas, many of which are home to threatened and endangered species. From this, an aggregation of the literature suggests that threatened and endangered species within mangrove areas may contribute to recreation, but this direct causal link is weak within the literature and there is no information about how changes in threatened and endangered species persistence would affect recreation.

Strength of Evidence

Fair. Evidence for a relationship between threatened and endangered species persistence and recreation in mangrove areas is documented and consistent within peer-reviewed scientific literature, but lacks causal linkages. The evidence included information from a variety of geographic locations, including a global review paper. While the literature indicates a relationship between wildlife and recreation in mangrove areas, the relationship does not necessarily address the influence of threatened and endangered species persistence. Further, any relationship that can be extrapolated is not necessarily causal and there may be some uncertainty in deciphering if threatened and endangered species persistence is a driver of mangrove-associated recreation activities or just a benefit observed by tourists and recreationists.

Some popular recreation activities (e.g., birdwatching, fishing) are directly related to wildlife populations and are casually related so that if wildlife populations were to decrease or increase, the amount of recreation could reasonably be assumed to increase or decrease. However, for many of the recreation activities that occur in mangrove areas (e.g., hiking, canoeing, photography) it is unclear from the literature if the existence of wildlife is a driver of recreation activities, or if wildlife presence and observation is simply a nice feature of recreation within mangrove areas but does not directly drive the occurrence of those activities. Similarly, it is unclear the role of threatened and endangered species persistence in recreation activity. Based on existing literature, it is not possible to know how changes in threatened and endangered species populations would affect recreation, or if it would have an effect at all (i.e., if these species disappeared, would it be possible for another similar species to fill this recreational niche).

Other Factors

The external factors that influence the relationship between threatened and endangered species persistence and recreation within mangrove ecosystems are very similar to those in Link 29 (wildlife populations → recreation). These factors include mangrove site accessibility, local community involvement, the quality of mangrove ecosystems, and the availability of mangrove tourism and recreation programs (Ahmad 2009; Hakim et al. 2017). Policies that conserve and protect mangroves have been found to benefit recreation activities because they promote biodiverse natural systems which people recreate in more frequently (Ahmad 2009). However, it has also been noted that the dense vegetation and root structure and muddy environment of mangroves may be a barrier for visitors exploring and recreating in mangroves (Hakim et al. 2017).

While policies that conserve and protect mangroves may benefit recreational activities, they may also hinder recreation associated with threatened and endangered species. The threatened or endangered classification of a species may result in strict protection policies and thus limited or no recreation in critical habitat areas for these species. In Mexico, tourism and fishing cooperatives have an internal agreement that implies avoiding the use of endangered Antillean manatees for tourist purposes because the presence and harassment from the boats may affect their behavior and could cause them to move far from their sites of regular use in the nature reserve. While this agreement is not respected by all members of the cooperative, special protections like this may result in reduced recreation in mangrove areas with highly protected threatened and endangered species (Robles Herrejón et al. 2020).

Predictability

While the literature does suggest a link between threatened and endangered species persistence in mangrove areas and recreation, Spalding and Parrett (2019) explicitly note that it is difficult to establish a direct link between mangrove wildlife populations and some forms of recreation that occur in mangrove areas. The relative importance of mangroves and their wildlife, especially threatened and endangered species, in relation to other features of interest varies considerably between attractions. There are many locations where mangroves are known to be the sole or core attraction, so it is likely that mangroves are attracting tens to hundreds of millions of visits per year worldwide, but it is unclear whether the threatened and endangered species that mangroves support are also a driver of recreationists and tourists for some recreation activities that do not directly involve wildlife (e.g., boating, hiking, photography). For example, Everglades National Park typically hosts one million visitors per year. It includes many habitats and a broad range of activities, so it is not possible with current data to know the role of mangroves and their associated threatened and endangered species in driving such numbers (Spalding and Parrett 2019). While mangroves or the wildlife they support—including threatened and endangered species—may not be a primary driver for destination and recreation, they offer a popular attraction. They may therefore influence destination choice and recreation activities, and their popularity appears to be growing (Marasinghe et al. 2021; Spalding and Parrett 2019).

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LINK 54: RECREATION → EROSION

Description of Relationship

There is some evidence that coastal recreation can enhance erosion of the shoreline. This can occur through increased wake and waves by recreational boat vessels, or potentially through the trampling of vegetation by foot traffic. Evidence for these relationships is scarce and extrapolations had to be made because the literature does not describe these relationships in mangrove ecosystems.

Summary of Evidence

Coastal erosion has increased in many locations from the consequences of human activity, including coastal recreation (Sanjaume and Pardo-Pascual 2005).

The relationship between erosion and wake and waves caused by recreational boat vessels was measured in rapidly eroding areas of the Boston Harbor Islands with high boat wake traffic. This study found that boat wakes can increase wave attack along shorelines, which may accelerate shoreline erosion. Boat wakes contribute significantly to energy reaching the shoreline, introducing larger waves and an order of magnitude increase in energy at the shoreline than the natural wave climate, which may contribute to shoreline erosion, especially in low-energy zones or during calm weather (FitzGerald et al. 2011). This relationship was also studied in the Chesapeake Bay, where it was found that frequent or intense vessel traffic can contribute to erosion of coastlines, which can be particularly evident in sheltered systems where shoreline erosion should be minimal in the absence of boat waves. In the Chesapeake Bay, 15% of the shorelines examined were experiencing high erosion (≥0.3 m/yr) that could not be attributed to wind wave energy, and thus it was assumed that at least some of this erosion was caused by vessel wake (Bilkovic et al. 2018).

Studies in nonmangrove areas have also found an increase in erosion from foot traffic associated with coastal recreation. Increased recreation in an area can lead to the trampling of vegetation, which may reduce plant life and increase susceptibility to wind and wave erosion (Burden and Randerson 1972; Carlson and Godfrey 1989; Kerbiriou et al. 2008). While this exact mechanism was not detailed in the literature, it may be because the roots of vegetation help to stabilize soil. This relationship has been studied at the Richard T. Crane, Jr. Memorial Reservation in Massachusetts, but it is unclear if extrapolation to mangrove systems is possible because of differences in vegetation (Carlson and Godfrey 1989).

Strength of Evidence

Low. Evidence for the relationship between mangrove-associated recreation and erosion does not currently exist in the literature. There is limited evidence that recreation can cause erosion because of increased wake and waves by recreational boat vessels, or through the trampling of vegetation by foot traffic. Extrapolations could potentially be made to understand how this relationship would affect mangroves, but it is unclear whether it would be reasonable/relevant to apply current evidence to mangroves because of the unknown impact of external factors.

Other Factors

Increased erosion caused by wake and waves caused by recreational boat vessels can be impacted by environmental parameters (water depth, seabed characteristics, tidal flows, natural waves) and by factors related to the vessel producing them (water line length, displacement, trim, loading, velocity, method of propulsion course, rate or change of course) (Bilkovic et al. 2018; FitzGerald et al. 2011). In more exposed regions or during storms and increased natural wave energy, wake-enhanced energy is not as significant (FitzGerald et al. 2011). Wakes tend to be most harmful in shallow and narrow waterways, or areas where there is low wind wave energy. While each boat passage generates a complex series of waves with unique characteristics, wake wave height can be reasonably predicted by vessel speed.

The frequency of vessel passage influences the overall amount of boat wake energy impacting a shoreline, with highly traveled waterways more likely to experience boat wake-induced shoreline erosion than those that are less frequently traveled. This may also vary temporally, with certain times of the year having increased boating activity (Bilkovic et al. 2018).

Regarding recreation-induced vegetation trampling, the species of vegetation may differ in their resistance to trampling, and thus each area may vary in its resistance to erosion from recreation (Burden and Randerson 1972).

Predictability

Because of the limited information on this relationship, the predictability is unclear.

Local Context

The workshop group at Jobos Bay reported observations of damage to fringe mangroves and associated erosion in areas that people frequent with boats. There are certain areas that are popular celebration locations, and when many boats tie up on the same location in the mangroves, damage can occur.

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LINK 55: AESTHETICS → RECREATION

Description of Relationship

Recreation in natural spaces is an important ecosystem service that can include activities such as kayaking, boating, fishing, wildlife viewing, and bird watching. There is evidence that suggests, while not the primary reason for recreation or tourism, mangrove aesthetics do contribute to recreational value, especially in regard to mangroves' unique biological features. While research exists on the recreational value people place on mangroves, there is relatively little evidence to link aesthetics with recreational activity. It is important to emphasize that mangrove aesthetics is only one factor among many that may impact recreation and tourism decisions (e.g., see Links 29 and 53).

Summary of Evidence

Visitation to and enjoyment of natural areas is recognized as one of the most prominent cultural ecosystem services (Balmford et al. 2015). *Ecotourism*, also called *nature-based tourism*, is a method of responsible travel that focuses on educating visitors, supporting the local population, and conserving the environment that has become popular in recent years (TIES n.d.). Mangrove ecosystems have increasingly become recognized as destinations for nature-based tourism. The rise of ecotourism and increasing awareness of mangrove ecosystems' value as a tourist and recreation destination has prompted research to understand mangrove tourism programs and what factors affect people's choices to recreate in these areas, as well as ensure that they sustainably support mangrove ecosystems (Hakim et al. 2017).

While mangrove ecosystems have been identified as important nature-based tourism destinations, the significance of the aesthetic appeal of mangrove ecosystems in the context of tourism is still not fully understood or appreciated. However, visitors are often drawn to mangroves' unique features, which differ from other tropical ecosystems (Hakim et al. 2017).

The benefits and appreciation of mangrove aesthetics vary depending on the type of recreational user. Tourism and recreation can be enjoyed by a variety of visitors, from international tourists to local residents. One study conducted in Mexico's coastal region found that mangrove ecosystems were most enjoyed by local populations, who are 2.2 to 2.5 times more likely to take photos of mangroves than other groups, which was seen as an indicator of aesthetic appreciation (Ghermandi et al. 2020).

Green spaces are highly valued as community assets, contribute aesthetic value, allow for the development of flora and fauna, and can provide recreational and economic benefits to the community. Mangrove vegetation can be seen as green space, and research conducted in Mamuju Regency, Indonesia, suggests that, when managed and preserved properly, mangroves have high aesthetic value associated with other recreational green spaces (Marsawal 2020).

Compared to coral reefs, sandy beaches, or other popular coastal tourist destinations, mangroves have not been as historically popular for tourism or recreation. A survey conducted in Indonesia suggests that people are less drawn to the muddy environment found in mangrove ecosystems and are sometimes physically obstructed from exploring mangroves due to their dense root structure (Hakim et al. 2017). While aesthetics of the mud and dense roots may play into recreation decisions, this is only one factor that contributes to instances where these sites are less attractive for ecotourism activities such as kayaking, sightseeing, and fishing.

Strength of Evidence

Fair. Evidence for the relationship between aesthetics and recreational activities is documented but quite limited. While there are many studies that examine recreation and tourism in mangrove areas, very few elaborate on how aesthetics of a mangrove site factor into the amount, type, or existence of recreational opportunities. Many of the studies that mention mangrove aesthetics as it relates to recreation were conducted in Asia.

Other Factors

It is difficult to definitively state the connection between mangrove aesthetics and recreation because of the multitude of factors that affect people's recreational preferences. One study found that important factors influencing destination attractiveness for nature-based tourism included the international importance of the location, biodiversity of plants and animals in the region, the presence of rare plants and animals, hotel and hostel accommodations, trail availability, and more (An et al. 2019). Nature-based tourism represents only a small subset of global tourism, and many people may weigh other factors such as famous destinations, more urban areas, and sandier beaches when deciding where to recreate. The status or type of mangrove forest may also impact the quality of mangrove aesthetics and recreation in those spaces.

The use of mangrove areas for ecotourism and recreation may create positive or negative feedback loops. Intact mangrove forests may be more appealing to recreate in, thus funding further mangrove protection and management. However, the opposite can occur if tourism and human activities occur unchecked in mangrove ecosystems. Ecosystem overuse can result in degradation or harm to the ecosystem, which might negatively impact not only the species and biological processes within the habitat, but also might ultimately make the area less attractive to recreate in (Nash 2001).

The location of the site is another factor to consider. More accessible mangroves will draw more tourists and people seeking recreation than those in obscure, difficult-to-reach areas. Mangrove ecosystems with recreational infrastructure in place will also likely be preferred.

Ultimately, recreational destinations are largely dependent on personal preferences. If a person prefers the aesthetic of mangrove foliage, then mangroves may encourage individuals to recreate in/around the ecosystem. However, individuals who do not value the appearance of mangroves will likely place a lower value on mangroves as recreational sites.

Predictability

Because of the limited and inconsistent information available, the relationship between mangrove aesthetics and recreation is not predictable. There is no evidence directly linking mangrove aesthetics to recreation, and information presented here is mostly based on inference. Aesthetics of a mangrove site is one factor of many that determines whether a particular person decides to recreate there. Additionally, the subjective nature of aesthetic preferences means that there is no reliable way to predict how changes to mangrove aesthetics will impact recreation.

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