The Climate-Smart Mangrove Tool

A decision support tool for guiding climate-smart mangrove conservation, restoration and management

The University of Queensland Australia

WWF

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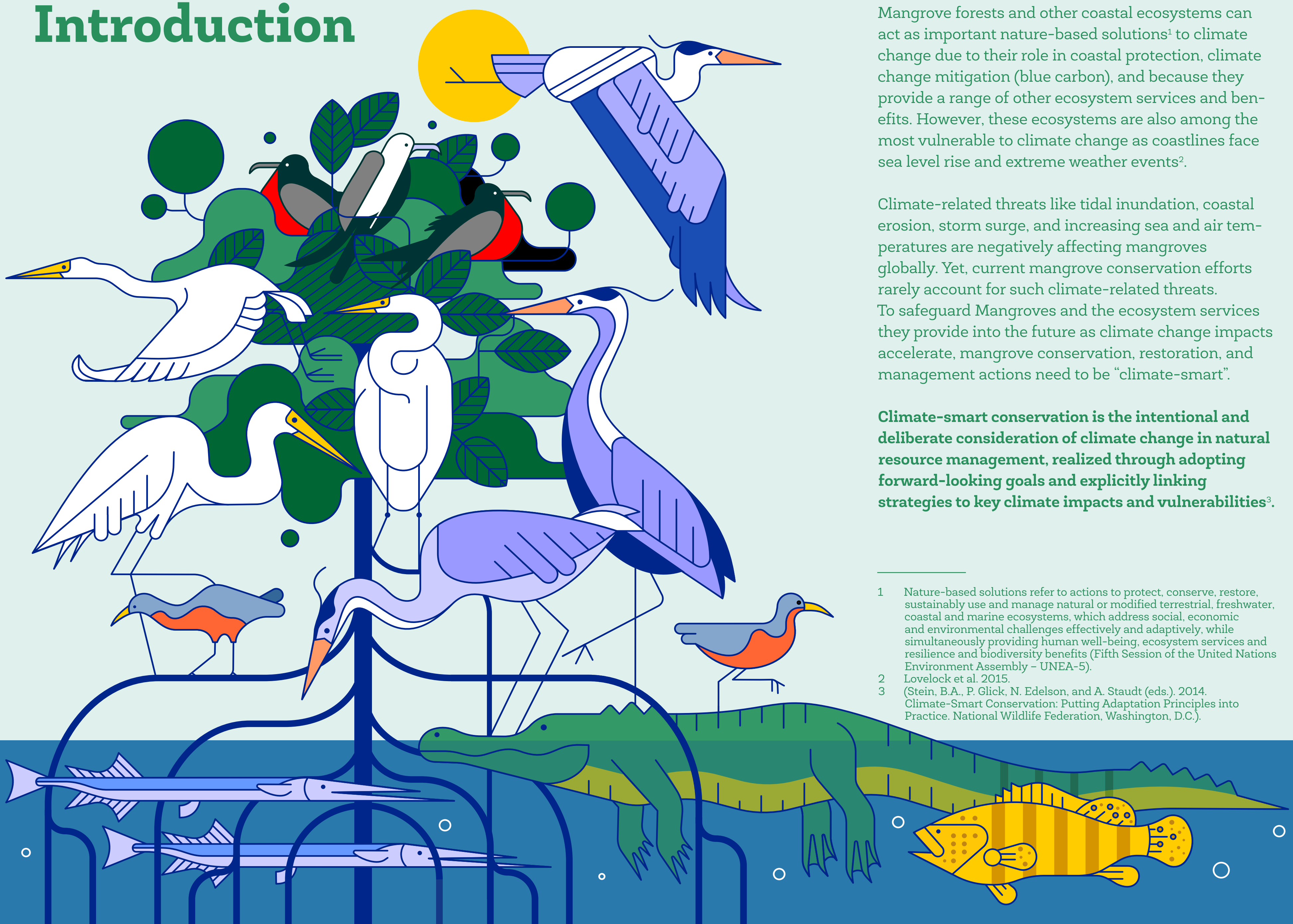
Introduction

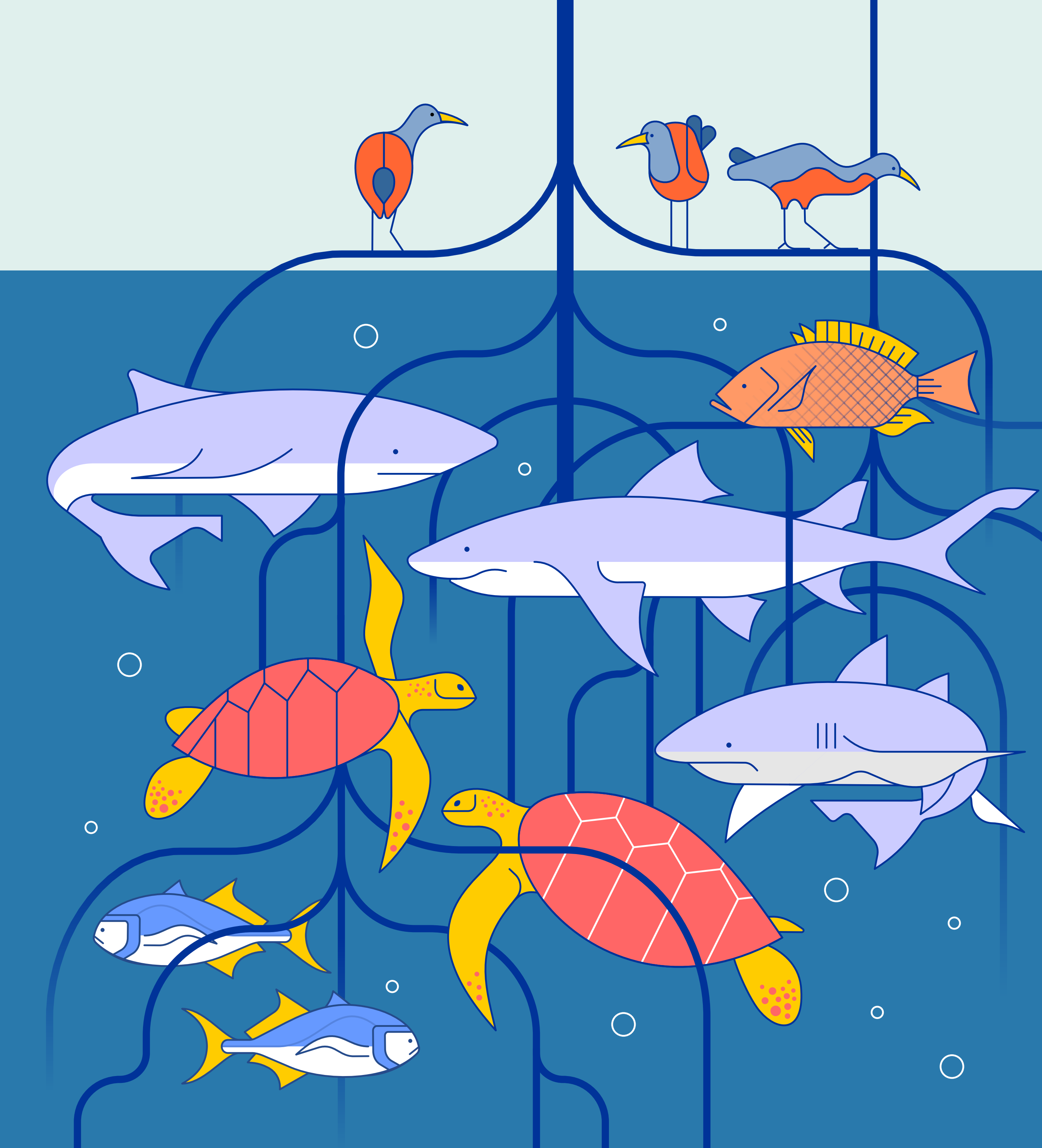


Mangrove forests and other coastal ecosystems can act as important nature-based solutions[1] to climate change due to their role in coastal protection, climate change mitigation (blue carbon), and because they provide a range of other ecosystem services and benefits. However, these ecosystems are also among the most vulnerable to climate change as coastlines face sea level rise and extreme weather events[2].

Climate-related threats like tidal inundation, coastal erosion, storm surge, and increasing sea and air temperatures are negatively affecting mangroves globally. Yet, current mangrove conservation efforts rarely account for such climate-related threats. To safeguard Mangroves and the ecosystem services they provide into the future as climate change impacts accelerate, mangrove conservation, restoration, and management actions need to be "climate-smart".

Climate-smart conservation is the intentional and deliberate consideration of climate change in natural resource management, realized through adopting forward-looking goals and explicitly linking strategies to key climate impacts and vulnerabilities[3].

1 Nature-based solutions refer to actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits (Fifth Session of the United Nations Environment Assembly – UNEA-5).
2 Lovelock et al. 2015.
3 (Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C.).



The development of climate-smart strategies is underpinned by knowledge of the vulnerability to climate change of a given ecosystem, which can then guide adaptive responses (Figure 1). Climate change vulnerability assessments follow a standard process comprising the identification of exposure to climate threats, evaluation of the sensitivity to those threats combined with an understanding of the adaptive capacity of the system, including social and environmental factors that can influence adaptation. Vulnerability assessments support management of socio-ecological systems like mangroves and the communities that rely on them by increasing knowledge of threats and associated risks and illuminating potential adaptive solutions.

The Climate-Smart Mangrove Tool provides conservation practitioners with a science-based methodology to select appropriate "climate-smart" actions to reduce the current and future impacts of climate change on mangrove ecosystems. The tool was developed by WWF and the University of Queensland, and has been applied in 4 countries–Colombia, Fiji, Madagascar and Mexico–as part of the Mangroves for Climate and Communities project (2020-2025).

Successful climate-smart strategies must be selected based on the unique ecological and social conditions of the mangrove forest site. The tool guides users through a series of steps to:

- Evaluate the vulnerability of mangrove sites based on site-specific biophysical characteristics and climate threats **(steps 1 to 3).**
- Assess socio-economic adaptive capacity conditions associated with the level of resources, community willingness, institutional/organizational capacity, governance, flexibility **(step 4).**
- Guide the selection and prioritization of climate-smart management actions to enhance the resilience of mangrove sites to short- and long-term climate stressors **(steps 5 and 6).**

The tool is intended to be used in conjunction with existing restoration, management, and conservation guidance, tools, systems, and processes. It focuses only on climate-smart components and considerations and does not cover all best-practice considerations for mangrove projects. Therefore, the tool is designed to supplement and not replace other established best-practice guidance or processes used by project teams to design project management activities (refer to Figure 2 on the adaptive management cycle).

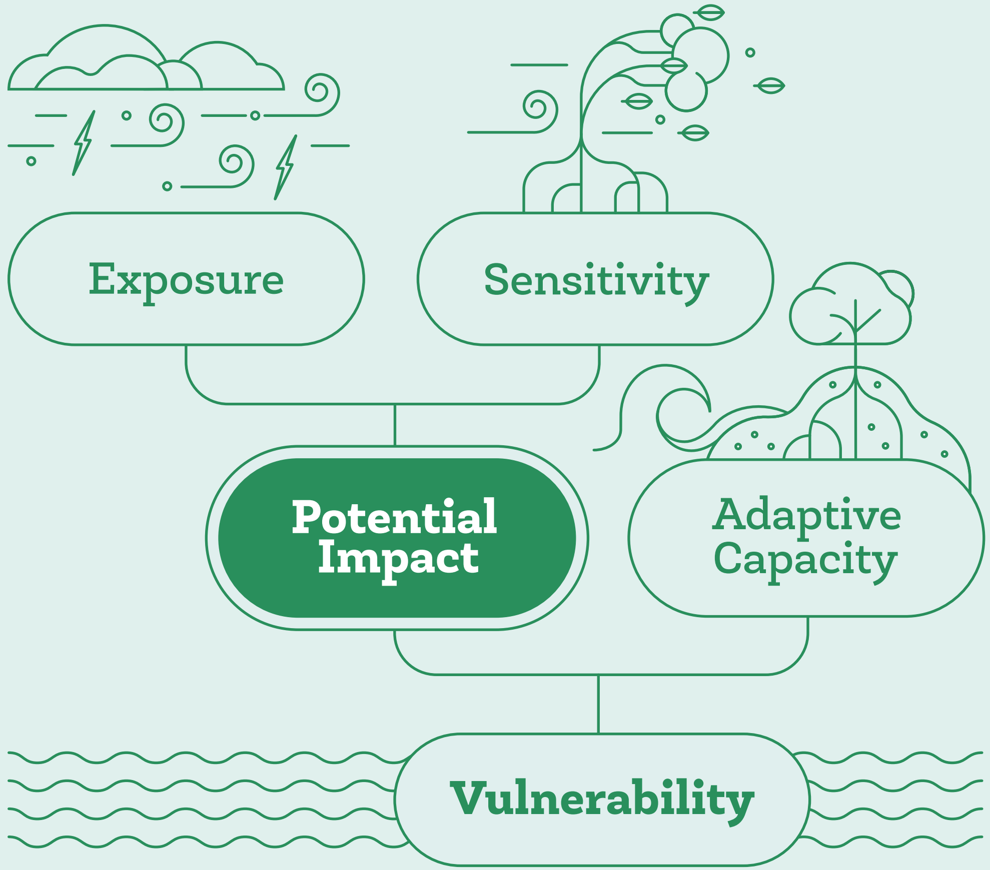


Figure 1 *Components of Climate Change Vulnerability*[4]

4 Adapted from Marshall et al. 2009

Other general guidance and tools are available for planning climate adaptation in ecosystem conservation and restoration, which can provide further information and options, including general guidance for protected area managers (IUCN Adapting to Climate Change https://portals.iucn.org/library/sites/library/files/documents/PAG-024.pdf), tools for Ramsar wetlands (e.g. IUCN https://www.iucn.org/sites/default/files/2022-08/vulnerability_assessment_and_adaptation_planning_guidance_note_final2.pdf) and nationally specific guidance (e.g. for Vietnam http://www.climatechange.vn/en/wp-content/uploads/sites/2/2016/12/VA-Approach_ENG.pdf). This tool is specifically for mangroves, and can be used together with the Best Practice Guidelines for Mangrove Restoration[5] and other Global Mangrove Alliance resources.

Steps 1 and 2 of the tool assess the biophysical **vulnerability** of mangroves to climate change by evaluating the **exposure** to climate change threats (e.g. sea level rise, rising temperature) and the **sensitivity** of the mangroves to those climate change threats based on site characteristics (e.g. sensitivity is influenced by geomorphic setting, mangrove ecotype and species composition). Anthropogenic threats, such as over-exploitation of timber and nutrient pollution, can increase mangrove sensitivity to climate change and reduce adaptive capacity, thereby increasing vulnerability by increasing the potential impacts of climate threats and by limiting recovery after disturbances. Management actions that reduce mangrove vulnerability thus often require directly reducing anthropogenic threats as part of a larger climate-smart management strategy.

Steps 3 and 4 draw together the exposure and sensitivities, which determine the potential impacts and the **adaptive capacity** of the system to identify key vulnerabilities to climate change[6]. The adaptive capacity describes the potential to modify or reduce the risks of climate change threats (e.g. through management actions like managing hydrological connectivity).

Figure 1 describes how potential climate change impact is a result of the site-specific sensitivities and exposure to climate threats (hazards) of the ecological system (e.g. mangrove ecosystem). This potential impact, combined with the adaptive capacity of the local social system, provide a measure of the vulnerability of the social-ecological system. Actions to reduce risk can focus on all components of vulnerability; however, there are limits to adaptation in most systems[7].

Steps 5 and 6 in the tool provide a range of management options that address factors of exposure, sensitivity, and adaptive capacity to reduce risks of impacts and build resilience. These steps use a prioritization process that enables the user to first identify climate-smart management actions. They also provide a framework for prioritizing actions based on several criteria that help evaluate whether management actions are sustainable and effective.

The tool is designed to be utilized in a workshop environment where a multidisciplinary group of practitioners, experts, researchers, and managers can work through the process in an iterative and collaborative manner. The tool also allows users to highlight and revisit identified data gaps, enabling a continuous process for the identification and adaptation of climate-smart management actions as conditions change and more information becomes available.

It is important to note that while the tool is designed to be as comprehensive as possible in supporting users to identify relative priority climate risks and interventions to address them, no single evaluated system or site will have perfect data. Users are encouraged to adapt the tool to their specific context based on capacity, time available, data limitations, and other relevant local conditions: developing actionable next steps is far more important than completing every step in the process.

5 Beeston, M., Cameron, C., Hagger, V., Howard, J., Lovelock, C., Sippo, J., Tonneijk, F., van Bijsterveldt, C. and van Eijk, P. (Editors) 2023. Best practice guidelines for mangrove restoration.

6 IPCC 2001 – Climate Change 2001 report

7 IPCC 2019 at https://www.ipcc.ch/site/assets/uploads/sites/3/2022/03/02_SROCC_TS_FINAL.pdf

Climate-smart Projects Adaptive Management Cycle

The process illustrated below provides an overview of the adaptive management cycle that was developed to guide the inclusion and assessment of climate-smart actions into mangrove restoration, conservation, and management projects.

The cycle is iterative. Periodic review and update of knowledge of climate threats, site characteristics, adaptive capacity and potential management actions for projects and sites may give rise to further insights for enhancing adaptation. The timing of periodic reviews may coincide with for example, management of new areas, changes in management goals, changes in governance or in response to extreme events, all of which provide opportunities to evaluate whether current management is climate-smart and what actions could further enhance climate adaptation and reduce climate risks.

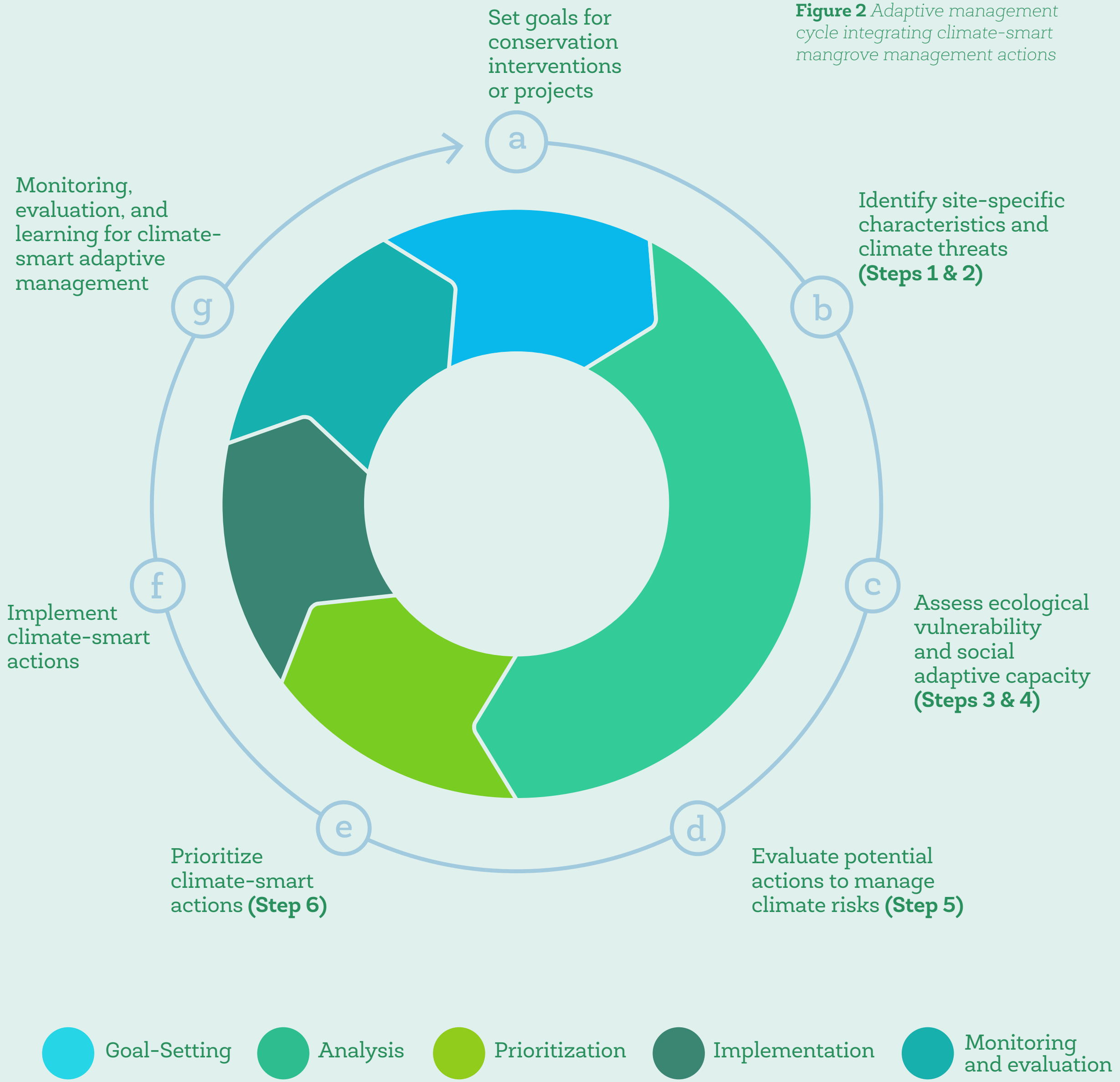


Figure 2 *Adaptive management cycle integrating climate-smart mangrove management actions*

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Decision Support Tool

Pg 52 Chapter 02

Supporting Information

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Who is the tool for?

The Climate-Smart Mangrove Tool is intended to assist practitioners in incorporating climate change considerations in the decision-making process and management of mangrove conservation (protection, restoration, and sustainable use) **projects.**

The tool can be used in a workshop setting[8] with a multidisciplinary group of practitioners, managers, specialists and experts, and local groups that are very familiar with the site (or sites) being evaluated.

Having a diverse group of people involved in the use of the tool is important to provide a broad range of views and information about the site's ecological characteristics and exposure to climate threats that contribute to vulnerability, and to determine which actions are likely to have the greatest impact for increasing and improving its adaptation to climate change impacts.

8 Reference duration of tool application workshop is 6 hours.

When can the tool be used?

The tool can be used at project inception, when a new project is being designed and management actions need to be identified as part of the project's scope and priorities. It can also be used for existing projects to assess the climate-smartness of proposed or current management interventions for conservation or restoration, and to identify additional actions needed to increase the resilience of project sites to climate change.

The tool can be used even with limited data, as expert opinion and local ecological knowledge can be used to rank climate threats and evaluate site characteristics. Low levels of data availability should not be an impediment to the use of the tool.

The tool supports an iterative and dynamic process. It is not designed to be used as a once off application, but rather throughout a project's lifetime (see Adaptive Management Cycle). It can be used to identify data gaps that limit confidence in decision making and can inform the design of monitoring or data collection programs that are specific to climate change. It can also be used periodically throughout the project design and implementation phase, and future project phases, to ensure that prioritized actions are climate-smart.

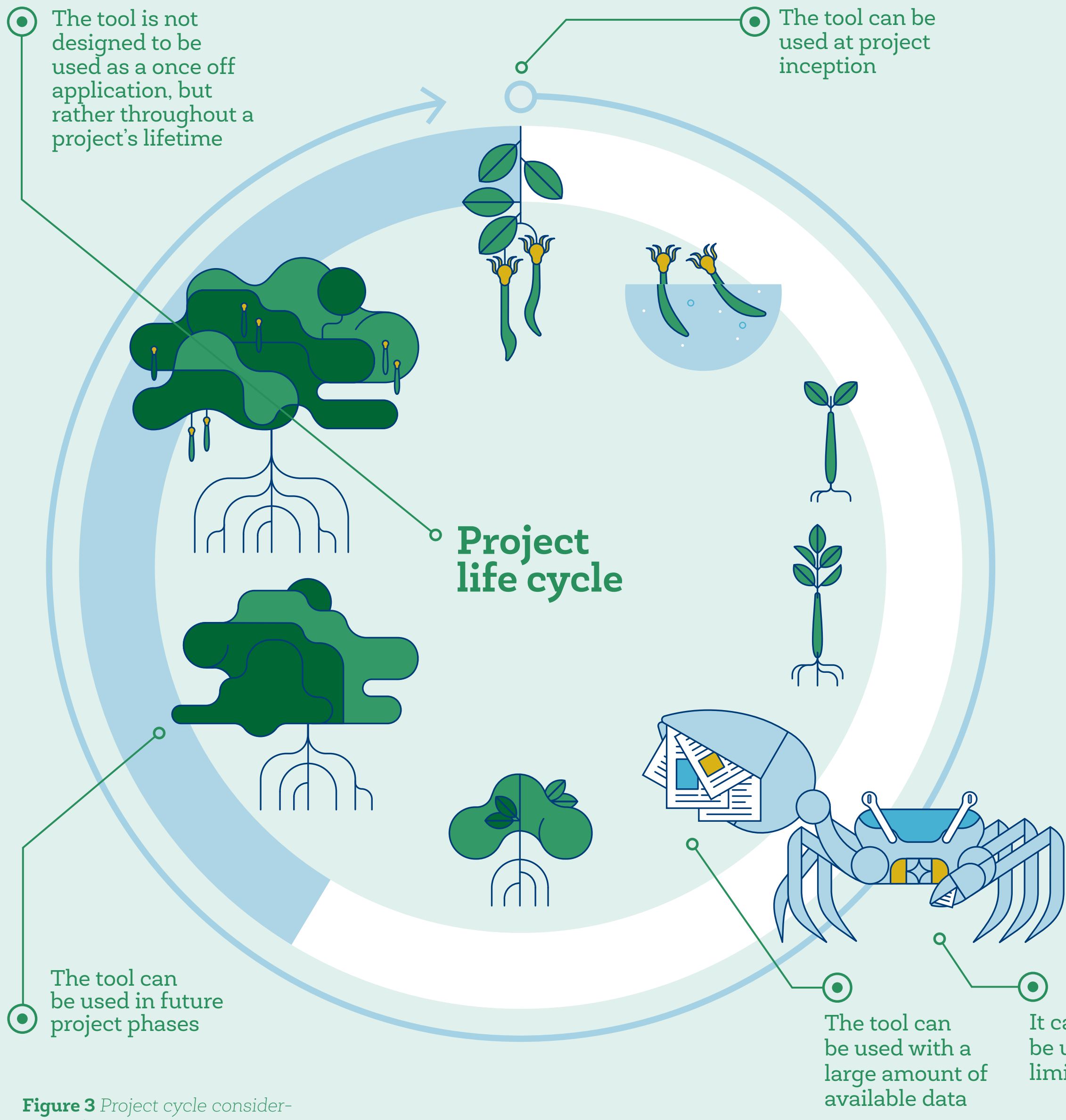


Figure 3 *Project cycle considerations for applying the tool*

Using the tool

The folowing section provides a step-by-step explanation of how to use the tool. Additional guidance on how to complete each step is provided in the detailed section for each step (see specific page numbers in the bottom right corner).

Although typically in vulnerability assessments climate threats are assessed first, this tool starts with evaluation of site characteristics or sensitivity. This approach was chosen because in workshop settings this enables the workshop participants to fully familiarize themselves (ground themselves) with the project or site that is under evaluation.

Step 1

Identify Site Characteristics

In the MS Excel worksheet tab labeled **'Step 1 – Site Characteristics'**, identify each of the specific characteristics as they relate to your site using the dropdown lists.

If you have a heterogeneous site (ie one that has multiple mangrove ecotypes, e.g. seaward fringing mangroves, basin mangroves and adjoining marsh ecosystem) then you will have to evaluate the characteristics and vulnerability of each habitat separately.

The climate threats may be similar across the site/project, but the vulnerability of different habitats could differ because of their different characteristics.

Mark as 'not applicable' those that are not relevant to your site.

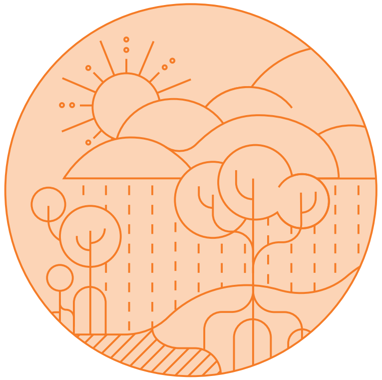
You can work with as many spreadsheets as you have habitat types.

Leave cells blank that are applicable to your site but required further information to complete the assessment.

The tab labeled **'Step 1 – Characteristics Table'** provides more information and details for each characteristic and sub-characteristic to help you determine which is applicable, as well as reference values to be used to rank risks in Step 3.

Make a note of the sources of information and knowledge, as well as a brief description of the site as it relates to that characteristic, in the justification column (C).

More information on page 22



Step 2

Assess the Climate Threats

Using the MS Excel worksheet tab labeled '**Step 2 – Climate Threats**', work through the **six climate threats and assess how they apply to your site**.

In the "rank" column (B), select a ranking for each factor and write a site-based justification (in column D) for your choice (i.e., the data/information sources used to make the determination, the site-based or historical knowledge and the source of that knowledge, etc.).

The tab labeled '**Step 2 – Exposure Table**' provides details on how to identify and assess each climate threat.

More information on page 28

Step 3

Combine Climate Threat and Site Characteristics

The site characteristics identified in Step 1 and the climate change threats (exposure factors) and their rankings selected in Step 2 will auto-populate in the tab labeled **'Step 3 – Vulnerability Assessment'**.

For each moderate, high, or very high "climate threat" category from Step 1, assess the level of "vulnerability" of your site (select from the drop-down menu), based on site characteristics.

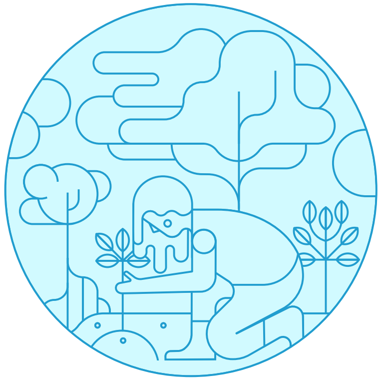
Identify specific vulnerabilities from the combination of every relevant (selected) climate threat factor and site characteristic. For example, if more high intensity rainfall events are projected for your region in the future (very high exposure) and your site has low elevation, the combination of this climate threat and elevation characteristic will result in high risk of flooding, which will negatively impact the mangrove.

Add details to the justification column and indicate your level of confidence in this evaluation.

Where combinations of climate threat type and site characteristic type are typically not relevant or a priority, the sheet cells for these areas will automatically gray out.

Vulnerability assessments for each combination that are given very low-to-medium levels of confidence should be revisited once additional information is available.

More information on page 34



Step 4

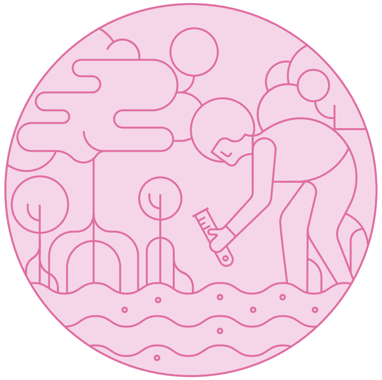
Identify and Assess Adaptive Capacity

Use the MS Excel worksheet tab labeled '**Step 4 – Adaptive Capacity**' to evaluate the social conditions that influence the vulnerability of the mangrove site and that enable or inhibit potential management actions to enhance adaptation.

To assign a rank from low – to – very high, use the information provided in the **Step 4 – Adaptive Table** tab, and provide a written justification for your choice.

Evaluating the adaptive capacity will also provide insight into the feasibility and constraints of your potential climate-smart management actions as they relate to local, regional, or national socio-economic conditions.

More information on page 38



Step 5

Identify Possible Climate -Smart Management Actions

Using the MS Excel worksheet tab labeled '**Step 5 Possible Actions**' and the tab labeled '**Step 5 – Actions Table**', identify appropriate actions related to the findings from the previous steps.

The outcomes of the vulnerability assessment conducted in Step 3 and the adaptive capacity assessment conducted in Step 4 are summarized in the **Summary Step 3 & 4** tab.

Use the information provided in this summary tab to **evaluate the identified management actions** that are specific to the climate threats and/or site characteristics targeted, as well as the adaptive capacity components associated with the action.

Pause at this stage to check the logic of the potential management actions, in terms of the specific vulnerability they would address. This is important to ensure that the selected management actions are climate-smart.

More information on page 42

Step 6

Prioritize Management Actions

The MS Worksheet tab labeled '**Step 6 – Prioritize Actions**' automatically populates the actions identified in Step 5 and guides you through a process of prioritization.

For each action, work through the columns and, using the dropdown boxes, **identify the importance, feasibility, benefits/impact, cost, urgency, likelihood of success, equity, and timing of each action** for your specific site/project.

Use the information provided in the **Step 6 – Prioritization Table** as guidance for this assessment.

More information on page 50

Key Considerations

This tool has been developed for the use of WWF and other mangrove conservation practitioners around the world. It can be used for specific project sites as well as at larger scales (e.g. regions). Examples of the tool's application can be found on WWF's Mangrove for Community and Climate project site.

The climate threats (exposure), site characteristics (sensitivity) and adaptive capacity included in the tool are important for projects to consider when assessing the risks climate change poses to their mangrove conservation and restoration efforts and to devise management actions to remediate these risks. However, there are other aspects that are not included in this tool that may be relevant to specific projects or locations, which can be integrated into the tool's use as appropriate. For example, certain institutional and governance arrangements for coastal wetlands can be unique to different countries or even states within countries. Additionally, while the tool assumes low levels of data availability, in some locations data will be abundant, and therefore quantitative (rather than qualitative) assessments could be conducted, along with modeling the outcomes of interventions[9]. Irrespective of the data availability, the process of applying the tool remains the same.

There are numerous global, regional, and national datasets, databases, spatial tools, and maps available that can be used to inform the tool's application where site-specific or field data is not available. Where appropriate these have been cited in the relevant sections[10], but likely improved resources will become available over time. The links and references included in this document provide users with additional sources of information if needed, but they are not exhaustive. Other sources may also be available and should be consulted if relevant to the project, site, or region.

9 Mazor et al. 2021 present examples of quantitative assessments

10 For example, Worthington et al. 2020

Schematic Overview

Step 1

Identify Site Characteristics

1. Geomorphic Setting

2. Relief and Elevation

3. Mangrove Ecotype

4. Tidal Range

5. Past Shoreline Change

6. Sediment Supply

7. Mangrove Condition

8. Ecological Connectivity

9. Land Use & Barriers

+

Step 2

Assess the Climate Threats

1. Increased rainfall

2. Decreased rainfall

3. Increased wind exposure

4. Increased wave exposure

5. Increasing air temperatures

6. Increasing sea level

>

Step 3

Combine Climate Threats and Site Characteristics

Vulnerability Assessment

Site Characteristics

+

Climate Threats

+

Step 4

Identify and Assess Adaptive Capacity

1. Level of resources

2. Community willingness

3. Institutional / organizational capacity

4. Governance

5. Flexibility

>

Step 5

Identify Possible Climate-Smart Management Actions

Based on key ecological vulnerabilities and social adaptive capacity aspects

>

Step 6

Prioritize Management Actions

1. Importance

2. Feasibility

3. Potential benefits / impact

4. Cost

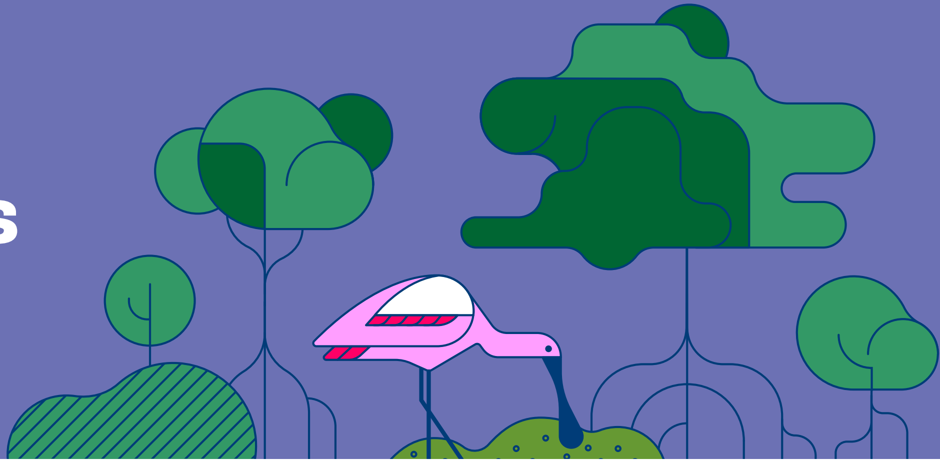
5. Urgency

6. Chance of success

7. Equitability / justice

8. Time to impact

Step 1 | Identify Site Characteristics

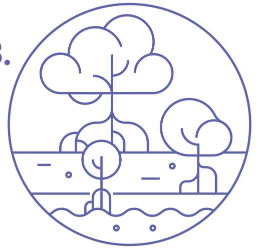


Populate the tab titled "Step 1 - Site Characteristics" in the MS Excel worksheet. Use the "Step 1 - Guidance" (or Table 1 below) to guide your responses.

There are nine site characteristics:

1. 
Geomorphic Setting

2. 
Relief and Elevation

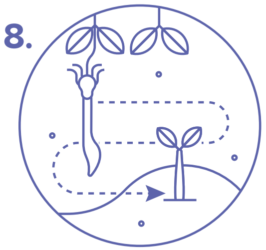
3. 
Mangrove Ecotype

4. 
Tidal Range

5. 
Past Shoreline Change

6. 
Sediment Supply

7. 
Mangrove Condition

8. 
Ecological Connectivity

9. 
Land Use & Barriers

- Each site characteristic has five categories (listed and described in Table 1)

Very Low | Low | Moderate | High | Very High

- Use information provided in Table 1, along with information on your site from:

Historical records | Data
Expert and local knowledge | Information sources and databases
Reports | Observations

- Select the relevant category from the dropdown box in Column C.
- For each selection, in Column D, write a justification and description of the characteristic and how you came to the category selection.
- If you are having difficulty completing this step because of lack of information or knowledge, you can use this as a prompt to develop a plan to collect more information.
- You might be able to answer some of the questions by including a specialist or manager with localized expert knowledge of the area in the process.
- It is acceptable to leave some sections blank while you collect more information and knowledge to complete the process. You can also select 'not applicable' for characteristics not relevant to your site.
- Use the Step 1 - Guidance tab to help guide the assessment.

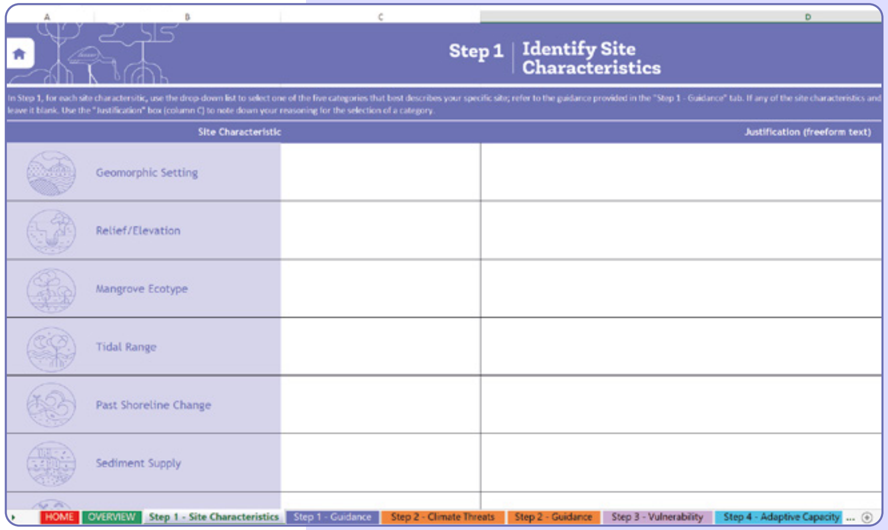
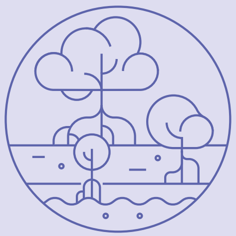


Figure 4 - *Illustration of the Step 1 process*

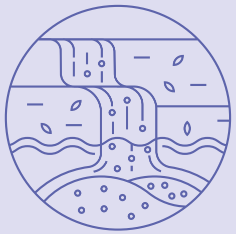
Site Characteristics and risk rankings
Table 1

Risk Ranking: Very Low, Low, Moderate, High, Very High

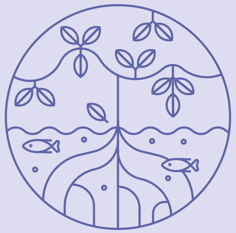
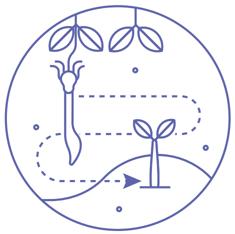
	Site characteristic	Risk Ranking	Explanation of potential impacts on the mangroves
	**Geomorphic setting**	Very Low: Within a delta Low: Within an estuary Moderate: Within a coastal lagoon High: Open coastline with low fetch (coastal embayment or bay) Very High: Open coastline with low to moderate fetch (coastal embay-ment or bay), and islands	Geomorphic settings vary in exposure to storm wind and waves (high in open coasts where fetch (wind-generated ocean waves – usually driven by the area of uninterrupted ocean surface) is greater). They vary in sediment supply (higher in deltaic settings and low in carbonate island settings) and thus the capacity to adapt to sea level rise. Risks of flooding from rivers can be high in estuarine and deltaic settings.
	**Relief and elevation (elevation above MSL)**	Very Low: Well above MSL (e.g. between mean high water spring tides and the highest astronomical tide Low: Moderate (e.g. between mean high water neap tides and mean high water spring tides) Moderate: Above MSL (between MSL and mean high water neap tides) High: At MSL Very High: Below MSL	Mangroves at higher elevation in the intertidal zone have lower risks from sea level rise than those at lower elevation (e.g., at mean sea level). Higher elevation mangroves are less exposed to wind and waves.
	**Mangrove ecotype**	Moderate: Scrub Low: Hammock Moderate: Basin High: Overwash Very High: Fringe	Different mangrove ecotypes have varying exposures and sensitivities - see Table 7.

Site Characteristics and risk rankings
Table 1

Risk Ranking: Very Low, Low, Moderate, High, Very High

	Site characteristic	Very Low	Low	Moderate	High	Very High	Explanation of potential impacts on the mangroves
	Tidal range	Macrotidal, very high (>6m)	Macrotidal, high (3 – 6m)	Mesotidal -high (3 – 4m)	Mesotidal - low (2 – 4m)	Microtidal (<2m)	High tidal range sites are less sensitive to sea level rise because the increase in tidal levels with sea level rise is a small proportion of the elevation range of the intertidal zone.
	Shoreline change	Minimal Erosion or accretion (<1m)	Low Erosion (1 – 2m)	Moderate Erosion (2 – 5m)	High Erosion (5 – 10m)	Very High Erosion (>10m)	High levels of erosion indicate physical conditions may be unsuitable for mangroves to establish or survive (i.e., wave, wind, and current energy is high).
	Sediment supply	Very High Water is highly turbid with high concentrations of suspended sediments	High Water is turbid year around	Moderate Water is turbid with sediment during wet seasons	Low Clear water for most of the year	Very Low Very clear water year-round	High sediment supply supports high rates of vertical accretion of soil, increasing elevation and therefore contributing to adaptation to sea level rise. Sediments deliver nutrients which can stimulate growth. Large pulses of sediments delivered in storms can smother mangroves and lead to mortality or alter hydrology which can contribute to extensive flooding, but smaller sediment pulses can stimulate plant growth and contribute to elevation.

Site Characteristics and risk rankings
Table 1

Site Characteristics		Risk Ranking: Very Low / Low / Moderate / High / Very High	Explanation of potential impacts on the mangroves
	**Mangrove Condition**	Very Low: Very Healthy Low: Healthy Moderate: Degrading High: Degraded Very High: Very Degraded	Understanding the existing condition of mangroves is important for understanding the extent of management required to increase resilience and the limitations to climate adaptation at some sites. Quantitative ecological measures can be used to determine condition through field assessments of health, or using aerial imagery.
	**Ecological Connectivity**	Very Low: Very high connectivity to sites with high number of reproductive mangroves to supply propagules Low: High connectivity to sites with high numbers of reproductive mangroves to supply propagules Moderate: Moderate connectivity to sites with reproductive mangroves to supply propagules High: Low connectivity to sites with re-productive man-groves to supply propagules Very High: No connectivity to sites with reproductive trees	Larger patches of mangroves are sources of mangrove propagules and biodiversity for adjacent sites. Larger patches are less exposed to damage from wind and waves. Areas of mangroves that are well connected and contain more reproductive trees, with evidence of reproduction through a high presence of propagules or seeds, are more likely to be self-sustaining.

Site Characteristics and risk rankings
Table 1

Risk Ranking

Very Low | Low | Moderate | High | Very High

Explanation of potential impacts on the mangroves

Site characteristic	Very Low	Low	Moderate	High	Very High	Explanation of potential impacts on the mangroves
Land Use & Barriers	Land is rural or natural with no impediments to landward migration Population <250 people/km^2	Land is rural with some impediments to landward migration (i.e., roads or walls). Sites may have man-made channels, earthen levees Population 250 – 500 people/km^2	Land is semi-rural with scattered buildings, agricultural and aquaculture developments. Sites may have dykes and dams Population 500 – 1000 people/km^2	Land is mostly urban with buildings, roads and other infrastructure that prevent mangrove establishment Population 1000 – 2000 people/km^2	Land is urban with permanent built structures and little opportunity for mangrove establishment Population >2000 people/km^2	Land-use adjacent to the intertidal zone can be a barrier to landward migration of mangroves with sea level rise. Population density has been used as an indicator of land-use. Low population density is associated with few structures on the land that would impede establishment of mangroves in landward direction. High population density is associated with intensive land uses (urban infrastructure) that offer few opportunities for landward migration. Some opportunities for conservation of mangroves can occur in areas around highly urbanized areas[11].

11 See Mazor et al. 2021 for more on the impacts and opportunities for ecosystem conservation adjacent to cities at https://doi.org/10.1016/j.oneear.2021.06.010

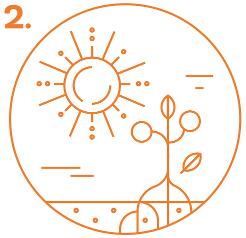
Step 2 | Assess the Climate Threats

Populate the tab titled "Step 2 - Climate Threats" in the MS Excel worksheet. Use the "Step 2 - Guidance" (or Table 2 below) to guide your responses.

There are six climate threats:

1. 

Increased rainfall

2. 

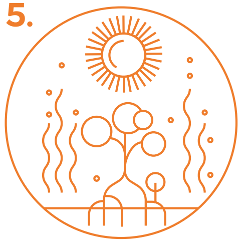
Decreased rainfall

3. 

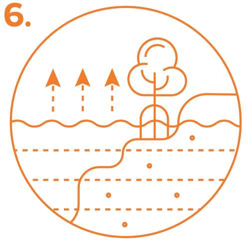
Increased wind exposure

4. 

Increased wave exposure

5. 

Increasing air temperatures

6. 

Increasing sea level

- For each climate threat assign a rank representing the level of risk and/or impact to your specific site.
- To determine the risk classification use:
  - Historical data
  - Reports
  - Mapping
  - Local knowledge
  - Expert advice
  - Publicly available databases
- Column C contains dropdown boxes with risk rank levels (very high, high, moderate, low, very low) and the cells will automatically color based on your selection.
- Re-read the rank explanation in Column D to make to make sure you are comfortable that it is appropriate for your site. In the in the justification column E, for each climate threat, explain how you came to the decision of the risk ranking selected.
- In Column D, name the sources of information and logic used so that others can understand why the decision was made if they were not part of the process.
- Use the Step 2 - Guidance tab to help guide the assessment.

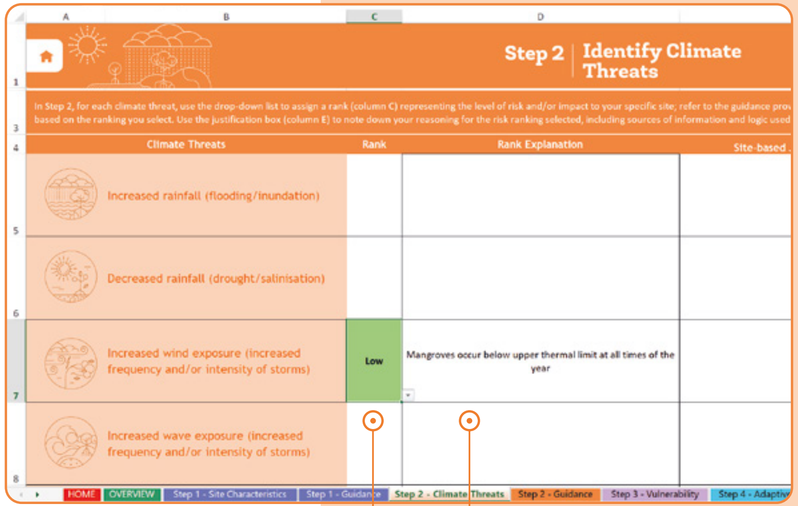
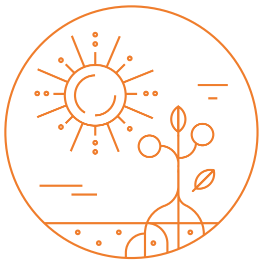


Figure 5 - *Illustration of the Step 2 process*

Climate Threats and risk rankings

Table 2

Risk Ranking: Very Low, Low, Moderate, High, Very High

Climate threat	Very Low	Low	Moderate	High	Very High	Explanation of potential impacts on the mangroves
 **Increasing air temperature (average annual)**	Mangroves occur well below their upper thermal limit at all times of the year	Mangroves occur below their upper thermal limit at all times of the year	Mangroves occur below their thermal limits but can approach their thermal limits in some warm years	Mangroves occur close to their thermal limit seasonally	Mangroves occur at their thermal limit for much of the year	Increasing air temperatures can reduce productivity where mangroves occur on their upper thermal limits, but increase productivity where mangroves occur at their lower thermal limit and can lead to poleward expansion. Increasing temperature increases evaporative demand and therefore mangroves close their stomata to reduce water losses, which reduces photosynthesis. High temperatures can have direct negative effects on populations. For example, the thermal limit for *A. marina* is where temperature of the warmest quarter is >37°C[12]. Sensitivity to increasing temperature varies among mangrove species.
 **Trend of increasing rainfall**	Limited change expected	Salinity of mangrove soils may be reduced	Salinity of soils reduced; increased flooding (i.e., 1m / event)	High rainfall events result in widespread intermittent flooding (i.e., 1.5m / event)	High rainfall events result in widespread and prolonged flooding (i.e., >2m per event)	Increasing rainfall could decrease salinity of soils which may result in increased growth of some species and potentially changes in plant community to those that are less salt tolerant. Widespread and prolonged flooding can result in mangrove mortality. The types of sites most at risk would be riverine and estuarine environments and those in basins (behind levees or sand ridges) where water can be trapped. The presence of land or anthropogenic features that limit drainage of sites could exacerbate impacts of increasing rainfall. Sediment delivery may be increased which could lead to enhancement in soil elevation contributing to resilience to sea level rise and nutrient delivery. The delivery of sediment pulses (sediment dumps) during floods can cause mortality of mangroves if aboveground roots are covered in sediments.

12 Martinez-Diaz et al. 2022 at https://onlinelibrary.wiley.com/doi/10.1111/ddi.13643

Climate Threats and risk rankings

Table 2

Climate Threats	Risk Ranking: Very Low	Low	Moderate	High	Very High	Explanation of potential impacts on the mangroves
 **Trend of decreasing rainfall**	Limited change expected (i.e., ‹1 ppt change)	Salinity of mangrove soils are increased (i.e., ‹3 ppt change)	Salinity of mangrove soils are increased (i.e., ›5 ppt change) Humidity declines seasonally	Salinity of mangrove soils are increased and could be hypersaline (i.e., ›10 ppt) change Humidity declines seasonally	Mangrove soils become hypersaline (i.e., ›15 ppt change) Humidity declines year round	Increasing salinity will result in changes to the plant community as less salt tolerant species are replaced by more salt tolerant species (e.g., *Avicennia sp.*). If a site reaches salinity of ›90 ppt (the salt concentration of seawater is usually 35 ppt) then mangroves may cease to grow and be replaced by microbial communities or highly salt tolerant herbs (e.g., *Sarcocornia sp.*). As humidity declines some species may be lost from the community as they are usually only found in humid tropical environments (e.g., *Rhizophora apiculata*).
 **Increasing wind, particularly during extreme events**[13]	None to limited change expected	Mean wind speeds increase seasonally	Annual mean wind speeds increase	Annual mean wind speeds increase, and extreme storms become more frequent	Average wind speeds increase, and extreme storms become more intense and frequent	Projection in changes in future wind speeds and storm intensity and frequency vary among regions. Loss of canopies can result in mortality in some mangrove species that have limited capacity to resprout after extensive damage (e.g., *Rhizophora sp.*). Other species that are more tolerant of storm damage may become dominant (e.g. *Avicennia sp.*) High wind speeds generate waves which can cause damage to trees, reduce recruitment of mangrove seedlings, and increase shoreline erosion.

13 Lobeto et al. 2021 have developed a global wind/wave model that is described in their paper at https://www.nature.com/articles/s41598-021-86524-4

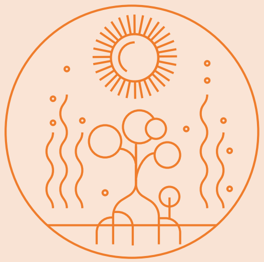
Climate Threats and risk rankings

Table 2

Risk Ranking

Very Low | Low | Moderate | High | Very High

Explanation of potential impacts on the mangroves



Increasing wave height

Very Low	None to limited change expected
Low	Small increases in wave height (i.e., 5% increase above historical average)
Moderate	Moderate increases in wave height (i.e., 5-10% increase above historical average)
High	Large increases in wave height (i.e., 10-15% increase above historical average)
Very High	Very large increases in wave height (i.e., 15-20% increase above historical average) Waves can overtop barriers and result in flooding from the sea

Projection in changes in future wind speeds and storm intensities and frequency vary among regions[14].

Higher wave heights during storms increase the risk of inundation, damage to vegetation, shoreline erosion, ecosystem loss/change and landward retreat.

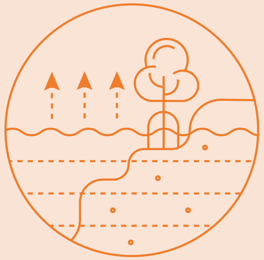
Recruitment of seedlings may be reduced by increasing wave energy as they fail to establish.

Increasing wave energy and sea level rise effects are likely to be synergistic[15]. Risks of damage may increase in a non-linear way with increasing wave heights.

14 Lobeto et al. 2021 at https://www.nature.com/articles/s41598-021-86524-4
15 Vousdoukas et al. 2018 at https://doi.org/10.1038/s41467-018-04692-w

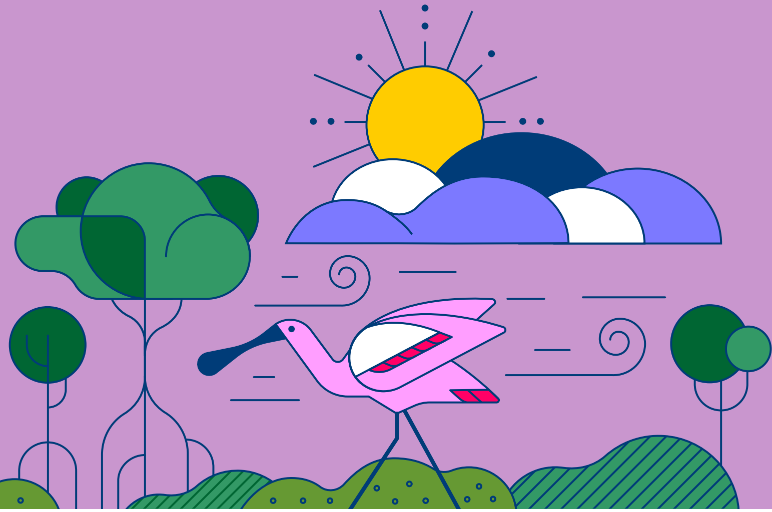
Climate Threats and risk rankings

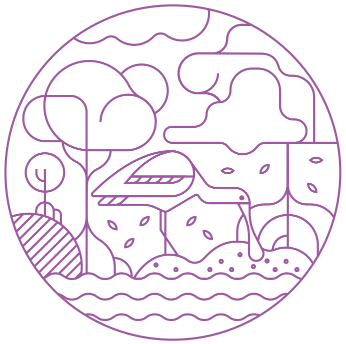
Table 2

Climate Threats	Risk Ranking: Very Low, Low, Moderate, High, Very High	Explanation of potential impacts on the mangroves
 Sea level rise (mm/year)	Very Low: ‹ 1; Low: ›2; Moderate: 2 – 4; High: 4 – 7; Very High: ›7	Higher rates of sea level rise increase the risk of inundation that exceeds tolerance of vegetation, resulting in tree mortality and ecosystem degradation. Rates of relative sea level rise are higher if land subsides, which can occur due to geological processes and because of human activities (e.g., extraction of groundwater or disturbance of soils). Increasing rates of sea level rise and increasing wave height may be synergistic (increased sea level allow waves to penetrate further inland).

Step 3 | Combine Climate Threats and Site Characteristics (Vulnerability Assessment)

Populate the tab titled "Step 3 - Vulnerability Assessment" in the MS Excel worksheet.





Step 1

+

Step 2

The purpose of Step 3 is to combine the climate change threats ranked moderate-to-very high with each relevant site characteristic to evaluate the risk of climate impacts on the mangrove site.

This will provide you with insights on the key climate risks for your site that will require attention and guide you in the selection of specific management actions to be prioritized.

- In the MS Excel worksheet, the tab labeled "Step 3 – Vulnerability Assessment" will partially auto-populate with the results of the results of Step 1 - site characteristics and Step 2 - climate change threats.

- The six climate threats will be located on the x-axis (Columns C to T), with row 5 indicating the risk ranking you selected in Step 2 (automatically colored for all moderate to very high risk climate threats that need to be addressed; or grayed out for lower risk climate threats.

- If a climate threat category highlights as yellow, this means the risk is moderate or high and, therefore, you need to assess the climate threat against the site characteristic.

- If the climate threat risk category is highlighted grey, then you identified that the risk of that climate threat is low or very low, and therefore you don't need to assess it against the site characteristics.

- Some combinations of climate threats and site characteristics are unlikely to occur or result in a high risks. These combinations are automatically grayed out the Step 3 sheet and may not need to be completed if you are time limited.

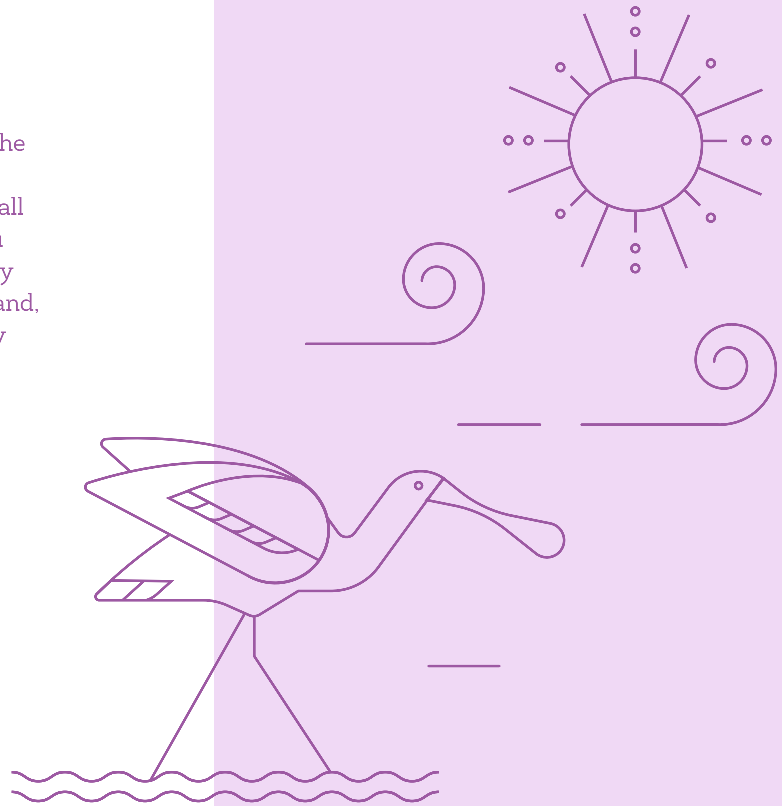
- When assessing moderate or high risk of climate threats against the identified site characteristics, you will need to use the same ranking concept used previously, i.e., very high – high – moderate – low – very low and populate the "Vulnerability column" (C, F, etc.) column for each of the moderate-to-high exposure to climate threats. Column B will automatically populate on the y-axis (rows 7-15) with the specific site characteristics you selected in Step 1 to make the comparison easier. Again, the vulnerability column cells will automatically color based on the ranking level you select.

- A justification column (D, G, etc.) is provided for you to document the method and reasoning behind your risk ranking choice. When doing the assessment, remember:

  Keep the climate threat in mind when assessing the risk of impact.

  Keep your ranking specific to the site characteristic.

- For each climate threat column there is a 'confidence' column (E, H, etc.). This is to document the level of confidence you have in the data, the determination, and the assessment of risk. While the outcome of your confidence may not impact the overall assessment, recording how confident you feel in the outcome enables you to identify potential weaknesses in the assessment and, if possible, seek to improve confidence by collecting additional data or information.



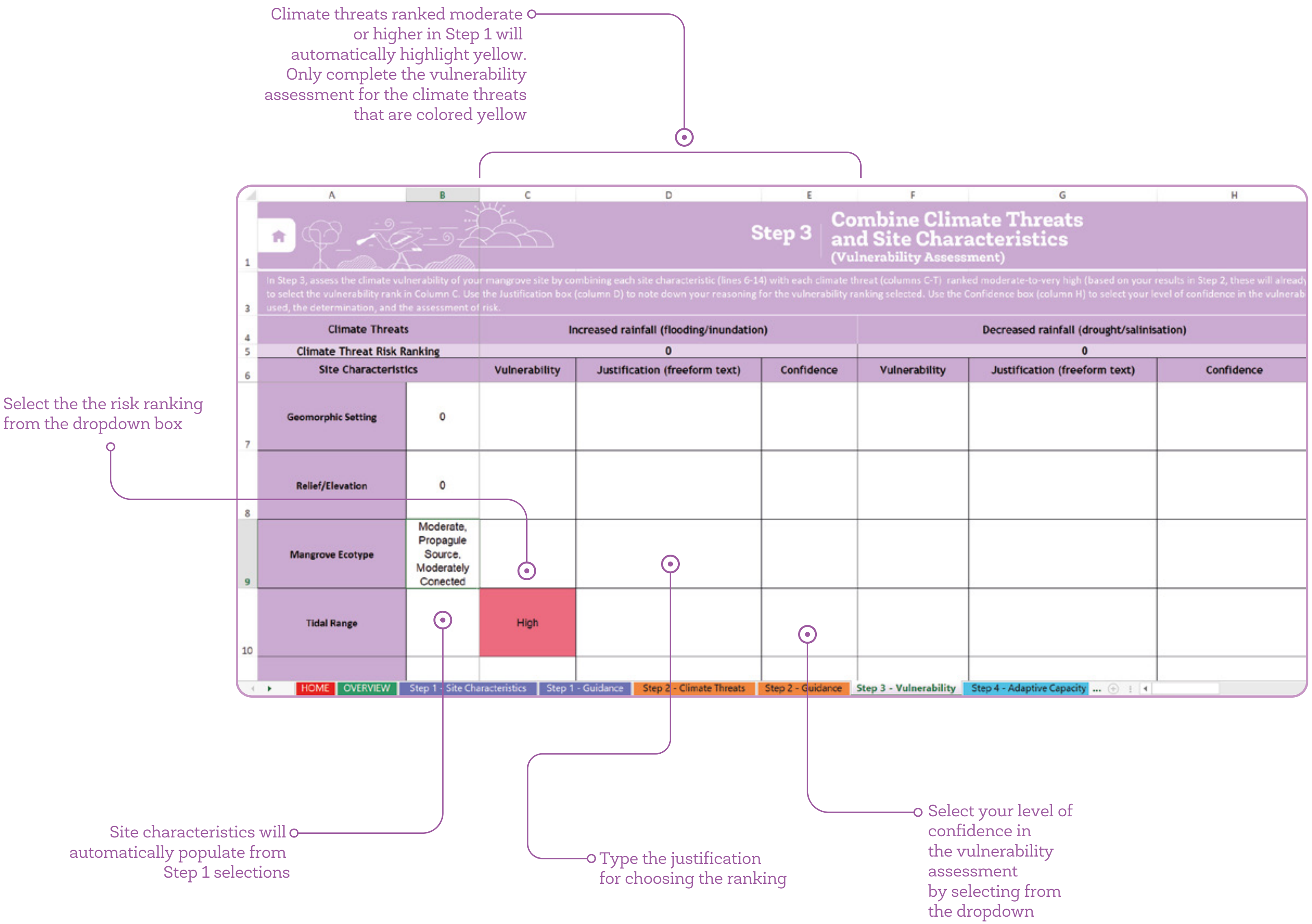


Figure 6 - *Illustration of the Step 3 process*

Combining Climate threats and Site Characteristics to Determine Potential Impact (risks)

There are 54 different combinations possible for determining potential impacts from the six climate threats and nine site characteristics. To provide some additional guidance on how to combine these, a selection of climate threats and characteristics are explained in more detail below.

Increased Rainfall + Low Relief/Elevation:

If climate data indicates that trends in the amount (monthly, annual, etc.) rainfall is increasing, and the relief (elevation) is low, there is an increased risk of the site becoming inundated, either by storm (flood waters) or from rising surface water levels (i.e., adjacent waterways and wetlands) – **High risk**. If mangroves are located at high elevation, then the risk of flooding occurring, despite increasing rainfall, would remain relatively low.

Increased Rainfall + Carbonate Geomorphic Setting:

Increasing rainfall can result in increasing groundwater/water tables. This is particularly significant if the geomorphic setting is carbonate (karst) or environments have groundwater close to the surface, and the mangrove area is hydraulically connected to groundwater sources – **High risk**. If the geomorphic setting is estuarine that is fed by freshwater, then the risk of flooding may also increase with increasing rainfall. However, if the site is a mangrove fringing the ocean the increased rainfall may have little influence (low risk of impacts).

High rates of sea level rise + High tidal range:

Sites with high tidal ranges are less susceptible to the impacts of sea level rise – **Low risk**. If the site is microtidal (tidal range < 2m), then the impacts of sea level rise may be more significant and the site may have higher risks.

Decreased rainfall + Moderate sediment supply:

If the sediment supply to an area is dependent on riverine sources (i.e., a waterway delivering sediments into a mangrove area either directly or indirectly), then reductions in average rainfall may result in that sediment supply being reduced – **High Risk.** If sediment supply is not dependent on river flows and instead sediments increase in elevation mainly due to root growth (as is the case in mangrove peat ecosystems) then the risk of impact would be low.

Increasing waves + Moderate past shoreline change:

If wave energy and height is projected to increase and/or the frequency and intensity of destructive storms is projected to increase, and the shoreline has a history of significant erosion or change, then the likelihood of future change is high – **High Risk**. If increasing intensity storms are predicted but the shoreline is highly stable, has been engineered to improve stability, or is rocky, then risks of impacts would be lower.

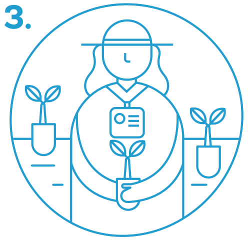
Step 4 | Identify and Assess Adaptive Capacity

Populate the tab titled "Step 4 - Adaptive Capacity" in the MS Excel worksheet. Use the "Step 4 - Guidance" (or Table 3 below) to guide your responses.

There are 5 adaptive capacity conditions:

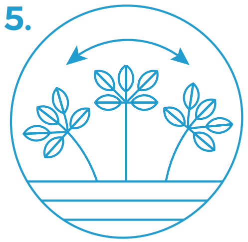
1. Level of resources

2. Community willingness



3. Institutional / organizational capacity

4. Governance

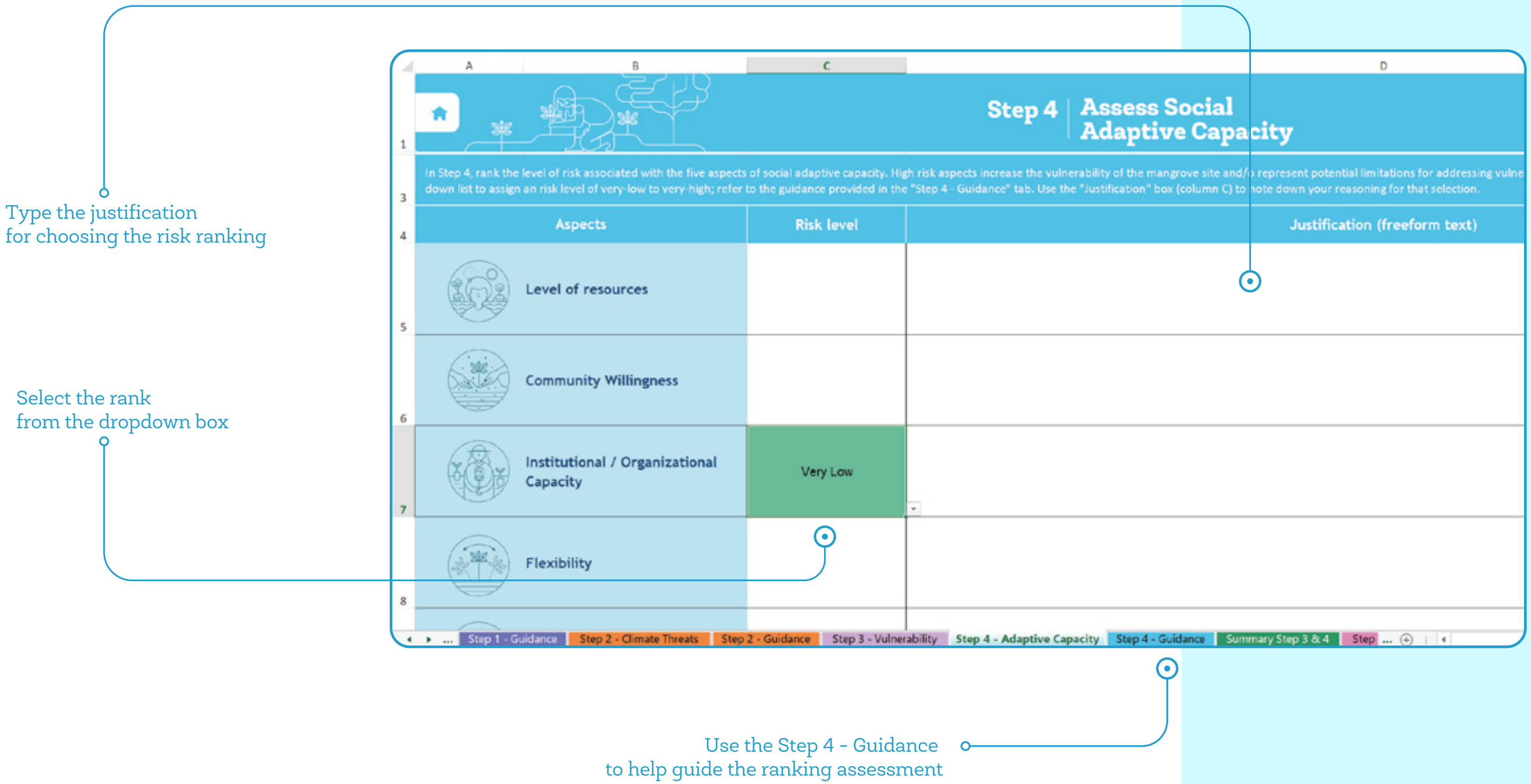


5. Flexibility

Before identifying appropriate management actions, the adaptive capacity of the socio-ecological system needs to be assessed. Adaptive capacity describes the potential for adjustment in ways that increase adaptation to climate change. Adaptive capacity is ranked for five categories:

- Using the Excel worksheet tab labeled "Step 4 – Adaptive Capacity" and Table (or the tab in the Excel worksheet labeled 'Step 4 - Guidance, complete the assessment using the same ranking profile as previously utilized.
- Column C provides the risk ranking using the same concept used previously, i.e., very high – high – moderate – low – very low and will automatically highlight the cell with the corresponding color.
- Use Column D to provide an explanation of the rank chosen.

Figure 7 *Illustration of the Step 4 process*



Levels of adaptive capacity

Table 3

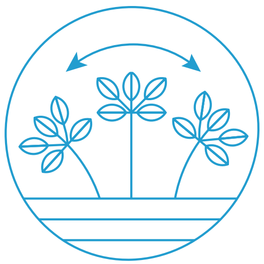
Level: Very Low, Low, Moderate, High, Very High

Levels of adaptive capacity	Level	Explanation of potential impacts on the mangroves
 **Level of Resources**	Very High; High; Moderate; Low; Very Low	The resources available to communities is known to affect the capacity of communities to adapt to climate change and may also influence community engagement in conservation or restoration of mangroves. Resources include financial and physical assets like land and equipment, and human resources. Influential leaders are important component of human resources.
 **Community "willingness"**	Very Willing; Willing; Passive; Reluctant; Very Reluctant	The willingness of the community to participate in mangrove conservation and restoration projects, including those to implement climate-smart management, is important in ensuring projects are successful in the long term and that mangroves are properly protected from human impacts and climate-smart. Community willingness is influence by multiple factors including social norms, personal experiences, gender, perceptions of risks imposed by climate change, learnings and also beliefs around peoples capacity to manage climate risks[16].
 **Institutional / organizational capacity**	Very High Capacity; High Capacity; Moderate Capacity; Low Capacity; No Capacity	The capacity of institutions and organizations to implement or support climate-smart mangrove restoration or conservation actions can influence long term success of climate-smart projects. The interacting network of institutions and organizations that affect mangrove landscapes can include government, local communities, community organizations, NGOs and others.

16 Pham et al. 2018 at https://doi.org/10.1016/j.ocecoaman.2018.07.005

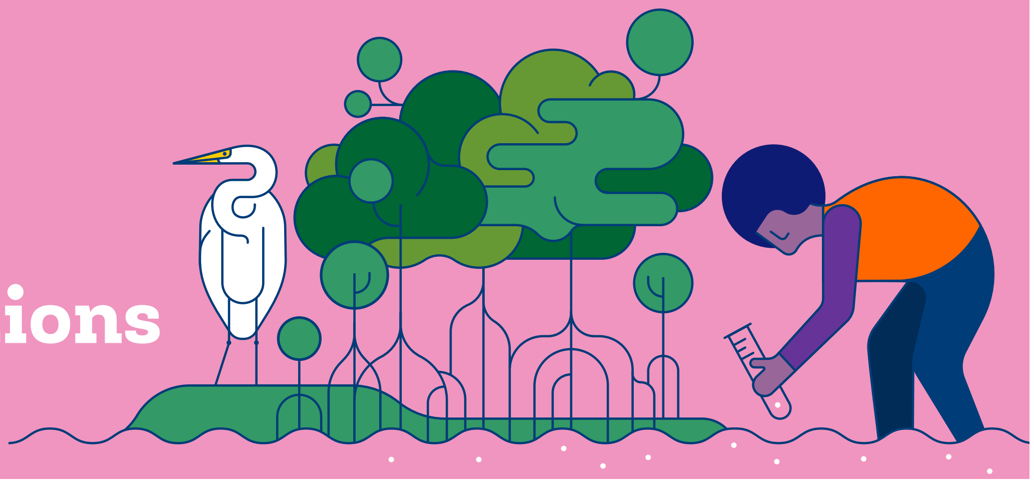
Levels of adaptive capacity

Table 3

Levels of adaptive capacity	Level: Very Low	Low	Moderate	High	Very High	Explanation of potential impacts on the mangroves
 Governance[17]	Very high levels of coordination and coopera-tion among institutions and stakeholders	High level of coordination and coopera-tion among most gover-nance components. Stakeholder engagement may be incomplete	Moderate co-ordination and cooperation among some component of the governance system E.g., important industries are not included	Low levels of coordi-nation and cooperation E.g., only the government is involved in de-cision making	Very low / limited coordination or cooperation among actors. Limited regulation or consultation	Governance refers to structures and processes designed to ensure accountability, transparency, responsiveness, rule of law, stability, equity and inclusiveness, empowerment, and broad-based participation. In the tool the assessment of governance arrangements for projects can include assessment of laws, policies, land tenure arrangements and formal and customary rights to land and natural resources.
 Flexibility	Very flexible	Flexible	Somewhat flexible	Limited flexibility	No flexibility	Flexibility is the ability of people and institutions to switch between strategies when faced with change. Flexibility is dependent on the diversity of options available and people's ability and willingness to engage in alternatives. Flexibility is linked to the conditions of community willingness, levels of resources, organization and governance.

17 Filho et al. 2019 at https://pubmed.ncbi.nlm.nih.gov/31539949/

Step 5 | Identify Possible Climate-Smart Management Actions



- Use the Step 5 - Possible Actions" tab in the Excel worksheet to document these actions. When selecting actions it is important to refer back regularly to the climate threat + site characteristic combinations (specific vulnerabilities) to ensure the actions are climate-smart. Remember that the purpose of the exercise is to devise actions that enhance the mangrove's adaptation to climate change.
- Using the Excel worksheet tab Step 5 - Guidance (or Table 4 below) as a guide, identify management actions that are applicable to your site and that address the moderate, high, or very high-ranking vulnerability and adaptive capacity outcomes (see "Summary Step 3 & 4" tab of the Excel worksheet). Note that this table provides a subset of all potential management actions and that others not listed and identified within the workshop may be appropriate.

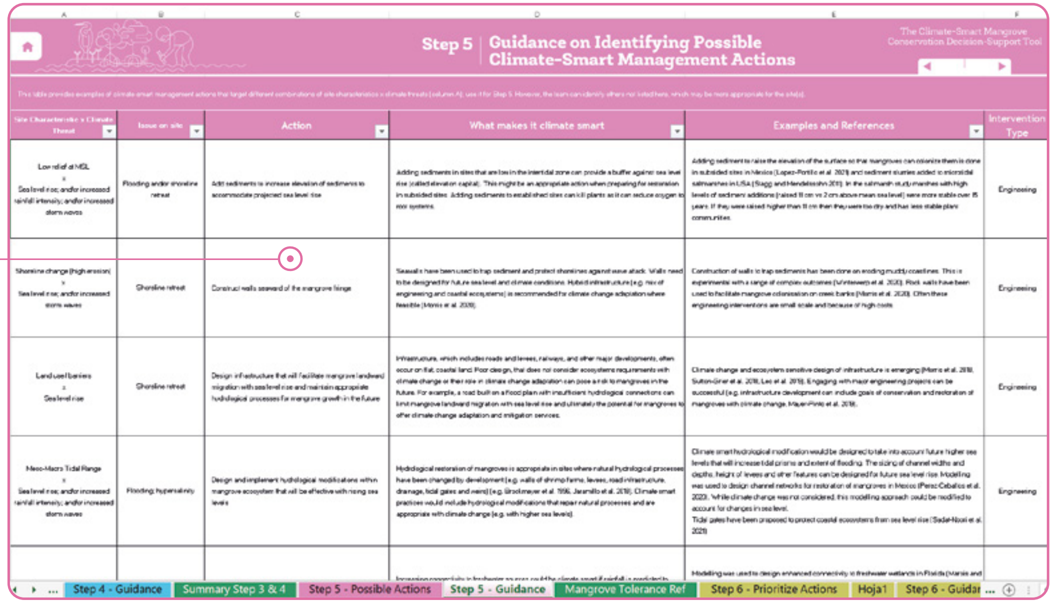


Figure 8 *Illustration of the Step 4 process*

Management options for different site characteristics and climate threats **Table 4** This table offers examples of climate-smart actions for a range of climate threat x site characteristic combinations.	**Action**	**What makes it climate smart**	**Examples and references**
Increasing sea level + Low relief at MSL	Add sediments to increase elevation to accommodate projected sea level rise.	Adding sediments in sites that are low in the intertidal zone can provide a buffer against sea level rise (called elevation capital). This might be an appropriate action when preparing for restoration in subsided sites. Adding large volumes of sediments to established sites can kill plants if it reduces oxygen to root systems.	Adding sediment to raise the elevation of the surface so that mangroves can colonize them was done in subsided sites in Mexico[18] and sediment slurries added to microtidal saltmarshes in USA[19]. In the saltmarsh study, marshes with high levels of sediment additions (raised 11 cm vs 2 cm above mean sea level) were more stable over 15 years. If they were raised higher than 11 cm then they were too dry and had less stable plant communities.
Increased wave exposure + Shoreline change (high erosion)	Construct walls seaward of the mangrove fringe.	Seawalls have been used to trap sediment and protect shorelines against wave attack. Walls need to be designed for future sea level and prevailing climate conditions. Hybrid infrastructure (e.g., mix of engineering and coastal ecosystems) is recommended for climate change adaptation where feasible.	Construction of walls to trap sediments has been done on eroding muddy coastlines. This is experimental with a range of complex outcomes[20]. Rock walls have been used to facilitate mangrove colonization on creek banks (called "rock fillets")[21]. Often these engineering interventions are small scale because of high costs.

18 López-Portillo et al. 2021 at https://doi.org/10.1002/9781119639305.ch9
19 Stagg et al. 2011 at https://www.jstor.org/stable/23023113
20 Winterwerp et al. 2020 at https://doi.org/10.1016/j.ecoleng.2020.106078
21 Morris et al. 2020

Management options for different site characteristics and climate threats Table 4	Action	What makes it climate smart	Examples and references
Increasing sea level + Land use intensity/barriers (peri-urban with barriers)	Design infrastructure that will facilitate mangrove landward migration with sea level rise and maintain appropriate hydrological processes for mangrove growth in the future.	Infrastructure, which includes roads and levees, railways, and other major developments, often occur on flat, coastal land. Poor design, that does not consider ecosystems requirements with climate change or their role in climate change adaptation can pose a risk to mangroves in the future through coastal squeeze. For example, a road built on a flood plain with insufficient hydrological connections can limit mangrove landward migration and thereby limit the potential for mangroves to offer climate change adaptation and mitigation services.	Climate change and ecosystem sensitive design of infrastructure is emerging[22 23 24] Engaging with major engineering projects can be successful (e.g., infrastructure development can include goals of conservation and restoration of mangroves with climate change)[25].
Rising sea level + Meso-macro tidal range	Design and implement appropriate hydrological interventions within mangrove ecosystems that will be effective with rising sea levels.	Hydrological restoration of mangroves is appropriate in sites where natural hydrological processes have been altered by development (e.g., walls of shrimp farms, levees, road infrastructure, drainage, tidal gates, and weirs[26]). Climate-smart practices could include hydrological modifications that repair natural hydrological processes and are designed to function under climate change scenarios (e.g., with higher sea levels).	Climate-smart hydrological interventions are designed to facilitate mangrove maintenance and expansion with higher sea levels. For example, the sizing of channel widths and depths, height of levees and other features can be designed to function with future sea level rise. Modelling has been used design channel networks for restoration of mangroves in Mexico[27]. While climate change was not explicitly considered, this modelling approach could be modified to incorporate sea level rise. Tidal gates have been proposed to protect particularly valuable coastal ecosystems from sea level rise[28].

22 Sutton-Grier et al. 2018
23 Morris et al. 2018
24 Leo et al. 2019
25 Mayer-Pinto et al. 2019
26 Brockmeyer et al. 1996
27 Pérez-Ceballos et al. 2020
28 Sadat-Noori et al. 2021

Management options for different site characteristics and climate threats Table 4	Action	What makes it climate smart	Examples and references
Decreased rainfall + Mangrove condition (degrading)	Increase or decrease hydrological connectivity to freshwater sources.	Increasing connectivity to freshwater sources could be climate-smart if rainfall is predicted to decline and increased connectivity could maintain salinity in mangroves within a range suitable for mangrove growth. However, if protecting the adjacent freshwater ecosystems was the goal then decreasing connectivity could be climate-smart.	Modelling was used to design interventions to enhance connectivity of mangroves with freshwater wetlands in Florida[29]. While climate change was not considered, this modelling approach could be modified to account for changes freshwater flows with climate change. Diversion of freshwater into coastal wetlands has been used to restore saltmarshes in the USA[30].
Increased wave exposure + Geomorphic setting (island/ high fetch)	Engineering approaches to protect and restore ecosystems seaward of mangroves.	In many locations low barrier islands provide protection to mangroves from wind and waves during extreme events. If they are degraded and eroded, restoration of these features could provide protection for mangroves in the future.	Increasing protection for mangroves from storm damage by restoring barrier islands has been practiced in the Mississippi Delta.

29 Marios and Mitsch 2017
30 Day et al. 2005

Management options for different site characteristics and climate threats Table 4	Action	What makes it climate smart	Examples and references
Increased intense storms + Mangrove condition (degrading)	Enrichment planting of suitable native species using plants grown in nurseries or distributing propagules.	Planting a range of species, particularly those that have high tolerances of emerging climate threats could increase the resilience of mangroves to climate change.	Some mangrove species are more tolerant of storm damage than others. There are a range of native species that tend to be more tolerant of defoliation and damage (e.g. *Avicennia sp*).compared to others (e.g. *Rhizophora sp*.). Planting mixes of native species that are tolerant of projected conditions, rather than monocultures, can enhance adaptation to climate change and other threats[31].
Increasing temperature + Mangrove condition (degrading)	Improve mangrove condition by improving conditions for growth.	Improving conditions for mangrove growth is expected to enhance resilience of mangroves to climate change and contribute to climate change adaptation. Actions could include reducing pollutants (e.g., excessive nutrients, oil, plastics), and reducing over-exploitation (e.g., wood extraction). For restoration, actions that secure seedling establishment in the face of climate stressors may increase success, e.g., choice of stress tolerant species, careful timing of planting to avoid seasonal climatic events, or manipulation of growth rates to rapidly enhance soil elevation through root growth.	Excessive nutrients are known to enhance sensitivity of mangroves to drought events[32]. Degradation of mangroves (e.g., from overexploitation of mangroves for timber) reduces their effectiveness for climate adaptation (e.g., degraded mangroves offer reduced protection to extreme storms)[33]. Restoration of mangroves in nutrient limited ecosystems can be enhanced by adding nutrients to increase plant root growth that increases vertical accretion[34]. In seagrass, restoration can be enhanced using bird roosts to naturally add nutrients[35].

31 Primavera et al. 2016
32 Sippo et al. 2018
33 Hochard et al. 2021
34 McKee et al. 2017
35 Kenworthy et al. 2018

Management options for different site characteristics and climate threats

Table 4

Management options for different site characteristics and climate threats	Action	What makes it climate smart	Examples and references
Increase wave exposure + Mangrove ecotype (fringe)	Improve the condition of ecosystems seaward of mangroves, e.g., seagrass, coral reefs, oyster reefs.	Ecosystems adjacent seaward of mangroves can provide protection from climate change impacts (e.g., wave events that will be more extreme with sea level rise and coastal erosion) and will enhance ecological resilience of the landscape (e.g., enhancing connectivity for many species).	The important role of linked ecosystems for mangrove resilience has been studied in Kenya[36], the Great Barrier Reef in Australia[37], Bangladesh[38] and in the USA[39]. Seagrass may also provide coastal protection to mangroves[40].
Increased rainfall + Mangrove condition (degrading)	For restoration use native mangrove species that are tolerant of inundation.	Appropriate species choices during restoration could increase long term survivorship under changing climates and improve resilience. Some species are more tolerant of inundation than others.	In experiments seedlings of *Rhizophora mangle* were more tolerant of anoxic conditions with prolonged inundation than *Avicennia germinans* or *Laguncularia racemosa*[41].
Decreased rainfall + Mangrove condition (degrading)	For restoration use native species that are tolerant of high salinity.	Appropriate species choices during restoration could increase long term survivorship under changing climates and improve resilience. Some species are more tolerant of high salinity than others.	In restoration projects in the Saloum Delta in Senegal *Avicennia germinans* was more tolerant of hypersaline conditions than *Rhizophora mangle*[42].

36 Huxham et al. 2018
37 Saunders et al. 2014
38 Chowdhury et al. 2019
39 Ridge et al. 2017
40 Twomey et al. 2022
41 McKee 1996
42 Devaney et al. 2021

Management options for different site characteristics and climate threats Table 4	Action	What makes it climate smart	Examples and references
Rising sea level + Intensity of Land use / Barriers (Urban with barriers)	Facilitate landward migration of mangroves by securing land of appropriate elevation for their growth on the landward edge of the mangroves.	Expansion of mangrove onto land that will be more regularly influenced by tides as sea level rises could maintain mangrove cover and, in some cases, increase mangrove cover in the landscape.	Securing land on the landward edge of mangroves[43] for their future distribution could be done by identifying land that will be influenced by sea level rise in the future (e.g., through modelling[44]). Identified land could be acquired for protected areas, secured by landholder agreements and land-use planning.
Rising sea level + Sediment supply (Low or declining)	Rates of sea level rise may be increased with subsidence. Reducing subsidence of the landscape, if possible (subsidence can be due to extraction of e.g., oil/gas/groundwater)	Subsidence of the land effectively increases the relative rate of sea level rise. Reducing subsidence can slow the impacts of sea level rise.	While subsidence can be due to natural geological processes it can also be due to extraction of groundwater or oil/gas[45]. Studies have used modelling to establish the effects of subsidence and sea level rise on mangrove survival[46 47]. They recommend a range of actions including reduce groundwater extraction, management of sediments and reforestation.
Decreased rainfall + Sediment supply (low)	Maintain sediment supply by modifying infrastructure, rewilding rivers and other actions to restore sediment supply.	Sediments are important for vertical accretion (increasing elevation) which reduces the impacts of sea level rise[48].	The delivery of sediments to the coast is influenced by catchment and climate processes. Dams have interrupted sediment delivery globally. Rewilding of rivers to reinstate flows, often by decommissioning dams, is an emerging process[49]. Modelling can help to identify suitable actions.

43 Leo et al 2019
44 Mazor et al. 2021
45 Syvitski et al. 2009
46 Minderhoud et al. 2017
47 Dang et al. 2022
48 Rogers 2021
49 Rideout et al. 2021

Management options for different site characteristics and climate threats Table 4	Action	What makes it climate smart	Examples and references
Decreased rainfall + Mangrove condition (degrading)	Monitor salinity to guide management (identify thresholds).	Knowledge of trends in salinity and thresholds of plant community tolerance could provide triggers to guide management actions, including timing of actions like planting or hydrological modifications.	Recovery of salinity of soil porewater to that similar to natural sites has been a key indicator of restoration of mangroves[50]. Salinity can be easily measured with a range of techniques. Salinity thresholds of mangrove species and communities vary depending on the conditions under which they grew and species characteristics.
Rising sea level + Mangrove ecotype (basin, scrub)	Monitor water levels to guide action (identify thresholds).	Knowledge of trends in inundation and thresholds of plant community tolerance could provide triggers to guide management actions, including timing of actions.	Recovery of hydrological regimes has been a key indicator of restoration of mangroves[51]. Hydrological conditions can be measured using multiple techniques, including using low-cost sensors[52].
Increased sea level + Ecological connectivity	Monitor mangrove aerial extent and condition to guide management.	Knowledge of mangrove extent and condition may provide guides to management actions, including the timing of actions. Over longer time scales changes in mangrove extent may provide guidance for management. E.g. tidally inundated sites without recruitment may indicate a need to evaluate and correct connectivity.	Changes in mangrove extent are available from the Global Mangrove Watch. Canopy condition can be measured by remoting sensing indicators[53].
Increased sea level + Land use / barriers (urban)	Plan for transformation of ecosystems and communities.	Where climate change impacts on mangroves are likely to result in loss, then adaptation actions could be focused on preparing human communities for changes in resources and ecosystem services. Substitutions (e.g. seawalls) or other interventions (retreat) may be considered.	Climate adaptation pathways and how they may be achieved have been described using multiple approaches[54], including knowledge / values / rules framework[55].

50 Jaramillo et al. 2018
51 Van Loon et al. 2016
52 Balke et al. 2021
53 Lewis et al. 2016
54 Fedele et al. 2019
55 Colloff et al. 2021

Step 6 | Prioritize Management Actions

- The final step is to prioritize the actions using the prioritization criteria provided in Table 5 and in the Excel worksheet tab titled "Step 6 – Prioritize Actions".
- The first column "Action" will automatically populate from "Step 5" where you identified possible actions.
- Use the information provided in Step 6 - Guidance as guidance for completing step 6.
- Remember, this is an opportunity to re-evaluate if your actions are climate-smart. When considering "benefits / impact" and "chance of success" especially, relate these specifically to the goal of reducing climate vulnerability and risks to your mangrove site.

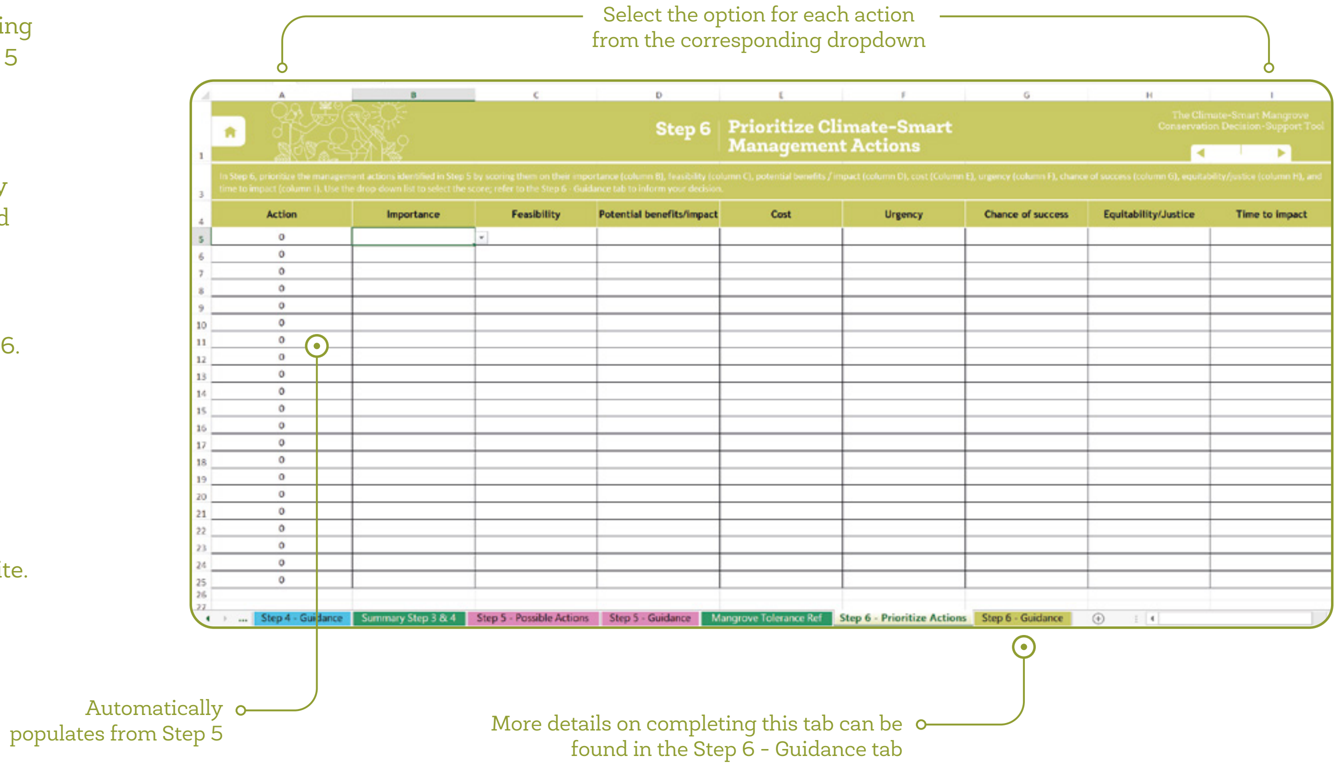


Figure 9 *Illustration of the Step 6 process*

Criteria for Setting Priorities[56]

Table 5

Criterion	Explanation	Subcriteria	Scores
Importance	"Does anyone care?" A measure of how much support there is likely to be.	Social and cultural importance (including charisma). Responsibility – how much of the species status depends on this project?	Important Moderately Important Unimportant
Feasibility	"How easy is this to achieve?" An assessment of the difficulty associated with this project.	Logistical and political, source of funds, community attitudes.	Feasible Moderately Difficult Difficult
Benefits	"What good will it do?" A measure of how much good will result from the project.	Biological: reduction in extinction risk, increase in population size, extent of occurrence. Collateral biological benefits, to other species or processes.	Highly Beneficial Moderately Beneficial Unclear Benefits
Costs	"How much will it cost?" An assessment of the relative economic costs of the project (or gains). In this criterion there are both positive and negative aspects which must be weighed against each other.	Direct and indirect costs of the project. Direct and indirect social and economic costs and benefits that will flow from the project.	Expensive Moderately Costly Inexpensive
Urgency	"Can it be delayed?" A measure of whether the project is time-limited, or whether it can be delayed without incurring higher costs or diminished outcomes.	Extinction risk, potential for loss of opportunity if delayed.	Urgent Moderately Urgent Less Urgent
Chance of Success	"Will it work?" An assessment of whether the actions will work.	Will it meet its specified objectives?	Achievable Uncertain Highly Uncertain

56 Mace et al. 2007 at https://www.academia.edu/19526475/Prioritizing_choices_in_conservation

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Decision Support Tool

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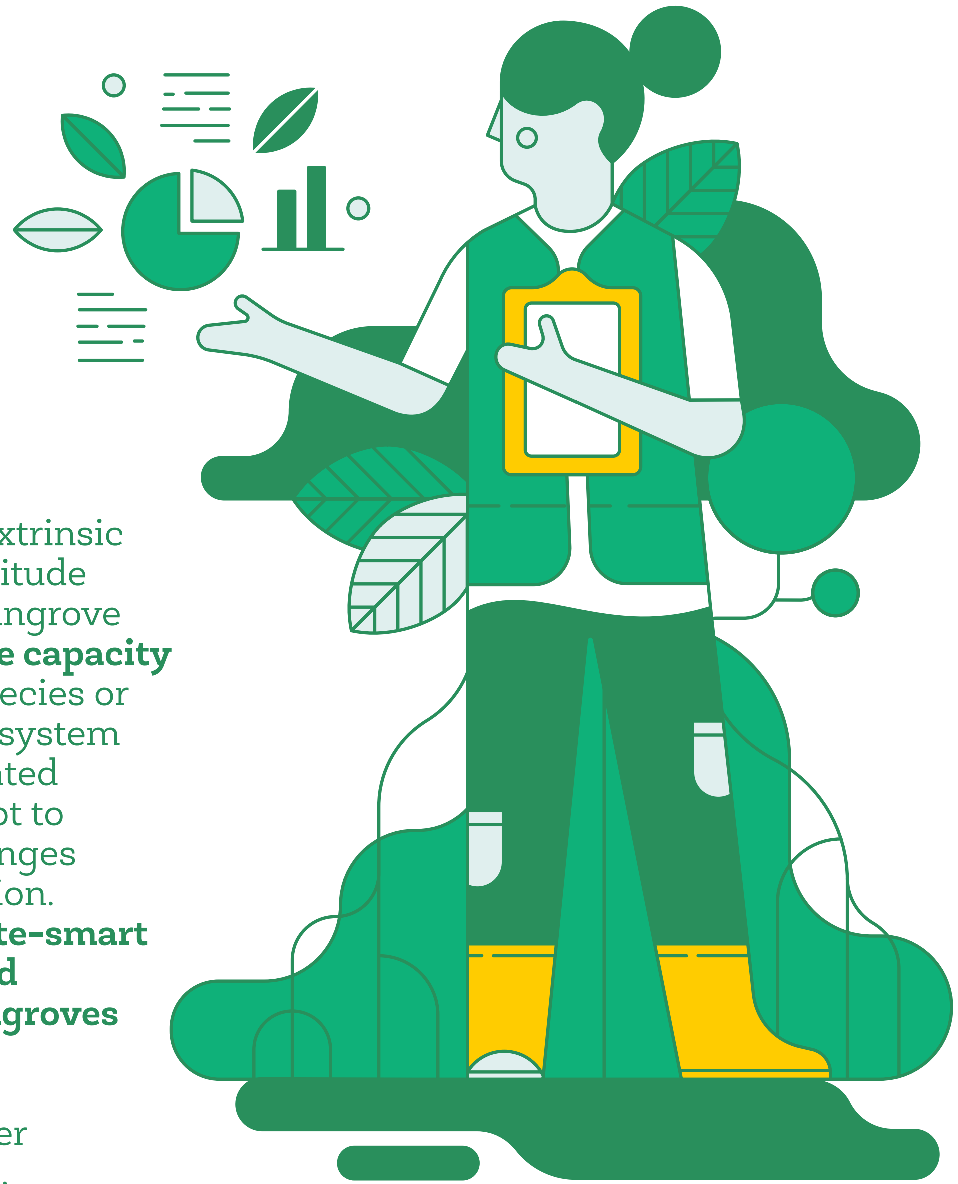
Supporting Information

Components of Vulnerability



Assessing mangrove vulnerability to climate change should inform the selection of climate-smart management actions. **Vulnerability** is a function of sensitivity, exposure and adaptive capacity to climate change, considering the speed at which change will occur. **Sensitivity** describes the characteristics of the species or ecosystem, determining how tolerant it is of changes to factors such as rainfall, temperature, humidity,inundation, or drought.

Exposure relates to extrinsic factors and the magnitude of their impact on mangrove ecosystems. **Adaptive capacity** is the ability of the species or the social-ecological system (mangroves + associated communities) to adapt to or accommodate changes with minimal disruption. **Implementing climate-smart actions can help build the resilience of mangroves to climate change**, that is, their ability to respond to and recover from climate impacts.

Site Characteristics

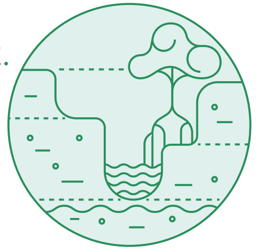
Knowledge of site characteristics provides indications of the likely sensitivity of the site to climate change impacts. Sensitivity is degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)[57].

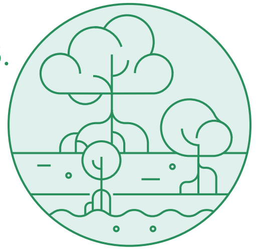
The sensitivity of mangroves to climate threats will determine their potential for conservation, management, and restoration and the appropriate strategies to pursue to reduce sensitivity (if possible). There are numerous components of sensitivity that have been considered in this vulnerability assessment component of this tool:

These are explained in more detail below.

1.

Geomorphic Setting

2.

Relief and Elevation

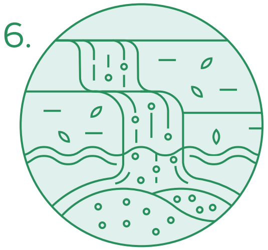
3.

Mangrove Ecotype

4.

Tidal Range

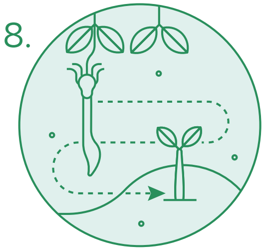
5.

Past Shoreline Change

6.

Sediment Supply

7.

Mangrove Condition

8.

Ecological Connectivity

9.

Land Use & Barriers

57 IPCC definition of sensitivity from The Fifth Assessment Report (WGII AR5) Climate Change 2014: Impacts, Adaptation, and Vulnerability

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Geomorphic Setting

Mangroves occur in a range of geomorphic settings, including rivers and their systems of channels, semi-enclosed estuaries and bays, open coastal settings, and on islands. Analysis of geomorphic setting provides information on variations in geomorphic processes that influence the mangroves, for example, sediment availability, strength of currents and how sheltered or exposed mangroves are to strong winds and waves, which is determined by the fetch. Geomorphic setting can be identified using local knowledge and aerial imagery to place the mangroves in the context of surrounding landforms and coastal formations. Larger sites will be comprised of multiple geomorphic settings. For example, mangroves within deltas may be protected, but those on the outer shorelines of deltas are exposed to oceanic forces and can be characterized as "open coast".

Table 6 *Descriptions of geomorphic characteristics used in the tool.*

Geomorphic Characteristic	Description
Delta	Shoreline protuberance typified by a wide fan-shaped alluvial (river) plain derived from large volumes of river transported sediment.
Estuary	Funnel shaped main channel with bidirectional tidal flows, often characterized by large catchment area and high precipitation inputs. Enclosed or semi-enclosed tidal estuaries with sheltered areas formed by landforms (e.g., mudflats, cliffs, headlands, man-made training/coastal protection structures).
Lagoon	Shallow coastal waterbody, intermittently separate from ocean inputs. Can be formed parallel to the shore or formed within reef systems.
Open coast with low fetch (coastal embayments or bays)	Semi-enclosed indentations on coastlines that provide shelter from oceanic and weather-driven conditions. Coastlines protected by natural geomorphological formations (such as sandbars, flats, cliffs, reefs) or manmade structures (such as seawalls, training walls, artificial reefs, etc.). Can be protected from weather-driven conditions and have low fetch.
Open coast with low to moderate fetch (coastal embayments or bays) and islands	Semi-enclosed indentations on coastlines that provide some shelter from oceanic and weather-driven conditions. Coastlines protected by natural geomorphological formations (such as sandbars, flats, cliffs, reefs) or manmade structures (such as seawalls, training walls, artificial reefs, etc.). Can be protected from weather-driven conditions and may have low to moderate fetch. Islands that are exposed to oceanic conditions. Islands can be comprised of carbonate rocks and sediments associated with coral reefs.

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Fetch is the distance that wind travels over open water without interference over which waves are formed. Generally, longer areas of fetch give rise to larger waves.

Fetch is an important aspect in planning for mangrove conservation and/or restoration as the greater the fetch the higher the exposure mangroves to intense and severe wave and wind forces, and therefore the risk of erosion, tree damage, and prolonged or increased levels of inundation.

Resources

For mangroves a global map of geomorphological setting is available[58] as well as a discussion of different geomorphic classifications for mangroves.

Fetch can be estimated using code functions in R or Python, or spatially using GIS[59]. To use these methods wind data must be collected and analyzed before it is used in the chosen software[60]. Fetched-based models are particularly helpful when knowledge of bathymetry is limited[61]. Most national meteorological administrations collect and predict relatively accurate wind data using meteorological equipment, ocean buoys, and models and these data can be used as an input or as an indicator of the likelihood of wave exposure if the fetch in the dominant direct of the wind is known.

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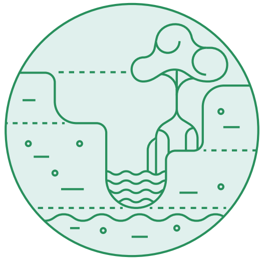
58 Available within Worthington et al. 2020, dataset at https://data.unep-wcmc.org/datasets/45 and https://www.nature.com/articles/s41598-020-71194-5
59 Refer to Callaghan et al. 2015 for more information.
60 Mason et al. 2018. Calculated 'effective fetch' and 'relative exposure index' in a study conducted to inform mapping of the Laurentian Great Lakes. This method can also be used for calculating fetch and relative exposure for mangroves.
61 See Callaghan et al. 2015.



Elevation and relief

The elevation and relief (topography) of sites are sensitivity factors that are critical to evaluate when designing climate-smart actions because:

- Elevation (relative to mean sea level) is a proxy for levels of tidal inundation (important for determining the suitability for mangrove growth).
- Relief or topography determines the potential for both coastal squeeze and lateral expansion of mangroves and thus the opportunity for landward migration in the future (see Barriers to Landward Migration).

Elevation

Mangroves grow in the intertidal zone and grow best (have high biomass) when inundation occurs periodically during high tides. Permanently flooded mangroves grow poorly because oxygen is low at their roots which limits their metabolic function. Land with elevations that are above the level of the mean tide (approximately mean sea level) are most appropriate for mangrove growth (with the exception of some species that are able to tolerate higher levels of inundation, e.g. Sonneratia sp). If land elevation is below the level of mean sea level, then mangroves will grow poorly. Mangrove planting projects often fail because propagules are planted at elevations that are below mean sea level.

Mangrove species tend to occupy broad ranges in elevation, but the range limits differ among mangrove species reflecting difference tolerances of inundation – some are more adapted to lower elevations (e.g., *Rhizophora* or *Sonneratia*), whereas others are less tolerant of inundation (e.g., *Ceriops*) and occur at higher elevations in the intertidal zone. Mangroves that occur at low elevations (near mean sea level), close to their inundation tolerance limits, may be more strongly influenced by rising sea levels compared to mangroves that are at higher elevation in the intertidal zone. Mangroves that are high in the intertidal zone are said to have "elevation capital", which describes the amount of elevation above mean sea level (when growth may become compromised). With accelerating sea level rise elevation capital is reduced (ie the site becomes closer to inundation limits of mangroves), unless the rate of sediment surface elevation (i.e. via sediment trapping or accumulation) matches the rate of sea level rise. In some cases, mangroves can maintain their elevation relative to mean sea level through trapping and accreting sediments (called vertical accretion) which may enhance their resilience to sea level rise (see Sediment Supply). Root growth, which adds to the volume of the soil, can also contribute to the maintenance of mangrove elevation within the intertidal zone (e.g. in Belize root growth contributed to maintaining elevation of mangroves as sea levels rose over thousands years[62]).

Relief

The relief of the landscape, or slope, in important to determining the long-term maintenance of mangroves with sea level rise. Lateral expansion of mangrove

62 McKee et al. 2007

landward can occur on very flat landscapes, like those on river floodplains, which are likely to accommodate landward migration of mangroves with sea level rise. In contrast, sites with steep relief (dunes, rocky shores, built infrastructure) limit the land available for mangrove landward expansion with sea level rise and can result in coastal squeeze.

Resources

There are a range of tools to characterize elevation and relief (topography) of mangrove landscapes. LiDAR[63] is perhaps the most useful tool in this regard to developing an accurate digital elevation model (DEM) of the broader project site. Such elevation models can be used to model effects of sea level rise[64]. However, LiDAR can be expensive to collect and might not be available for some sites. Some government agencies and organizations may already have LiDAR monitoring programs for coastal areas and those data may be available for public use. Drones (sometimes called unmanned aerial vehicles or UAVs) provide new ways to develop elevation data over landscapes. Real time kinetic global positioning systems (RTK GPS) can be used at sites to obtain elevation data at points over the landscape and can be used to verify remotely sensed data.

Laser rangefinders are a local, ground-scale options for measuring elevation and relief[65]. These are handheld devices, similar to a scope, that are used by surveyors and trades people and are available from most hardware stores. They can be used to provide a local scale estimate of elevation and relief for specific projects. Other low-tech methods can be explored that use Archimedes principle using water in tubing[66].

Change in the elevation over time can be used to evaluate whether mangroves are gaining elevation at a similar rate to sea level rise and thus are maintaining their position in the intertidal zone, or if they are declining in elevation (losing elevation capital). Changes in elevation can be measured with surface elevation tables (SETs, https://www.usgs.gov/centers/eesc/science/surface-elevation-table). There is a global network of SETs in mangroves with data usually held by individual scientists that may be engaged in projects. Knowledge of elevation change along with information on e.g. sediment supply and tidal range can provide an informed understanding of how elevation may change over time, and thus vulnerability to sea level rise, as well as providing insights on the processes that may be managed to maintain elevation of mangroves.

Back to Tool

63 LiDAR, or light detection and ranging, is remote sensing technology that measures the distance from a set elevation – usually flown from light aircraft or drones set to a specific altitude – to the ground. Lasers are set to a specific resolution that measure at set intervals (e.g., 1-meter) producing a grid of elevation points that can then be meshed to form a digital elevation model. The DEM can be developed in 3-D and provide a topographical model of the area measured.

64 For example, used by Mazor et al. 2021.

65 Sreeranga et al. 2021 used a laser rangefinder to estimate elevation and relief of a mangrove area in a low-cost community-based project, which provides a good example of how they can be used to inform management.

66 Brown and Lewis 2014 Ecological Mangrove Rehabilitation Guide https://ocean.floridamarine.org/CHIMMP/Resources/Lewis%20and%20Brown%202014%20Ecological%20Mangrove%20Rehabilitation.pdf


© naturepl.com / Tim Laman / WWF

Mangrove Ecotype

Mangroves are characterized into different ecotypes[67]. Different ecotypes are differentially exposed to climate change threats and have differing sensitivities to climate change, giving rise to a range of vulnerability. Most project sites are likely to be comprised of multiple ecotypes (for example, a fringing mangrove or riverine mangrove may have scrub mangrove on their landward edge); therefore, considering the climate vulnerability of all ecotypes at a site can provide a more complete picture of the likely impacts of climate change. You may have to disaggregate sites into their different mangrove ecotypes to do a landscape-scale vulnerability assessment.

All ecotypes are exposed to climate threats (e.g. sea level rise and rising temperature), but some ecotypes are likely to be more sensitive than others to different climate change threats, some examples of which are described in Table 4.

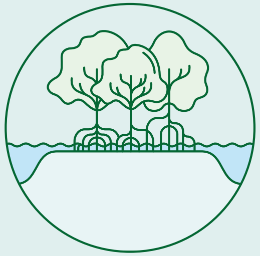
Resources

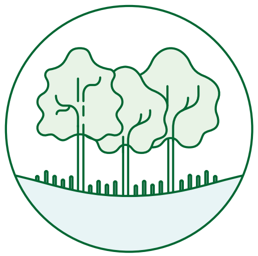
Mangrove ecotypes have been described[68]. The concept has proved useful over decades and has been used to describe variation in mangrove biogeochemistry, ecology, and functions, including processes like carbon sequestration[69]. Table 7 describes mangrove ecotypes, their main climate threats, sensitives and likely vulnerabilities. Vulnerability will be sensitive to local settings and could differ from those described in the table.

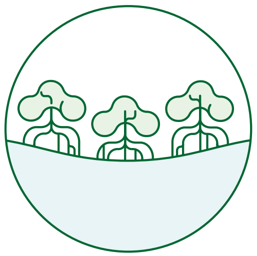
67 Odum et al. 1982 at https://apps.dtic.mil/sti/citations/ADA323074

68 Lugo and Snedaker 1974
69 Twilley et al. 1999

Table 7 *Mangrove Ecotype Descriptions and indications of Vulnerability*

Ecotype	Climate threats	Sensitivity	Vulnerability
Overwash islands Low elevation and frequently inundated by tides. 	Low elevation and proximity to open water results in high exposure to sea level rise and increases in wind and wave regimes, which may be particularly intense with increasing sea level.	This type of mangrove can be found in carbonate systems and within lagoons. Tides inundate these types of mangroves regularly. Sediment supply could vary, but is often low in reef lagoons, increasing the sensitivity to erosive forces of increasing wind and wave forcings and sea level rise. This ecotype is often moderately productive and has the capacity to adjust to sea level rise through increasing elevation, providing mangroves are in good condition and sediment supply is adequate.	High vulnerability to increasing wind and wave regimes that cause erosion, and to sea level rise.
Fringing mangroves Fringing the edges of water bodies 	Low elevation and proximity to open water results in high exposure sea level rise and to increasing wind and wave regimes, which may be particularly intense with increasing sea level. Storms can deliver pulses of sediments.	This type of mangrove is present where mangrove fringe the water's edge of bays, lagoons, or estuaries. Mangroves can be at low elevation (often at mean sea level). Tides inundate these types of mangroves regularly and they can have high biomass. Fetch can vary depending on local conditions. Groundwater may emerge in fringing mangroves and they can be sensitive to declining rainfall. Sediment supply can vary depending on geomorphic setting, but in deltas and estuaries they may trap large volumes of sediment giving rise to elevation gains. Large sediment pulses associated with storms can cause mortality. This ecotype is often highly productive, and if mangroves are in good condition with adequate sediment supply, they have capacity to adjust to moderate to high levels of sea level rise and can recover from damage from storms.	Moderate vulnerability to changing wind and wave regimes that cause erosion, and to sea level rise. Vulnerability will vary with factors like sediment supply and fetch.

Ecotype	Climate threats	Sensitivity	Vulnerability
Riverine mangroves Mangroves at varying elevation along the edges of rivers. 	This ecotype can vary in elevation. Its association with rivers gives high exposure to increases in rainfall that can cause flooding. Rising sea levels can increase the frequency of flooding.	This type of mangrove occurs in deltas and estuaries. Mangroves can be at low elevation but elevation may vary along rivers. Tides can inundate these types of mangroves regularly. Groundwater may emerge in riverine mangroves and they can be sensitive to declining rainfall. Sediment supply can vary and can be high, but water flow rates can also be high resulting in sediment erosion from surface sediments. Depositional environments tend to occur downstream in rivers and thus sediment trapping may be higher in downstream vs. upstream riverine mangrove. This ecotype is highly productive (high biomass), and if mangroves are in good condition with adequate sediment supply, they have capacity to adjust to moderate to high levels of sea level rise and can recover from damage from storms and other extreme events.	Moderate vulnerability to flooding caused by increasing rainfall and extreme events. Moderate to low vulnerability to sea level rise, depending on mangrove condition and sediment supply.
Basin mangroves Mangroves within low elevation depressions in the landscape. 	This ecotype is often at low elevation. They are hydrologically isolated by levees or barriers to tidal and river flows such that they receive tidal water intermittently, may remain flooded for extended periods of time and then drain slowly. They have low direct exposure to wind and waves as they are often protected by fringing or riverine mangroves. High exposure to increases in rainfall that can cause flooding. Rising sea levels can increase the frequency or extent of flooding.	This type of mangrove can occur in deltas, estuaries, lagoons, or more open coastal settings. Mangroves are at low elevation (often at mean sea level). Tides may inundate these types of mangroves infrequently, but when they do, they may remain inundated for extended periods. They can be influenced by groundwater and thus sensitive to changes in rainfall (increasing or decreasing). Sediment supply is often low. This ecotype can be highly productive, and if mangroves are in good condition, they have capacity to adjust to moderate levels of sea level rise through root production. In good conditions they can recover from damage from storms and other extreme events. If sediments are organic subsidence can occur which can limit recruitment and recovery.	High vulnerability to flooding caused by increasing rainfall and extreme events. Moderate vulnerability to sea level rise and low rainfall.

Ecotype	Climate threats	Sensitivity	Vulnerability
Hammock mangroves Mangroves on high elevation patches in a landscape 	This elevation of this ecotype can vary. They occupy raised areas (hammocks) often within a saltmarsh matrix. They receive tidal water intermittently and may use fresh groundwater for their metabolism. They have low direct exposure to wind and waves as they are often inland and distant from open water. High exposure to increases in rainfall that can cause flooding. High exposure decreases in rainfall and drought. Rising sea levels can increase the frequency of flooding.	This type of mangrove can occur in deltas, estuaries, lagoons, or open coastal settings. Mangroves can be at higher elevation, although elevation varies. Tides inundate these types of mangroves infrequently. Declining rainfall could increase the impacts of sea level rise allowing saltwater into the hammock soils. Sediment supply is low. This ecotype has often low to moderate productivity. If mangroves are in good condition, they have the capacity to adjust to low to moderate levels of sea level rise (root growth may increase elevation) and can recover from damage from storms, drought, and other extreme events. If sediments are organic mortality of trees could lead to subsidence and loss of the hammock.	High vulnerability to flooding caused by increasing rainfall and to declining productivity with decreasing rainfall. High to moderate vulnerability to sea level rise (community change could occur).
Scrub mangroves Sometimes called dwarf mangrove, these are low stature mangroves that are found in the interior or landward. 	This elevation of this ecotype can vary. They are short mangroves (often < 2 m tall) and occupy interior areas, landward of fringing or riverine mangroves. They receive tidal water intermittently and may be have permanently flooded soils (depending on elevation and presence of barriers to drainage) or be hypersaline. They have low direct exposure to wind and waves as they are often distant from open water and protected by fringing stands of mangroves. High exposure to increases in rainfall that can cause flooding. High exposure decreases in rainfall and drought. Rising sea levels can increase the frequency of flooding with salt water.	This type of mangrove can occur in deltas, estuaries, lagoons, or open coastal settings. Mangroves can be high in the intertidal zone or at low elevation behind a tidal barrier. Tides inundate these types of mangroves infrequently. Sediment supply is low. This ecotype has low productivity. In sites that are inundated frequently (or permanently) mangroves will have limited capacity to adjust to low to moderate levels of sea level rise. In sites where scrub mangroves are hypersaline, increasing sea level will increase inundation reducing salinity and enhanced growth may occur.	Where scrub mangroves are flooded they will have a high vulnerability to flooding caused by increasing rainfall and to sea level rise. High vulnerability to decreasing rainfall in hypersaline scrub mangroves.

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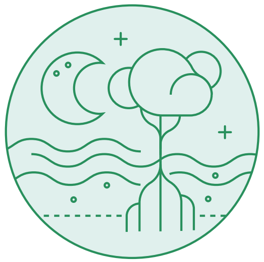

Tidal Range

Mangroves occur in intertidal areas, usually between mean sea level and the level of the highest astronomical tide (ie the upper half of the intertidal zone). Tidal range combined with local relief or topography defines the extent of land that can potentially be occupied by mangroves. Anticipated sea level rise is a smaller proportional change compared to the amplitude of the tide in areas with high tidal ranges compared to those with small tidal range (Figure 14). Therefore, mangroves that grow in geographies with smaller tidal ranges can be at greater risk from sea level rise and inundation with sea level rise than those in sites with high tidal ranges. For example, a 30 cm change in sea level where tidal range is 100cm (i.e., mangroves would occur over 50 cm of the elevation range of the tide) could negatively affect 60% of the elevational distribution of the mangroves; in contrast a 30 cm increase where the tidal range is 300 cm (ie mangroves occur 150 cm of the elevational range of the tide) only 20% of the elevational range of the mangroves would have levels of inundation that likely exceed tolerance of the mangroves.

Therefore, locations (sites) with low tidal ranges are anticipated to be more vulnerable to sea level rise and sea level rise could lead to losses of low elevation mangroves and rapid retreat inland where conditions allow. Regions with low tidal range are the Caribbean region, south eastern parts of North America, parts of eastern Asia and south western Australia (Figure 11).

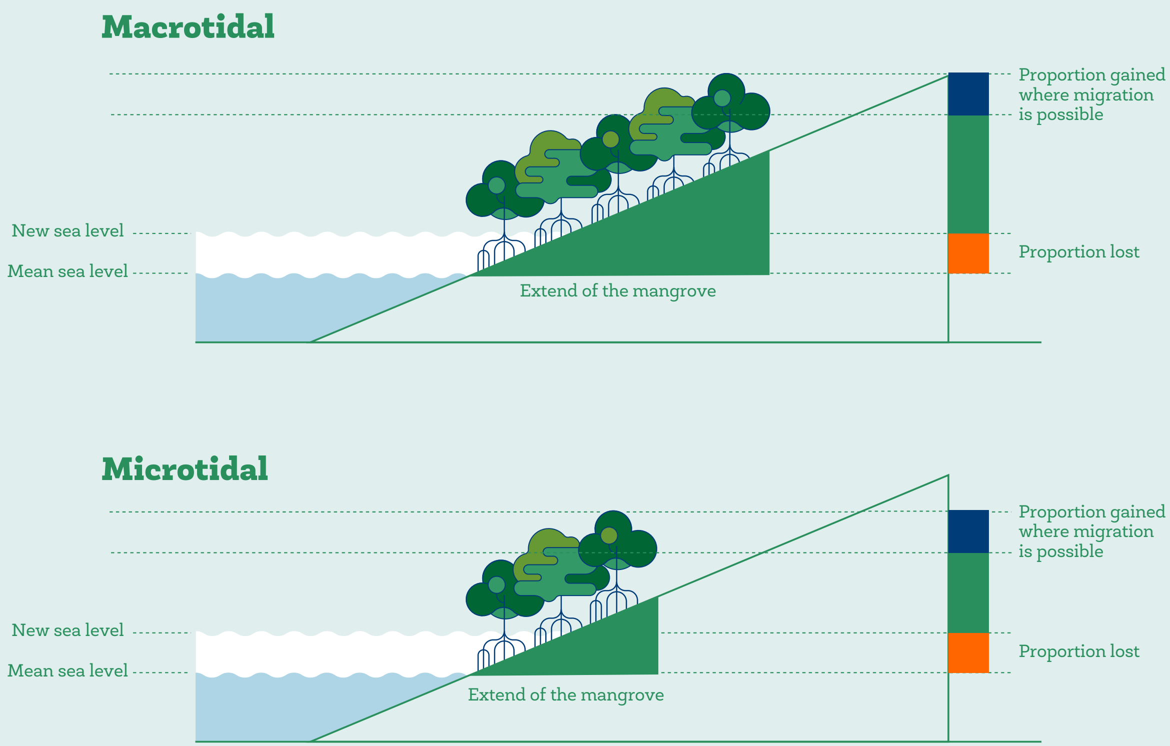

Figure 10 - *Effects of tidal range on the proportion of mangroves affected by rising sea level. With similar bathymetry a greater proportion of mangrove forest will be vulnerable in settings with low (microtidal) compared to high (macrotidal) ranges*[70]

70 From Lovelock and Ellison, 2007

Resources

Tidal range is usually measured from the lowest astronomical tide (LAT) to the highest astronomical tide (HAT) and can vary from ‹1 m to ›10 m depending on location (Figure 11). Microtidal sites have tides less than 2m, meso-tidal sites have tidal range of 2 to 4m, and macrotidal sites have tides more than 4m[71]. Regions with very low tidal ranges are coastal and maritime administrations commonly report on tides for shipping purposes and this information is usually publicly available. Tide gauges are also useful tools for measuring low and high tide and are usually managed by government or research institutions. Local variation in levels of tides can also be assessed through low-tech methods (e.g., dyed cotton strips on stakes or using floats and magnetic devices[72]). Tides in locations far from the ocean (e.g., within estuaries and tidal creek networks) can be attenuated (i.e., smaller than anticipated) compared to that at the coast, which can influence the land expected to be inundated with tidal flows[73].

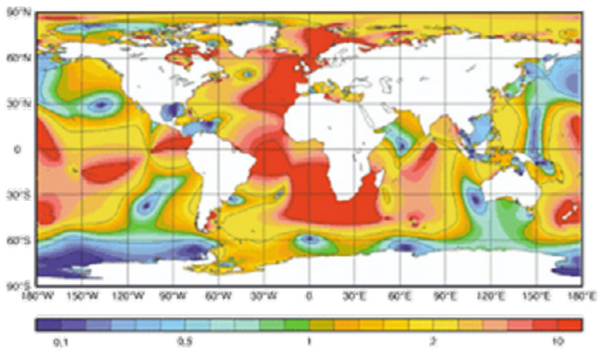

Figure 11. *Global variation in tidal range measured by satellite altimetry. From https://www.aviso.altimetry.fr/en/applications/ocean/tides/tides-around-the-world.html*

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Shoreline Change

Changes to the shoreline position indicate areas of erosion and accretion. This information is key for understanding where areas of the coast are most vulnerable to change and therefore which areas are more or less at risk for mangrove restoration and conservation. Mangrove restoration has sometimes targeted areas of eroding coastline where mangroves are intended to enhance shoreline stabilization and coastal protection. However, this can be risky, because erosive forces may increase with climate change limiting mangrove establishment and successful restoration or conservation. Engineering solutions are often needed to establish mangroves on eroding shorelines. Shorelines that are rapidly eroding where mangroves already occur may indicate changing hydrological conditions (e.g., changes in currents or bathymetry), reduced sediment supply, or perhaps loss of mangrove condition (areas of dieback), although dieback may be a response to shoreline change. Rapidly accreting shorelines can be sites of mangrove expansion, with many seedlings present and dense areas of small trees. Areas of rapid accretion can occur in river deltas with high sediment loads and are often targeted sites for mangrove afforestation in some nations.

Resources

Shoreline change can be measured using historical aerial imagery, and/or conducting a comparison of areas where accretion or erosion have occurred. Citizen science projects have been used in some countries to identify erosion and accretion, although this has been mostly used to monitor beaches (https://www.coastsnap.com/). LiDAR technology that measures changes in the level of the sediments can also be used if available to measure spatial changes in the surface level. Local knowledge of events that may have caused shoreline changes, such as cyclones/hurricanes or significant storms, can also be valuable in identifying areas that may be more vulnerable to change than those that are more stable and therefore may be less risky to restore or conserve. Some government agencies monitor shoreline change using satellite data (e.g., climate data in Australia[74] or ESA in Europe[75]) that may provide useful information for projects, dependent on geography.

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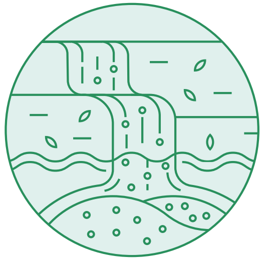
71 Definition of macro, meso, and micro tidal as per Encyclopaedia Britannica
72 Wunsch and Ferrari 2004
73 Balke et al. 2016

74 https://cmi.ga.gov.au/data-products/dea/581/dea-coastlines
75 ESA monitor shoreline retreat across multiple geographies using satellite imagery https://www.esa.int/Applications/Observing_the_Earth/Space_for_our_climate/Measuring_shoreline_retreat



Sediment Supply

Sediment trapped in mangroves contributes to increasing elevation through vertical accretion (i.e., raising the level of the soil surface) that can maintain suitable inundation regimes (tidal inundation) for mangroves in the long term. If vertical accretion is the same or greater than sea level rise then mangrove may withstand sea level rise for decades to millennia[76,77], even if they are relatively low in the intertidal zone. Maintaining sediment supply to mangroves is therefore important for the long-term maintenance of mangroves. In some settings maintaining mangrove health is also critical for maintaining soil elevation as mangrove roots contribute to gains in elevation and soils can subside and decline in elevation if forests are damaged.

Sediment supply is often primarily from river sources, although marine sources can also be important in some cases (e.g., coral atolls, sand islands). Sediments can also be resuspended with wind and waves which is then delivered to mangroves as tides enter mangroves. Finally, in some systems with very low sediment supply (e.g., on atolls) mangrove roots make peat soils. In these settings the health of the mangroves is most

76 Lovelock et al. 2015
77 Krauss et al. 2014

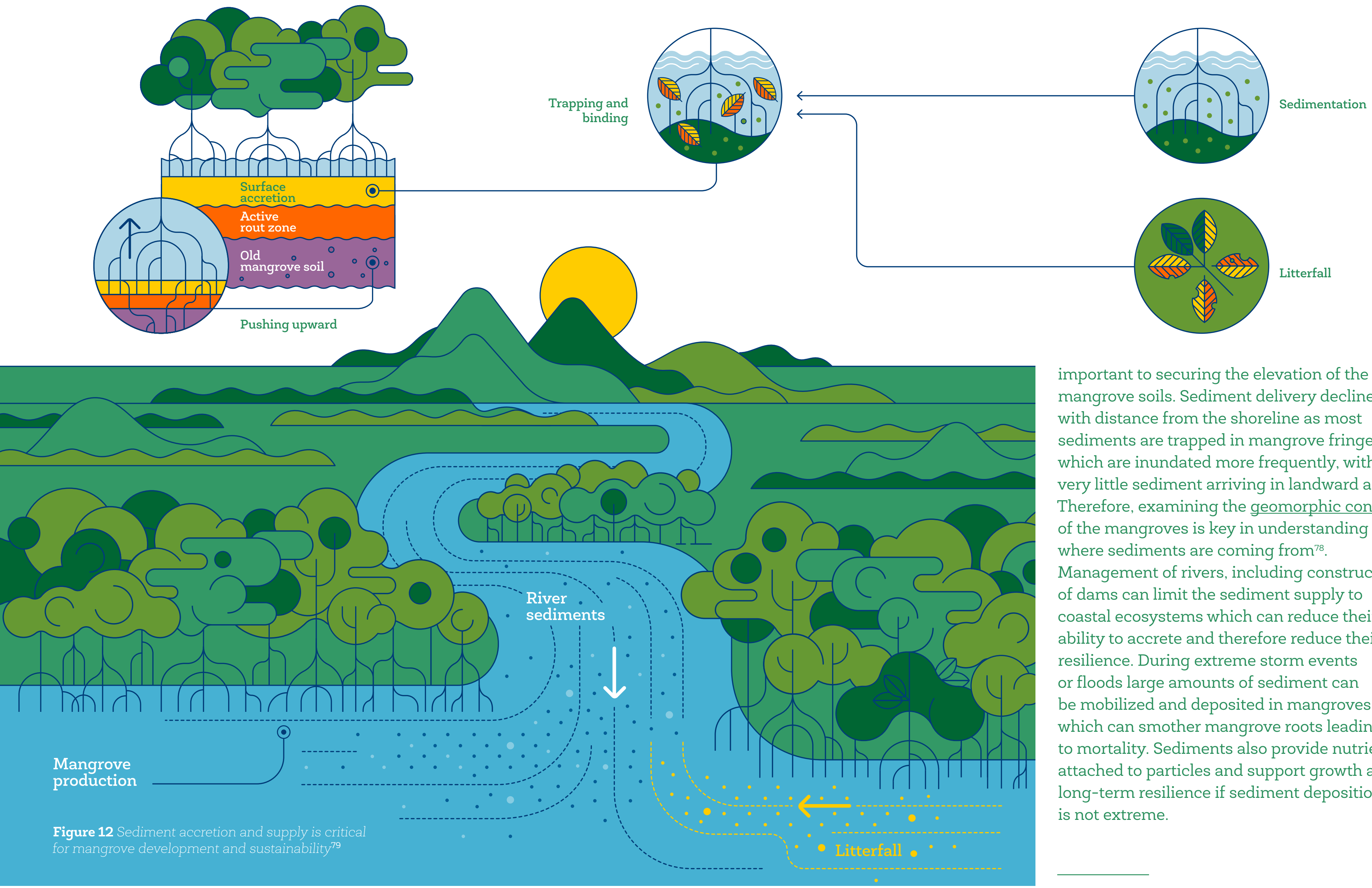


Figure 12 *Sediment accretion and supply is critical for mangrove development and sustainability*[79]

important to securing the elevation of the mangrove soils. Sediment delivery declines with distance from the shoreline as most sediments are trapped in mangrove fringes which are inundated more frequently, with very little sediment arriving in landward areas. Therefore, examining the geomorphic context of the mangroves is key in understanding where sediments are coming from[78]. Management of rivers, including construction of dams can limit the sediment supply to coastal ecosystems which can reduce their ability to accrete and therefore reduce their resilience. During extreme storm events or floods large amounts of sediment can be mobilized and deposited in mangroves which can smother mangrove roots leading to mortality. Sediments also provide nutrients attached to particles and support growth and long-term resilience if sediment deposition is not extreme.

79 See Spalding et al. 2014

78 This is discussed in depth in Woodroffe et al. 2016, which provides some useful considerations when looking at the sources and supplies of sediments to mangroves.

Resources

Sediment supply can be inferred from historical aerial imagery where lateral accretion (may be indicative of high sediment supply) and erosion (may be indicative of low sediment supply) can be identified over certain time scales. Changes in sediment supply can be assessed from remote sensing images of total suspended solids (from Modis - NASA). Field methods have been developed for characterizing sediment supply, loads, and delivery including the Rapid Assessment Manual developed by the Global Mangrove Alliance, which can be referred to when conducting local analysis[80]. Surface elevation tables with marker horizons are a tool for long term monitoring of sediment accretion on soil surface and elevation change[81].

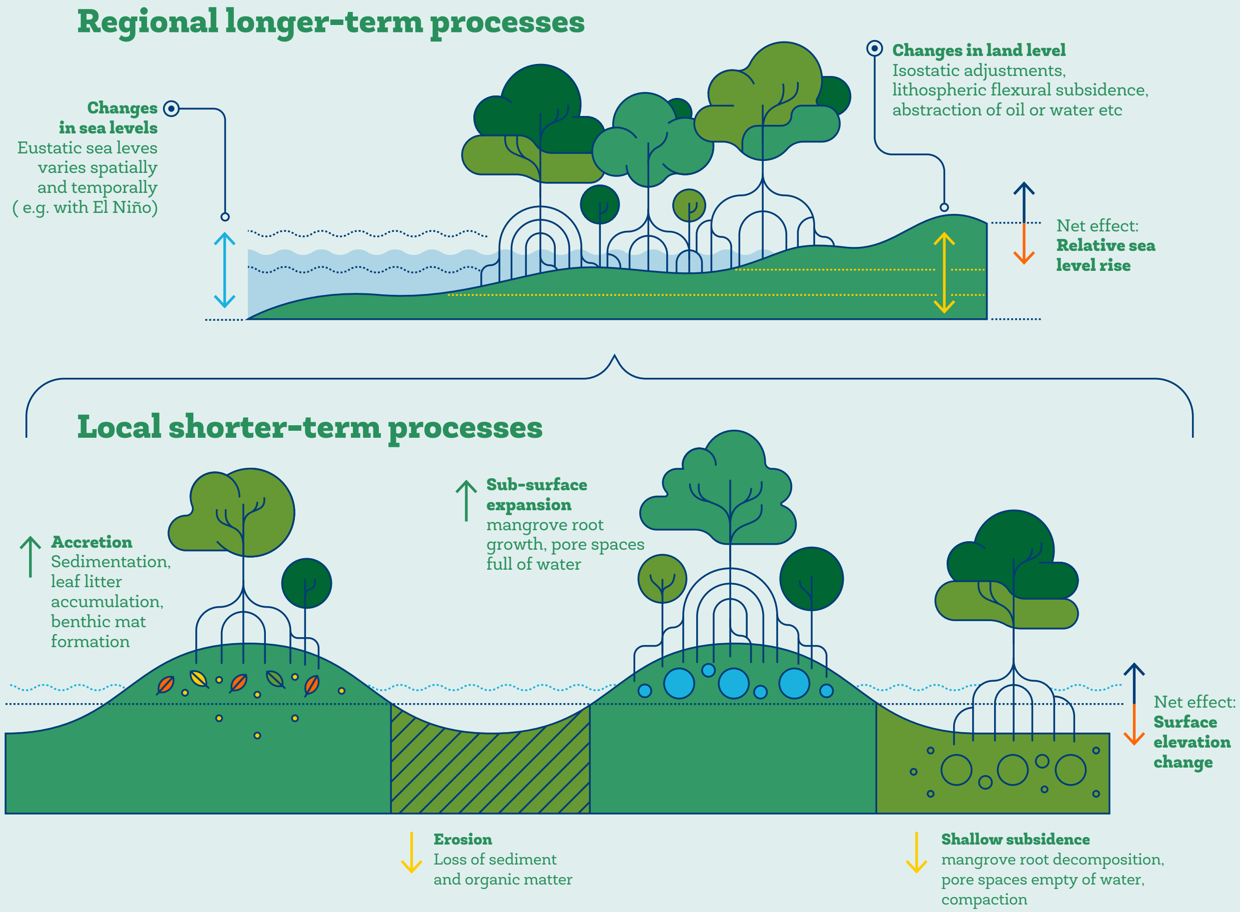


Figure 13 *Regional and local processes affecting the elevation of the mangrove surface relative to local mean sea level*[82]

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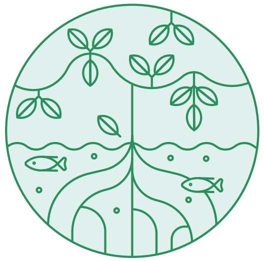
80 BMZ, WWF, and the IUCN have developed a 'Rapid Assessment Guidance Manual' for assessing sediment flow in the context of mangrove restoration and conservation. The manual is available via the Global Mangrove Alliance at https://www.mangrovealliance.org/wp-content/uploads/2020/01/WWF-MCR-Sediment-Flow-in-the-Context-of-Mangrove-Restoration-and-Conservation-v6.5-WEB.pdf

81 See Lovelock et al. 2015

82 McIvor et al. 2013



Mangrove Condition

Mangrove condition describes the overall "health" of the mangrove. Mangroves can be very good condition or can be degraded and in poor condition. The indicators used to assess condition vary depending on local needs and applications. Indicators used are always in comparison to a mangrove in very good condition of the same ecotype and environment. Indicators are usually comprised of measures of:

1. Canopy cover
2. Canopy greenness
3. Presence of dead or dying trees
4. Species richness
5. Presence of litter (leaf litter and woody debris)
6. Recruitment of new individuals

Resources

Table 8 provides an example scheme for qualitatively assessing mangrove condition. Quantitative assessments are also possible, for example using monitoring of tree growth or canopy greenness from satellites. Locally appropriate assessment protocols may be available.

Species Composition

Mangroves are diverse ecosystems that, when healthy, can host several different species of flora and fauna, including different species of mangrove trees. The species composition in mangroves can be important in restoration and rehabilitation projects, where species can be specifically selected and planted that offer greater resilience and adaptive capacity to the conditions in the area as well as those projected for the future. Table 5 can be used to determine which species might be suitable for a site with changing conditions. Otherwise, refer to Rehabilitation/Restoration.

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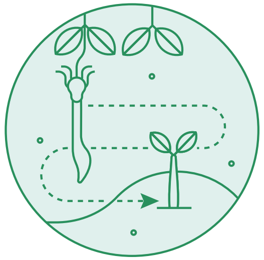
Table 8 *Assessing Mangrove Condition – examples of indicator states*

Mangrove condition	Description
Very poor (highly degraded)	Canopy is very thin, patchy, or absent. Most trees are dead or dying. Species richness is low compared to mangroves in very good condition. There is little leaf litter, but abundant woody debris (from dying trees and canopy). There are no recruits (seedlings or saplings).
Poor (degraded)	Canopy is very thin or patchy, dead branches. There are many dead trees. Species richness is low compared to mangroves in very good condition. There is little leaf litter, but abundant woody debris (from dying trees and canopy). There are few recruits (seedlings or saplings).
Moderate (some evidence of degradation)	Canopy is thinning but intact. There are some dead branches. There are dead trees. Species richness is similar compared to mangroves in very good condition. Leaf litter and woody debris are present. There are patchy recruits (seedlings or saplings).
Good (very little evidence of degradation)	Canopy is intact. There are few dead branches. There are few dead trees. Species richness is similar compared to mangroves in very good condition. Leaf litter and woody debris are present. There are many recruits (seedlings or saplings).
Very good (not degraded)	Canopy is intact. There are very few dead branches. There are very few dead trees. Species richness is similar compared to mangroves in very good condition. Leaf litter and woody debris are present. There are many recruits (seedlings or saplings).



Ecological Connectivity

The connectedness of mangroves to other mangroves and other coastal ecosystems plays an important role in how they function (e.g., fish habitat, coastal protection) as well as their ability to receive and contribute materials, including mangrove propagules and detritus. Mangroves form part of complex coastal landscapes that are interdependent and important for a range of marine species, such as fish, marine mammals, reptiles; and terrestrial species[83] that move among habitats. The connectivity of mangroves to saltmarsh, tidal flats, coral and rocky reefs, seagrass meadows, other coastal wetland forests and terrestrial ecosystems is important for planning to achieve a diverse and productive landscapes for conservation or restoration. For example, fish may spend juvenile life stages in mangroves before migrating to reefs as they mature; and larger mature mangrove patches may be sources of propagules of trees and benthic fauna for other areas.

Resources

Connectivity can be measured spatially, usually using some measure of patch size and proximity (distance of pathways between locations), either by examining aerial imagery[84], or by using local knowledge and data collection (i.e., in-field surveys and assessments of neighboring mangrove areas and other coastal ecosystems). For mangrove trees, the principles of landscape ecology indicate that connecting small patches through restoration to make larger patches contributes to forest resilience.

Figure 14 *Components of landscapes that can be arranged in ways to enhance connectivity and overall productivity and resilience*[85]

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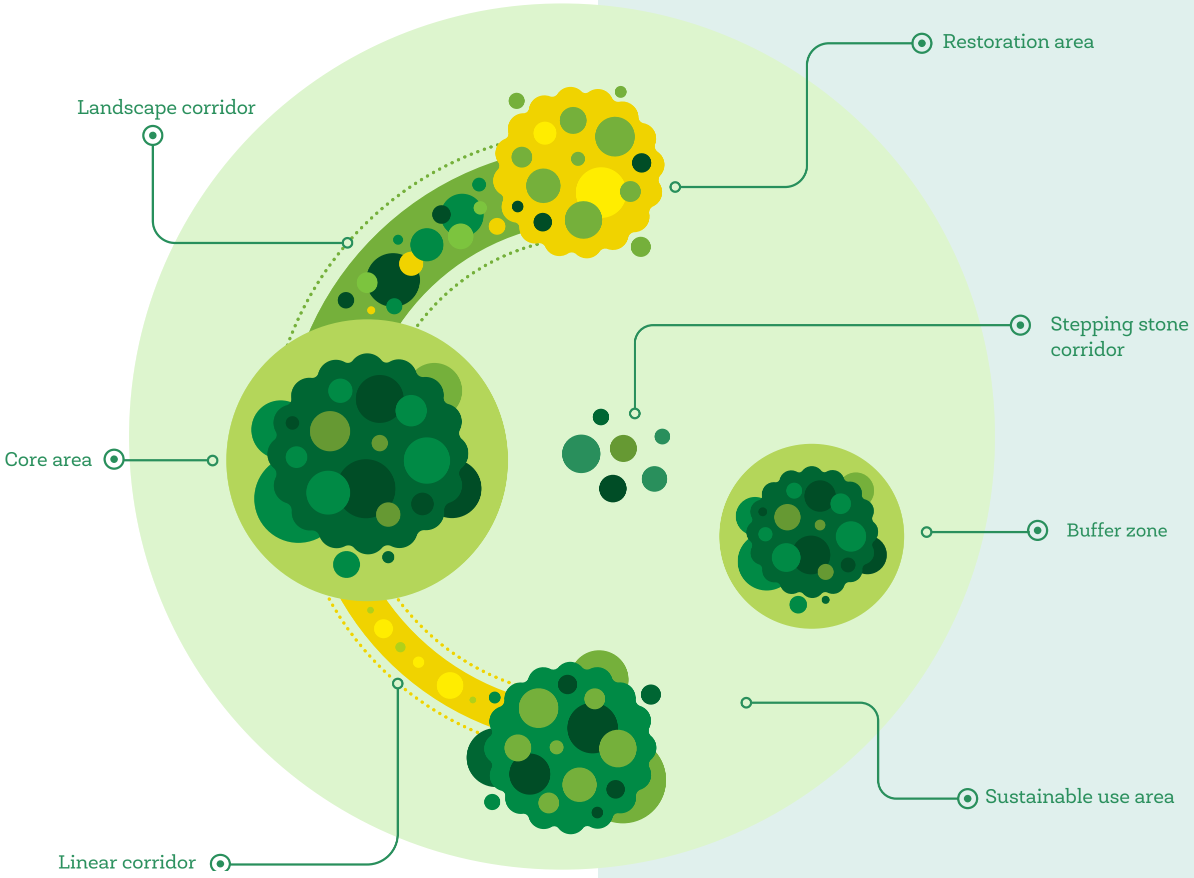

83 Thompson and Rog 2019

84 d'Acampora et al. 2018 present a useful method scheme for determining ecological connectivity (Figure 1 at https://doi.org/10.1016/j.ecolmodel.2018.06.005)

85 Lawton et al. 2010

Barriers to Landward Migration

Different types of barriers (built structures) on the landward edge of mangroves, may limit the landward migration of mangroves with sea level rise, and will influence the potential for communities to plan and facilitate landward migration of their mangroves and therefore adaption to climate change. This is because management of built structures, including modification or removal) will require resources and power. For example, if a highway will prevent landward migration of mangroves unless suitable culverts to facilitate tidal flows are added to the structure, the adaptive capacity of the community could be low if resources available to the local community are limited, or their ability to influence the form of the infrastructure is low (limited power). In contrast, if there are few or limited barriers to mangrove landward establishment, for example earthen walls of extensive aquaculture owned by the local community, then communities with limited resources may be able to plan to modify structures for the long-term conservation of their mangroves.

When hydrological conditions such as sea level, flood and inundation frequency increase, or the elevation of the soil surface declines (i.e., subsides), sites often become less suitable for mangrove growth and survival. The maintenance of mangrove cover under these conditions requires that mangroves establish in sites that have suitable inundation regimes, which with sea level rise are likely landward of existing mangrove stands. Mangroves have a natural ability to recruit and establish in landward locations when conditions are suitable, often called "landward migration" which ensures their survival in the landscape. When barriers on the landward side of mangroves exist (e.g., levee banks, seawalls, or infrastructure) these barriers limit the available area for mangroves to establish in the future. Barriers to mangrove landward migration will result in the loss of mangroves and is known as 'coastal squeeze'[86], which describes the squeezing of mangrove habitat between rising sea levels and landward barriers.

A barrier can be any man-made or naturally occurring structure or form that prevents mangroves from establishing in a landward direction. These might include:

- Levees
- Walls (structural) and berms (agricultural)
- Flood or tidal gates (often within drained landscapes)
- Hard surfaces (bitumen, transport infrastructure, urban areas)
- Natural topographical features (dunes or hills/ mountains)

86 Mills et al. 2015 explain coastal squeeze and propose adaptation options for managing it in their paper at https://doi.org/10.1111/conl.12213

Resources

Methods for determining and mapping the barriers to landward migration for mangroves are available[87]; however, it is likely local knowledge is useful to develop a discussion in workshops of the barriers to future mangrove growth that are specific to the project site settings.

Land-use

Land use can present a barrier to the landward migration of mangroves with sea level rise, as some land uses may be difficult or even impossible to change, for example, urban development. Some land uses can also cause stressors and pressures on existing mangroves (e.g., pollution, exploitation, or hydrological stresses). Additionally, some land-uses provide valuable livelihoods (cattle production, tourism developments) and therefore the opportunity costs for conservation and restoration projects can be large. Some research[88] indicates that managing land use adjacent to mangroves can improve mangrove ecosystem health and resilience. Intensive land use, such as urban areas, industrial activities, and agriculture, can place pressure on mangroves, including land clearing (for development or resources), changes in hydrology, excessive nutrient and sediment inputs.

Land uses that can pose threats to mangrove conservation or protection include aquaculture (if conversion of mangrove occurs or nutrient effluent is delivered to mangroves), pasture (if converted for pasture or due to excessive fertilizer use or animal damage), and agriculture (if converted and also if excessive fertilizers are

87 Enwright et al. 2016 document numerous methods and approaches to identifying and quantifying barriers for the landward migration of coastal wetlands in https://doi.org/10.1002/fee.1282
88 Sasmito et al. 2019 have studies the impacts of land use on mangroves and noted that certain land uses can have significant impact on the ability to implement proper mangrove protection

applied)[89]. Understanding current and future land use and its impacts on adjacent mangroves can therefore help guide management, conservation, and restoration approaches for mangroves. In many countries integration of mangroves within farming (aquaculture or agriculture) landscapes is key to human safety and landscape productivity (Nature-based Solutions).

Land-use can span from natural ecosystems to highly urbanized landscapes (e.g., cities). For large scale (global, regions) the density of people (often expressed as people per km^2) living in the coastal zone can be used as an indicator (a proxy) for land use. Mangrove sites adjacent to high populations centres often have a greater risk of damage, overutilization, and deforestation[90]. High human population densities are usually assumed to limit the land available for landward migration of mangroves with sea level rise, as it is assumed that current land uses are valuable for people and that infrastructure (e.g., barriers) are or will be constructed to protect from sea level rise that inevitably will prevent landward establishment of mangroves.

Knowledge of land-uses can assist in exploration of the types of land that may be available or benefit from conservation or restoration in the future and aid economic analyses of the costs and benefits of adaptation to sea level rise.

External pressures on human societies associated with climate change may influence behaviors that influence land use. External pressures can be socio-economic or climatic. For example, interrupted supply chains with the COVID19 pandemic placed greater pressure on mangrove resources in some regions. Emerging industries like oil palm place pressure to convert mangroves to alternative land uses and cultural practices (e.g., funeral ceremonies) can put pressure on certain mangrove species. Knowledge of interdependent processes associated with mangroves is important for diagnosing projected changes in land use and devising strategies to manage these pressures.

Resources

Land cover is mapped globally (e.g. https://land.copernicus.eu/global/products/lc). Population density information is collected by government agencies by way of public census. At a global scale, the NASA Socioeconomic Data and Applications Center (SEDAC) have developed a 'Gridded Population of the World' (GPW v4) based on United Nations WPP-adjusted population density data[91], which can be used as a reference when conducting projects at larger scales. The intensity of night lights has been used to infer global variation in economic development (https://www.earthdata.nasa.gov/learn/backgrounders/nighttime-lights).

Local government offices, non-government organizations, and civilian record repositories may also provide useful sources of information for assessing land-use and barriers to landward migration of mangroves. Maps of future projected land use or planning may also be available. High resolution aerial imagery (e.g. from Google Earth or other sources) may also be useful in determining land-use and barriers to landward migration of mangroves.

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89 Murdiyarso et al. 2020 have looked at land use change and its impact on the carbon storage capability in mangroves

90 Turschwell et al. 2020 present useful information on the socio-economic pressures, including population density, on mangroves from a global lens. Table 1 is of usefulness with regards to providing links and sources for data and information on human pressures that can be used as a reference for determining local stressors.

91 SEDAC GPW v4 https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11

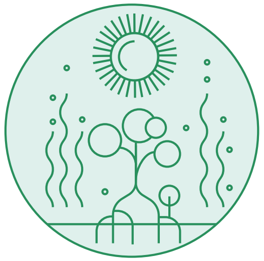
Exposure to climate threats

Exposure to climate change threats is defined as "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected"[92]. The exposure of mangroves to climate threats will determine appropriate management actions to support resilience of conserved and restored mangroves. There are six climate threats considered within the tool that are evaluated in the vulnerability assessment steps of this tool (step 2). Additional climate threats (see summary of climate change factors affecting mangrove forests in Table 1, Appendix A) may be evaluated if they are relevant for projects or locations, including El Niño Southern Oscillation (ENSO). Climate threats evaluated in the tool are:

- Increased air temperature – direct effects on plant photosynthesis and growth. While higher temperatures can enhance growth when trees are well below their thermal limits it can reduce productivity when they are at their limits. High temperatures cause higher water loss from leaves (evapotranspiration) and sediments that contributes to water deficits and salinization of soils.
- Increased rainfall – hydrological intensification that contributes to flooding/inundation that can adversely affect mangrove tree physiological functions by reducing oxygen within sediments. Increased rainfall may also lead to declining salinity which may result in changes in the composition of plant communities.
- Decreased rainfall - contributes to drought and salinization of soils that adversely affects mangrove organisms because high levels of salt, beyond tolerance limits are toxic.
- Increased wind speeds (can be linked to frequency/intensity extreme storms) - contributes to canopy damage and other damage associated with waves.
- Increased wave energy (can be linked to frequency/intensity of extreme storms), - contributes to tree damage and shoreline erosion.
- Sea level rise – contributes to increased inundation and can act synergistically with increased wind species and wave height to increase inundation and shoreline erosion.

Each of these climate threats (exposure factors) are described below with suggestions of where information and/or data can be sourced to determine the specific vulnerability for the project site under evaluation.

92 IPCC definition of exposure from The Fifth Assessment Report (WGII AR5) Climate Change 2014: Impacts, Adaptation, and Vulnerability



Increasing Temperatures

Projections for increases in global temperature in the future have high certainty, although there is regional variations in the extent of temperature increases that are projected (Figure 12). Increasing air temperatures can have direct effects on metabolic process, including photosynthesis and respiration, which influences plant growth. At higher latitudes increases in temperature may increase mangrove growth and extent (at the expense of marshes), while at lower latitudes higher temperatures may reduce productivity as higher temperatures can cause reduced rates of photosynthesis and enhanced rates of respiration[93].

Rising temperatures influence evapotranspiration (evaporation of water from canopies of trees and soils) which can lead to increased salinization of soils[94]. In some regions aridity may increase with increasing temperature and declining rainfall, leading conditions less favorable to growth and decrease in tree stature (scrub forms), species turnover to more salt tolerant communities, and in some instances losses of mangrove cover and replacement by microbial communities (e.g., cyanobacterial mats).

Resources

Regional projections for increases in temperature are available from IPCC Assessment Report 6[95] and can be viewed at https://interactive-atlas.ipcc.ch/. Changes in temperature affect the water cycle of the globe leading to variation in rainfall patterns and evapotranspiration (Figure 12). Regional or national projections for temperature may be available from national government agencies.

Different socio-economic pathways give rise to different estimates of temperature increases[96].

Increasing temperatures also influence the water cycle, including patterns in precipitation and evapotranspiration.

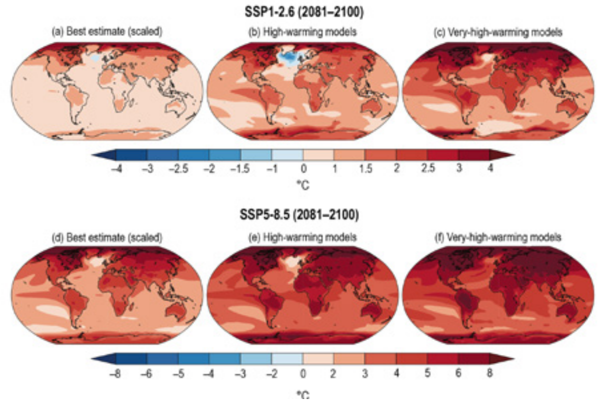


Figure 15 *IPCC Warming model predictions*[97]

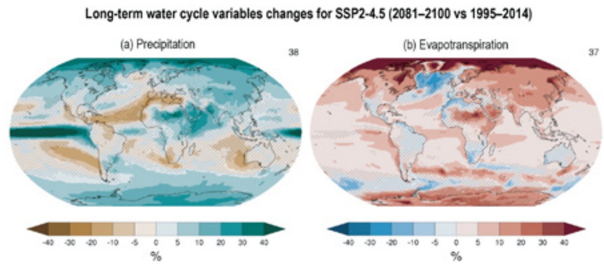


Figure 16 *Temperature impacts on the water cycle*

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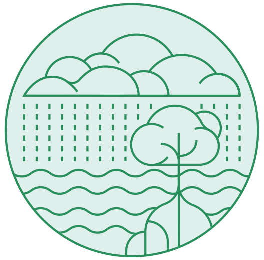
93 Lovelock et al. 2016 at https://link.springer.com/chapter/10.1007/978-3-319-27422-5_7
94 Osland et al. 2016 at https://doi.org/10.1111/gcb.13084
95 IPCC Assessment Report 6: https://www.ipcc.ch/assessment-report/ar6/
96 Working Group 1, Technical summary https://www.ipcc.ch/report/ar6/wg1/
97 IPCC Assessment Report 6: https://www.ipcc.ch/assessment-report/ar6/



Increased Rainfall (precipitation) and associated flooding

Increased rainfall can increase the risk of flooding and can lead to declines in salinity of soil porewater.

Flooding

Understanding the extent and depth of flooding in mangroves, both from "normal" tidal inundation and flooding caused by extreme rainfall events and storms, is important when determining the long-term suitability of an area for mangrove conservation and restoration. This kind of data is also important for land-use planning at the landscape scale.

Mangroves are sensitive to flooding depth and duration because extended flooding results in depletion of oxygen concentrations within mangrove roots that disrupts metabolic function (and thus freshwater and nutrient uptake) and can lead to mortality. Oxygen concentrations are lower in sediments and water compared to air. While mangroves transport oxygen from air into the sediments via their roots (through lenticels and spongy tissues in their roots), their capacity to do this can be reduced if contact of aboveground roots to the air is limited by flood waters and deposited sediments.

Flooding can come from both the land and the sea and these often occur simultaneously during extreme events. Saltwater flooding, caused by storm surges and tidal waves, can result in mangroves being inundated with more saltwater than usual, which can reduce oxygen levels in roots and alter the salinity of sediment porewater (see Decreasing Rainfall); both which can lead to mortality of mangroves. Saltwater inundation can also result in sediments from the marine environment being deposited into mangrove areas, causing changes to the physical-chemical characteristics of soils as well as potentially smothering root systems, which can limit mangrove growth, and in some situations cause tree death. Large amounts of sediments deposited in mangrove areas whether from freshwater or saltwater flooding can also alter hydrology which can influence tidal water flows (drainage), which can lead to mangrove death if water is ponded for longer periods than usually experienced at the site.

Land-derived sediments are often finer in particulate size and higher in nutrient content than marine sediments. Sediment contributions during flooding can be important for mangrove growth. It is important to recognize that sediments delivery during seasonal flooding can support mangrove growth, productivity and resilience (see Sediment Supply).

Reductions in salinity

Sustained increased levels of rainfall may to lead to declines in salinity of soil porewater in mangroves. Reductions in salinity of soil porewater is associated with changes in plant community composition such that species that are less tolerant of saltwater can enter the community. This could increase diversity of the mangrove community, but it also may lead to changes to other ecosystem types, for example a transition to herbaceous freshwater wetland types. Weedy species may also be favored under fresh or brackish water conditions and may require management.

Resources

Global and regional precipitation projections for the future are available from IPCC (e.g. https://www.ipcc.ch/report/ar6/wg1/chapter/atlas/ The interactive atlas is available at: https://interactive-atlas.ipcc.ch/). Other useful resources are available from the World Bank (country level, https://climateknowledgeportal.worldbank.org/). National level projections for future precipitation may also be available (country dependent).

Local level data on potential for flooding can be measured using spatial technology (e.g. with drones), or depth and extent could be locally known through observations of past flood events. Tide gauges can provide a useful data for measuring the flood depth where they are available[98]. Using permanent flood or tide gauges are the most efficient way of characterizing exposure to flooding associated with high rainfall; however, if this is not possible, measurements can be taken using water level loggers or manually (see methods). Alternative methods for measuring flood extent and frequency include using aerial imagery or spatial data. NASA's Landsat Science platform provides access to historical imagery that can be used to identify flood frequency, duration, and whether flooding is terrestrial (storm/event based) or coastal (tidal inundation)[99].

Changing salinity over time can be monitored on site using simple tools (e.g. water extracted from the soil and measured with handheld refractometer - see Decreasing rainfall resources section), or through monitoring changes in species composition.

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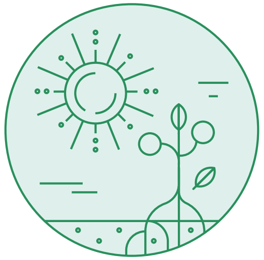
98 Baker et al. 2015 and Minello et al. 2012 both use local tide gauges measured hourly over a defined period to calculate flood. See bibliography for links to the papers.

99 NASA Landsat Science https://landsat.gsfc.nasa.gov/



Decreasing Rainfall and associated drought

Decreasing rainfall can results in drought which can cause reductions in groundwater and river flows within mangrove ecosystems that can lead to salinization of soils and can lead to mangrove mortality and changes in the plant community.

Changes to the salinity of the environment in which mangroves grow has the potential to both positively and negatively affect their growth. Where saline conditions already occur, declining rainfall and associated increases in soil porewater salinity could reduce mangrove growth and only species that are highly salt tolerant would be present. Understanding the natural range of salinity of sites, or the potential for salinity change at a site can help identify where efforts to conserve or restore mangroves may be most rapid, or where and what other management methods could be useful to enhance mangrove cover.

Mangroves can grow in environments that span almost freshwater (brackish) to hypersaline conditions (where soil salinity are higher than the salt concentration in seawater, ›35 parts per thousand, or ppt, grams of salt per litre of water). Some mangroves can survive salinity of 90 ppt (e.g., Avicennia growing in the high intertidal zone of arid locations like those that occur in Puerto Rico, Mexico, Australia, and parts of Africa), but at very high salinity mangroves grow very slowly and are typically shrub form. Experiments with potted plants have shown that in most mangrove species growth is rapid at 25% seawater (~ 9 ppt) and that tolerance of higher levels of salinity varies among mangrove species. For this reason, understanding how salinity of soil porewater (not surface tidal water, which can be different to that in the soil) varies over the site and the tolerance of salinity of local mangrove species is important[100].

100 Duke et al. 1998 includes useful information on various species of mangroves and their known tolerances and spatial distribution based on condition.

Table 9 *Tolerance of some mangrove species to high salinity, high aridity, and temperature extremes*[101]

Species	Relative Tolerance				Extreme Conditions			
	Salinity	Aridity	Low Temp	High Temp	Precipitation (mm/yr)	Extreme min. temp	Mean min. temp	Mean max. temp
Acrostichum aureum	Mid	Mid	Mid	Low	800-1200	0-5	8-12	34-37
Aegialitis annulato	High	High	Mid	Mid	‹400	0-5	8-12	37-40
Aegiceras comiculatum	Mid	High	High	Mid	‹400	-5 to 0	4-8	37-40
Avicennia germinons	High	High	High	Mid	‹400	‹ -5	4-8	37-40
Avkennia marina	High	High	High	High	‹400	‹ -5	4-8	›40
Bruguiera gymnorrtiiza	Mid	High	High	Mid	‹400	-5 to 0	4-8	37-40
Bruguiera sexangula	Low	Mid	Low	Low	›1200	0-5	12-16	34-37
Ceriops australis	High	High	Mid	Mid	‹400	-5 to 0	4-8	37-40
Ceriops decandra	Low	Low	Low	Mid	800-1200	5-10	12-16	37-40
Ceriops tagal	Mid	High	Mid	Mid	‹400	-5 – 0	8-12	37-40
Exccecona agallocha	Low	Mid	High	Mid	400-800	-5 to 0	4-8	37-40
Heritiera littoralis	Mid	Mid	High	Mid	400-800	-5 to 0	8-12	37-40
Kandelia candel	Mid	Low	Low	Low	›1200	5-10	›16	34-37
Kandelia obovata	Low	Low	High	Low	›1200	‹ -5	4-8	34-37

101 Table 1 adopted from Lovelock et al. 2016

Species	Relative Tolerance				Extreme Conditions			
Laguncularia racemosa	Mid	High	Mid	Mid	<400	< -5	8-12	37-40
Lumnitzera littorea	High	Low	Low	Mid	800-1200	0-5	12-16	37-40
Nypa fruticans	Low	Low	Low	Low	800-1200	0-5	12-16	34-37
Osbornia octodonata	Mid	Mid	Mid	Mid	<400	0-5	8-12	37-40
Rhizophora apiculata	Mid	Mid	Mid	Mid	400-800	0-5	8-12	37-40
Rhizophora mangle	High	High	Mid	Mid	<400	< -5	8-12	37-40
Rhizophora mucronata	Low	High	Mid	High	<400	0-5	8-12	>40
Rhizophora stylosa	High	High	High	Mid	<400	-5 to 0	4-8	37-40
Sonneratia alba	Mid	Mid	Mid	Mid	400-800	0-5	8-12	37-40
Sonneratia lanceolata	Low	Low	Low	Low	>1200	5-10	>16	34-37
Xylocarpus granatum	Low	Mid	Mid	Mid	400-800	0-5	8-12	37-40
Xylocarpus moluccensis	Mid	Mid	Mid	Mid	400-800	0-5	8-12	37-40

Salinity of soil water varies over mangrove landscapes depending on rainfall and groundwater influences, salinity of tidal water, frequency of tidal inundation and evaporative demand. Where rainfall is high and fresh groundwater is abundant the salinity of soil water in mangroves tends to be relatively homogenous and less than seawater (<35 ppt) and could be similar to the salinity of surface (tidal) water. These conditions usually support growth of a high diversity of mangrove species.

- Where rainfall is moderate to low, and evaporation is high at some periods of the year then landward areas that are inundated infrequently may build up salt in the soils to levels greater than seawater (>35 pt.) which will limit mangrove growth resulting in shrub tree forms of few salt tolerant species (see table above). Low intertidal seaward fringing mangroves will have soil water salinities that are close to the salinity of tidal water enabling development of taller mangroves.
- Saline intrusion into landward agricultural areas may indicate potential for mangroves to migrate inland, and therefore planning related to creating space for landward retreat of mangroves can be made (see Barriers to Landward Migration)

Resources

Global and regional precipitation projections for the future are available from IPCC (e.g. https://www.ipcc.ch/report/ar6/wg1/chapter/atlas/ The interactive atlas is available at: https://interactive-atlas.ipcc.ch/). Other useful resources are available from the World Bank (country level, https://climateknowledgeportal.worldbank.org/). National level projections for future precipitation may also be available (country dependent).

There are no global data resources that project future changes in porewater salinity. Because salinity is relatively easy and inexpensive to measure, salinity of sites can be monitored which can give insights into likely changes in salinity and plant communities with reduced rainfall. The most straightforward way to measure salinity is to conduct in-field testing for soil water and tidal water salinity using samples obtained using a suction device to extract porewater and a handheld refractometer (cost around $100-300) or a probe with an electrical conductivity sensor (cost around $300) to measure salinity.

Mangrove roots are exposed to soil water, which is not necessarily the same salinity as the surface tidal water, because diffusion of tidal water into soils is very slow. Extracting soil water can be done using a suction device or by digging holes at low tide and collecting water samples from the hole as water seeps into the hole.

Suction devices can be simple and comprise of a large plastic syringe attached to tubing. By taking measurements seasonally and over the landscape, data can be gathered to identify variations and changes to salinity in soils and water environments. If reference sites are available, consider using those to characterize the salinity conditions of natural mangroves. Another straightforward method for estimating (or inferring) salinity is to identify existing plant species growing in the proposed project area. If the species identified are known to be tolerant or intolerant to saline conditions, then this can be used to infer the salinity conditions for that area. Looking at historical aerial imagery where species and vegetation types can easily be identified is another method of determining levels of salinity

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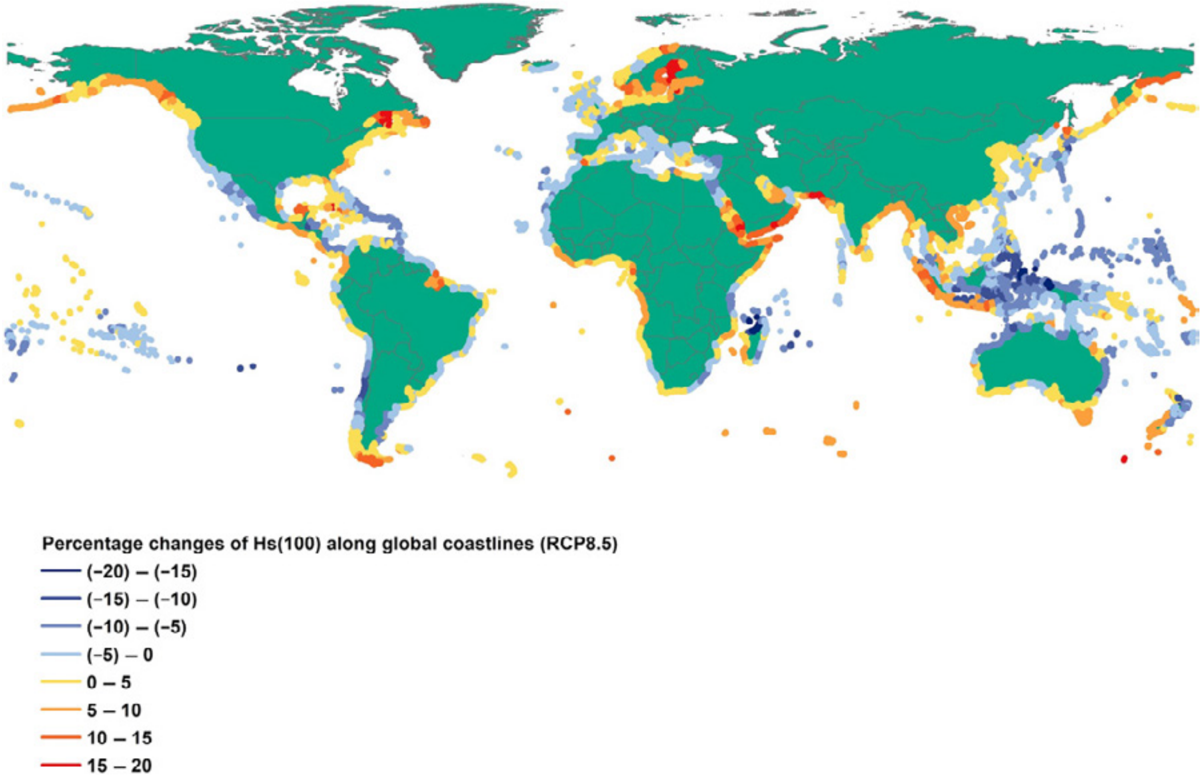
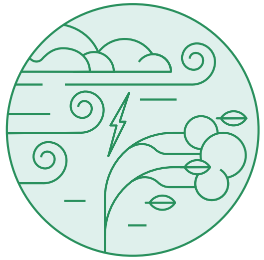


Figure 17 *Percentage change in 100-year extreme value significant wave heigh along the global coastline between the historical dataset (1979-2005) and future projection (2081-2100) for RCP8.5*



Increased Wind and/or Wave Exposure associated with increased storms

Mangroves occur in settings that are protected from wind and wave energy. Therefore, increases in wind speeds and wave heights may cause significant damage to mangrove coastlines through direct damage to canopies, disruption of recruitment processes, erosion or accretion of sediments and inundation of areas with salt water. This damage can cause loss of mangrove land area (coastal retreat), reduced land elevation (from erosion), and changes to sediment characteristics that can limit mangrove growth. In many locations extreme wind and wave severity and frequency is anticipated to be greater with climate change, but projections vary over the oceans and have higher levels of uncertainty that projections for temperature or sea level rise (Figure 17). Global projections for changes in wind and waves for RCP 8.5 are shown in Figure 17, but local geomorphic features (e.g., coastal bathymetry, or whether mangroves are on a coastal embayment vs. within an estuary) will moderate the impacts of wind and waves on mangroves.

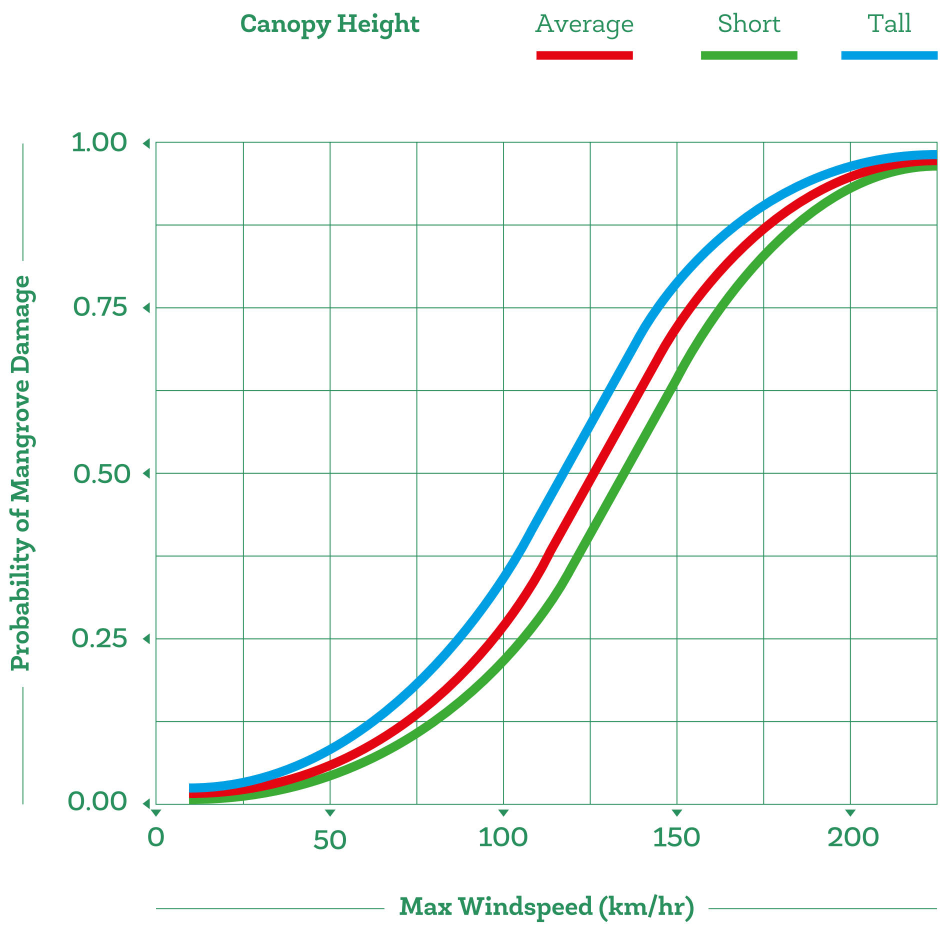


Figure 18 *The probability of NDVI in Caribbean/Mesoamerican mangroves decreasing by at least 0.2 (metric of mangrove damage) as a function of maximum wind speed during the 2017 hurricane season and canopy height*[102].

Wind speeds of greater than 100 km/hr have approximately 50% chance of causing damage to mangrove canopies (Figure 18 shows region that taller canopies have a greater probability of damage than shorter canopies in the Caribbean region[103]). The measure of significant impact or risk to mangroves (moderate or greater) by storm waves have been described as occurring when waves are greater than 4 meters in height (on average through the storm). Wind and wave height data can be acquired (see next paragraph), but if this is not possible, then the use of local knowledge of the past occurrence of large storms and their wind and waves and the intensity of their damage can be useful in evaluating future risks with higher wind and wave energy. For example:

- Moderate damage may be described by waves that caused canopy damage, but the mangrove remains largely intact, recovers, with little shoreline erosion.
- High level of damage may be described by toppled or broken trees with some shoreline erosion, and
- Very high levels of damage as those that led to death of large stands of mangroves, loss of shoreline with limited or no recovery of the mangrove.

102 From Taillie et al. 2017

103 Taillie et al. 2020

Figure 19 *Mangrove damage from intense wind generated by Hurricane Irma three years after Hurricane Irma. Very little mangrove recovery is evident*[104]

Resources

Projections for global future wind speeds[105] and modelled projections for wave conditions[106] are available. National projections for changes in wind and waves with climate change may be available from national government agencies.

Wave height can be measured by calculating the vertical distance between the crest (peak/top) and the trough (bottom) of a wave[107]. There are several instruments that can be used to measure wave height, such as acoustic Doppler velocimeters (ADVs), acoustic Doppler current profilers (ADCPs), and buoys that measure acceleration. These instruments require deployment, maintenance, and the capability to store and analyze large quantities of usually real time data, which can be costly, although some less expensive options are becoming available that have been used to characterize environments in mangrove restoration (e.g., mini buoys[108]). Note that in some countries Wave Rider Buoys' have been deployed by government agencies monitoring nautical conditions and this can also be used to inform wave height information. National meteorological networks, including the US National Oceanic and Atmospheric Administration (NOAA)[109], the Australian Bureau of Meteorology (BOM)[110], and the Fiji Meteorological Service[111], provide real-time data and historical databases of wind, wave and oceanic conditions that can help to inform whether certain areas and coastlines are at higher risk of experiencing significant winds and wave heights with the potential to cause significant damage to mangrove coastlines during storm events (see Figure 19). Where data is not available, manual methods[112] and those used by the surfing community[113], although not as accurate, can be used to estimate wave height.

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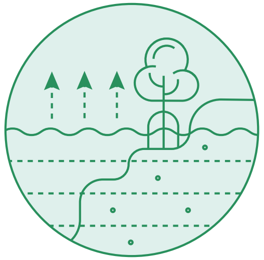
104 NASA, David Lagomasino, East Carolina University)
105 IPCC Interactive Atlas https://interactive-atlas.ipcc.ch/
106 Meucci et al. 2020 https://www.science.org/doi/10.1126/sciadv.aaz7295
107 NOAA – Wave Height Explanation https://www.weather.gov/dlh/WaveHeightExplanation#:~:text=How%20is%20Wave%20Height%20measured,were%20perfectly%20calm%20and%20flat.
108 See Balke et al. 2021.
109 NOAA has several marine environmental buoys deployed across the Atlantic and Pacific Oceans that are collecting data at set intervals. The database is publicly available and can be accessed at https://www.ncei.noaa.gov/access/marine-environmental-buoy-database/
110 BOM has wave rider buoys deployed around Australia and offshore that may be useful for the Pacific region http://www.bom.gov.au/metadata/catalogue/19115/ANZCW0503900478
111 Fiji's Meteorological Service provides real time and historical data related to tropical cyclone and storm events https://www.met.gov.fj/index.php?page=south_west_pacific_marine#20
112 Gal et al. 2011 utilized video time stacks to estimate wave height. Similar methods using video footage can be utilised. doi: 10.1109/DICTA.2011.68.
113 The Bascom method, developed by Willard Bascom in the 1950s, is one accepted method for measuring wave heights used by surfers across the world. https://www.jstor.org/stable/24940361



Sea Level Rise

The rate of sea level rise is influenced by: 1) increases in the level of the sea, and 2) changes in the elevation of land due to geological processes (subsidence or uplift). The term "relative sea level rise" is used to describe the sum of these processes. Tide gauges generally incorporate both sea and land components of sea level rise (see the Permanent Mean Sea Level project, https://psmsl.org/ for global locations of tide gauges and further explanations) while satellite altimetry methods for measuring the level of the sea do not include land movement (see https://www.star.nesdis.noaa.gov/socd/lsa/SeaLevelRise/). Knowledge of vertical land movement can be important to understanding risks of sea level rise to mangroves. For example, a moderate rate of sea level rise in a location with rapid land subsidence gives rise to high rates of relative sea level rise; or a high rates of sea level rise in a location with rapid land uplift (e.g. due to tectonic activity) may have a low rate of relative sea level rise.

1) Increases in sea level: Global sea level rise projections due to thermal expansion of the oceans have a high level of certainty. Rates of sea level rise are projected to accelerate after 2050, but projected rates of sea level rise vary over the globe. Because level of the sea (and tidal variations) influences the distribution of mangroves, increases in sea level are expected to have large effects on mangrove extent, although these effects will be variable over the globe. It is expected that relative sea level rise and erosion will result in substantial reductions in areas of mangroves and other intertidal wetlands in the future[114]. Over time as sea level rise progresses it is expected that low intertidal mangroves may retreat landward as their tolerance of inundation is exceeded (as they get deeper relative to mean sea level). This pace of this process could be influenced by storm activity (which may accelerate retreat), it may also be slowed if sediment supply is high, sediment accretion occurs (elevation of the surface increases), and mangroves can maintain their position relative to mean sea level. At the landward edge of mangroves, increasingly frequent tidal inundation with rising sea level will result in conditions suitable for mangrove growth and thus mangroves will expand in a landward direction. Sea level rise may also result in changes to the salinity as seawater affects groundwater making land less suitable for plants dependent on freshwater and more suitable for salt tolerant plants like mangroves.

Sea level rise impacts are likely to proceed more rapidly in areas with low tidal range compared to high tidal range (see Tidal Range) and in areas where the land is subsiding rapidly due to geological processes (e.g., southern edges of the North American continent[115]).

Resources

Rates of sea level rise vary regionally. The Intergovernmental Panel on Climate Change (IPCC) provides sea level projections within AR6, but has not yet made available sea level projections in the climate atlas explorer (at the time of writing). NASA has developed a "Sea Level Projection Tool" that provides global and regional sea level rise relative to a 1995-2014 baseline[116]. NASA provides global sea level rise data that can be used to inform the level of risk of sea level rise in the project area[117]. The European Space Agency (ESA)[118] and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO)[119] also collect data using satellite altimetry, autonomous floats, gravimetric data, and local tide gauges to measure sea level. These data are publicly available and may provide more refined resolution for local conditions of some projects. Local data at a finer resolution may be available from local authorities where climate adaptation planning has occurred.

2) Changes in land elevation (subsidence and uplift): Changes in the elevation level of the land can be due to geological uplift and subsidence of land. Subsidence or uplift can be due to glacial isostatic adjustment which describes the adjustments of the continents that is ongoing due to glacial retreat during the Holocene and the decreases the mass of ice on one-side of continental plates, resulting in tilting of the plate (e.g. North America). Local tectonic activity (e.g. associated with earthquakes or volcanoes) can also lead to change in the elevation of the land. Subsidence of land can also be caused by anthropogenic factors like withdrawal of oil and gas and groundwater.

Previous assessments of vulnerability defined a range of variables that influence vulnerability of mangrove ecosystems to sea level rise[120] (see table 10)

114 Goldberg et al. 2020
115 See Herrera-Garcia et al. 2021

116 IPCC Sea Level Projection Tool https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool
117 NASA Sea Level Rise data https://sealevel.nasa.gov/
118 ESA Sea Level data https://climate.esa.int/en/projects/sea-level/data/
119 CSIRO Sea Level data https://research.csiro.au/slrwavescoast/sea-level/measurements-and-data/
120 Adapted from Mcleod and Salm 2006

Table 10 *Mangrove vulnerability to sea level rise (adapted from Mcleod and Salm 2006)*

Vulnerability	Local conditions	Details
Most vulnerable	Low relief islands	Restricted sediment source/accretion, subject to drought and wave erosion, likely to experience flooding, soil salinity increases, and inundation.
	Areas without rivers	Lack of sediment or freshwater source inputs.
	Carbonate environments	Landward migration limited, restricted sediment sources.
	Areas experience subsidence (tectonic activity, groundwater extraction, underground mining)	Greater impacts from sea level rise, inundation is a threat.
	Micro-tidal environments starved of sediments	Lack of sediment inputs, inability to naturally accrete with sea level rise, problems establishing species diversity, changes to geographic distribution of mangroves.
	Mangroves with landward edge limited by coastal development or steep topography	Inability to move landward with sea level rise, no space to retreat.
Least vulnerable	For islands, mangroves in deeper sediments on high-lying islands or in deltaic settings	Structurally stronger and less vulnerable to storm surges than those on low-lying islands or in shallow sediments; higher islands better adapted to survive climate change with larger surface areas, more reliable freshwater sources, more fertile and structurally diverse soils, and more diverse resources.
	Riverine mangroves	Larger, more reliable sources of sediment, higher nutrient concentrations available.
	Macro-tidal sediment rich environments	More reliable sources of sediment, strong tidal currents to distribute sediments.
	Mangroves with room to move landward	Areas backed by low-lying, undeveloped areas or salt flats provide space for mangroves to retreat inland with sea level rise.
	Mangroves in remote areas	Limited stresses from other anthropogenic sources (e.g. exploitation, deforestation, etc.) and more likely have room to retreat where not impeded by development.
	Mangroves surrounded by high quality dense forests	Communities that are surrounded by dense mangroves have greater and more reliable sources of seeds and propagules for reproduction.

Resources

Changes in the level of the land due to glacial isostatic adjustment is available from satellite data (Grace Tellus, https://grace.jpl.nasa.gov/data/get-data/gia-trends/) (Figure 20). The potential for subsidence due to groundwater extraction has also been mapped globally (Figure 20).

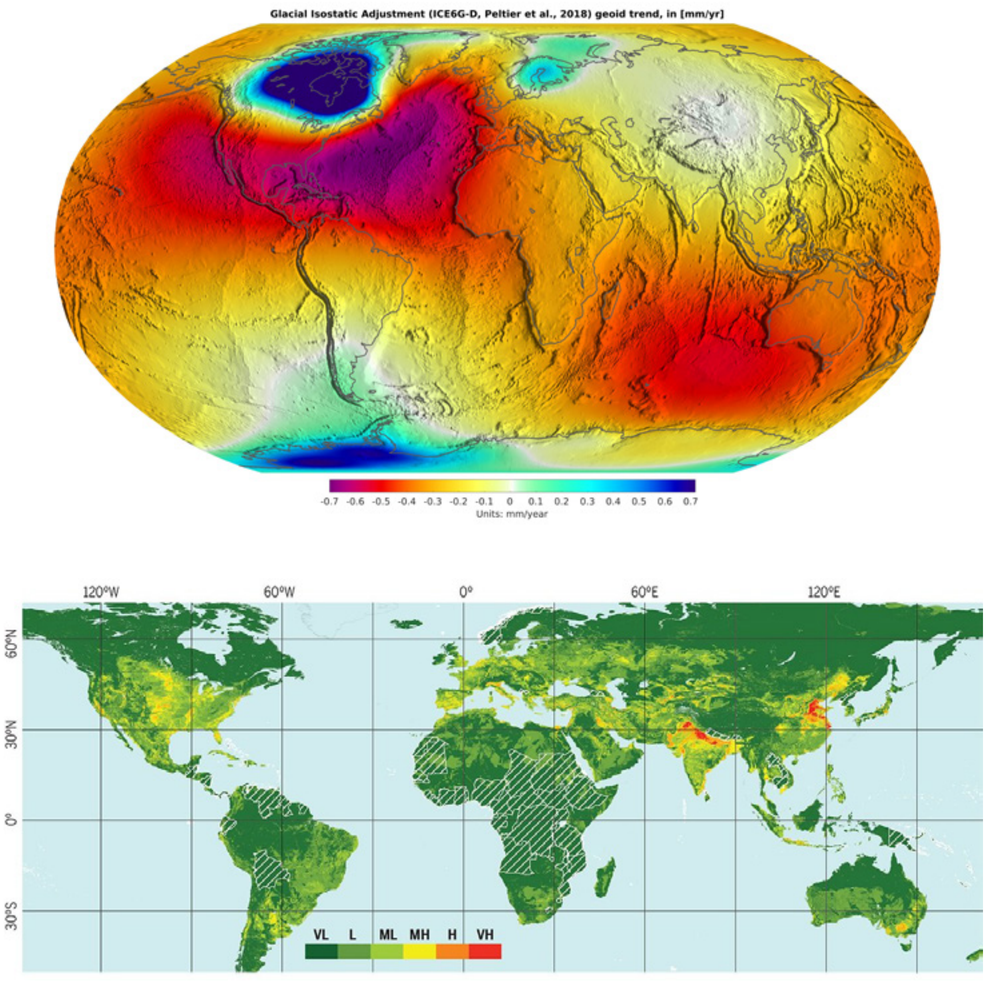


Figure 20 *Upper panel- The influence of glacial isostatic adjustment on vertical land movement (from GRACE Tellus satellite missions https://grace.jpl.nasa.gov/data/get-data/gia-trends/). Lower panel, potential global subsidence due to groundwater extraction*[121].

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121 See Herrera-Garcia et al. 2021 https://www.science.org/doi/10.1126/science.abb8549

Adaptive Capacity

Adaptation is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. Incremental adaptation occurs where the central aim is to maintain the essence and integrity of a system or process at a given scale. Transformational adaptation occurs when the fundamental attributes of a system change in response to climate and its effects[122]. The adaptive capacity of human communities (societies) describes their capacity to respond to climate-related threats. It is assumed that high levels of adaptive capacity in communities will result in greater capacity to manage mangroves under climate change achieving beneficial outcomes for communities as climate change progresses. There are numerous components of adaptive capacity that interact (Figure 21).

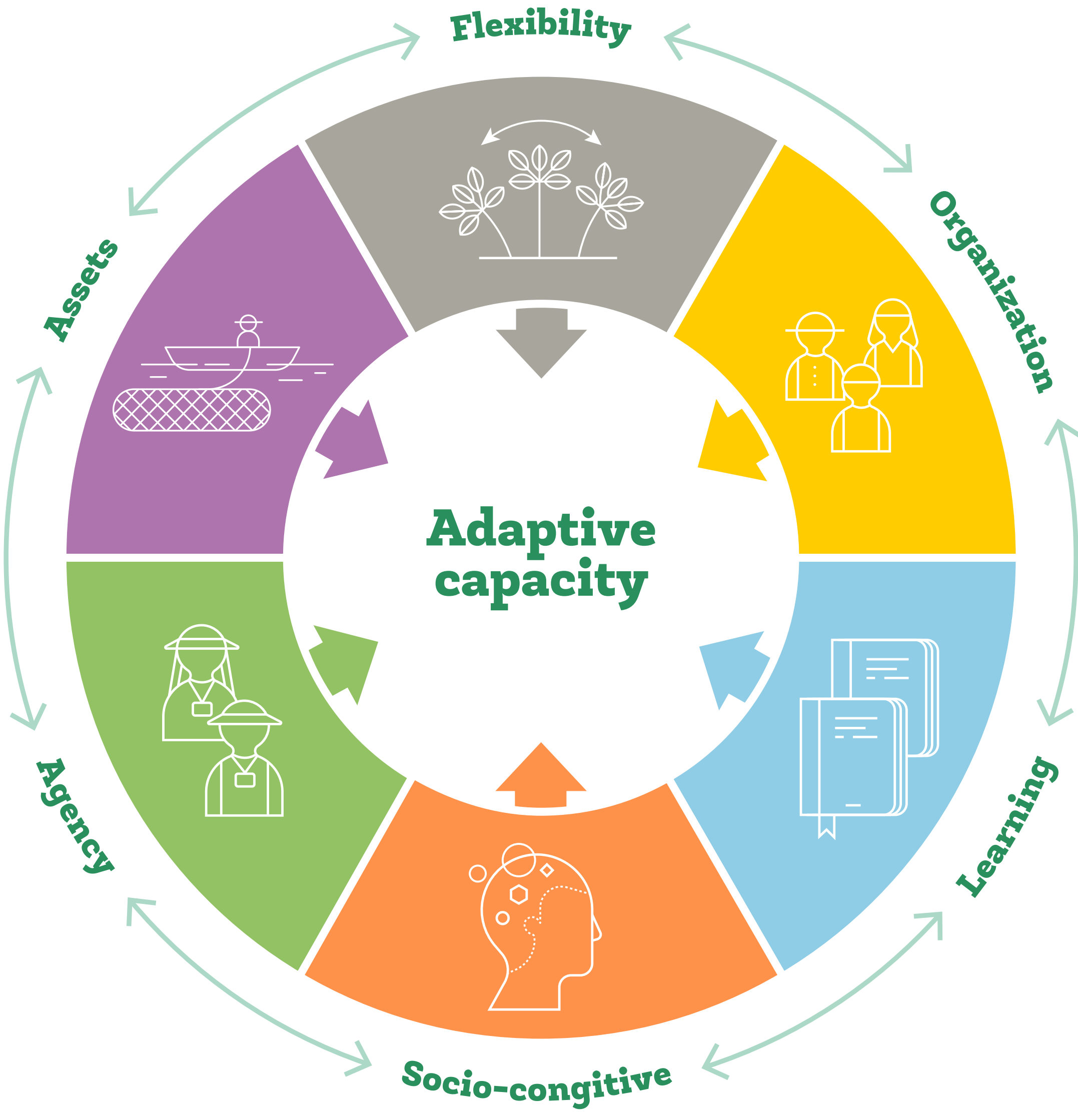

Figure 21. *Components of adaptive capacity[123]: assets, flexibility, social organization, learning, socio-cognitive constructs, and agency. The six domains are interlinked; feedbacks and interactions can occur among any of the domains and not just the neighboring ones graphically represented by connecting arrows.*

122 IPCC definition of adaptation from The Fifth Assessment Report (WGII AR5) Climate Change 2014: Impacts, Adaptation, and Vulnerability
123 Cinner and Barnes 2021.

Table 11 *Human Factors Influencing Mangrove Vulnerability and resilience to Climate Change*[124].

Factor	Descriptions	Categories used in the tool
Assets	The financial, technological, service-related (i.e., health care), and other types of assets available to people.	Level of resources
Socio-cognitive constructs	Risk attitudes, personal experience, perceived social norms, and cognitive biases. Risk attitudes include perceptions about the probability and severity of risk as well as the costs and benefits associated with adapting.	Included within Community Willingness
Learning	People's capacity to recognize change, attribute this change to causal factors, and assess potential response strategies. Access to information, experiential and experimental processes that enable people to frame or reframe problems.	Included within Community Willingness
Agency	Agency reflects people's free choice in responding to social-ecological changes including aspects of empowerment and self-efficacy. People's belief in their own ability to manage prospective situations and control the events that affect them, which is closely linked to the cognitive dimensions of resilience discussed above.	Included within Community Willingness
organization	The formal and informal relationships that support these key social processes include both social networks and institutions, which can operate at different scales. For example, recovering from natural disasters often requires not only individual people to help each other out but also state agencies to coordinate relief efforts.	Institutional or Organizational Capacity; Governance
Flexibility	The capacity of both individuals and institutions to deal with change by being able to switch between strategies. Flexibility is dependent on the diversity of options available but also people's ability and willingness to engage in alternatives. Constrained by internal factors for example, the extent to which people's identity is tied to occupation or place.	Flexibility

124 *Adapted from Cinner and Barnes 2021.*

In the tool, components of adaptive capacity from Cinner and Barnes (2021) have been modified (Table 11). The tool category of Community willingness is comprised of multiple components described by Cinner and Barnes (2021). The tool explicitly considers Governance as a separate category (from within Organization), because of the important influence Governance arrangements can have on conservation and restoration projects and in planning for climate adaptation. Users of the tool may consider the sub-categories of any of the adaptive capacity categories, depending on local conditions, project goals and levels of data.

- Level of resources (Assets)
- Community Willingness is a collation of Socio-cognitive constructs, Learning and Agency.
- Institutional or Organizational Capacity (Organization)
- Governance (Organization)
- Flexibility

Each of these factors that influence adaptive are explained with suggestions of where information and/or data can be sourced to determine the adaptive capacity of communities that manage mangrove sites.

Level of Resources

The resources available to communities is known to affect the capacity of communities to adapt to climate change and may also influence community engagement in conservation or restoration of mangroves. Resources include financial, physical assets like land and equipment, and human resources. Influential leaders are important component of human resources.

Household income is often used as an indicator of resource availability. Household incomes have been linked to levels of education and power (ie. Learning and Agency, Table 11). However, low levels of resources and poverty can also be associated with reliance on mangroves for resources[125], and therefore a clearer understanding of their value (links to Community Willingness).

Resources

Project teams will understand the levels of financial and other resources that are available for climate-smart projects. Government and philanthropic institutions may provide financial resources, while communities could hold physical assets and human capacity (including leadership). Capacity within the project teams can also be considered (e.g. time, skills, relationships within communities).

If using indicators of adaptive capacity, household income and community-scale income data are often collected by government authorities and may be publicly available through relevant authorities. Local data can also be collected by researchers or project teams. Global data is available from OECD[126] and the World Bank[127]; however, the resolution of these data may not be suitable at the local scale.

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125 Nchimbi et al. 2019 conducted a study in Zanzibar that looked at household income (among other metrics) as a measure of the impact and risk of exploitation of mangroves

126 OECD Data Online for Household Disposable Income https://data.oecd.org/hha/household-disposable-income.htm

127 World Bank data portal (using the search function to filter for specific areas) https://data.worldbank.org/

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Community Willingness

The willingness of the community to participate in mangrove conservation and restoration projects, including those to implement climate-smart management, is important in ensuring projects are successful in the long term and mangroves are properly protected from human impacts and are climate-smart. Community willingness is influence by a multiple factors (Table 11) including social norms, personal experiences, perceptions of risks imposed by climate change, learnings and also beliefs around peoples capacity to manage climate risks.

Willingness to participate in climate-smart projects[128] can be assessed in several ways, including:

- Assessing the interest within community in the mangroves and/or related projects,
- Assessing the community's understanding of the value of mangroves (e.g., whether they are seen as an important for reducing risks of climate change).

Resources

Evaluation of levels of community willingness uses local knowledge of the communities' values and beliefs. Community surveys, interviews, and group meetings are valuable tools for gathering information from the community on their current perceptions and attitudes to mangroves as well as their willingness to be involved in either direct or indirect management and/or conservation activities to increase climate adaptation[129]. Local social scientists may be key partners in growing knowledge of local adaptive capacity.

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128 Arifanti et al. 2022 explore community willingness and willingness to participate in mangrove management in their recent study.

129 Vo Trung et al. 2020.

Institutional or Organizational Capacity

The capacity of institutions and organizations to implement or support climate-smart mangrove restoration or conservation actions can influence long term success of climate-smart projects. The interacting network of institutions and organizations that affect mangrove landscapes can include government, local communities, community organizations, NGOs and others. These can be listed and their relationships mapped to provide a visual assessment of organization. Mapping roles, responsibilities and flows of resources and information among institutions and organizations can help to understand where power is concentrated.

Resources

Evaluation of institutional and organization capacity can use local knowledge of the area and the community. Tools like NetMap (https://netmap.wordpress.com/) and others can be used. Local social scientists may have knowledge of local institutions and their roles, interactions, and competencies in mangrove management and for climate change adaptation.

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Governance

Governance refers to structures and processes designed to ensure accountability, transparency, responsiveness, rule of law, stability, equity and inclusiveness, empowerment, and broad-based participation. In the tool the assessment of governance arrangements for projects can include assessment of laws, policies, land tenure arrangements and formal and customary rights to land and natural resources. Assessment of governance arrangement can help project teams to evaluate potential limitations and enablers for climate-smart projects, and also identify actions for enhancing climate-smart projects and mangrove governance processes.

High levels of participation, coordination and cooperation among institutions, organizations, and communities, including women and Indigenous people, involved in mangrove governance can enable implementation of climate-smart approaches. Indicators of low levels of adaptive capacity in governance could include the inability to develop and implement appropriate land-use planning, the inability to regulate land-use change or construction of infrastructure, or decisions are made by government agencies without stakeholder engagement.

Resources

Evaluation of governance arrangements can use local knowledge of the area and the community. IUCN provides guidance on analysis and integration of governance arrangements to support restoration https://portals.iucn.org/library/node/50050 as a new component of the Restoration Opportunities Assessment Methodology (ROAM). Although the IUCN guidance focuses on restoration the general principals apply to developing climate-smart strategies. Local social scientists may have knowledge of governance of mangroves and may provide important insights for evaluating the potential success of mangrove conservation or restoration and planning for their maintenance with climate change. Governance of mangroves is an emerging area of study. Analysis of governance to support mangrove conservation with climate change is available for Indonesia[130].

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130 Mursyid et al. 2021

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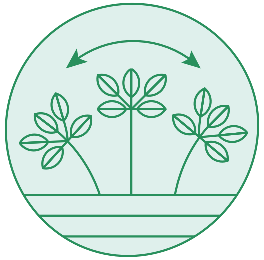


Flexibility

Flexibility is the capacity of both individuals and institutions to deal with change by being able to switch between strategies. Flexibility is dependent on the diversity of options available but also people's ability and willingness to engage in alternatives. For example, high levels of flexibility would be evident if building seawalls was the option to protect land against sea level rise, but once learning about Nature-based Solutions, mangroves were incorporated into the design as an alternative strategy. Flexibility may be constrained by a range of different factors, including levels of resources, the organizational structure (and governance), gender and components of Community Willingness (Socio-cognitive constructs, Learning and Agency). For example, the willingness to change land-uses may be tied to occupations, or political pressures may limit flexibility of government policies. Evidence of flexibility to engage with policies and actions that specifically support climate change adaptation, mangrove restoration or conservation, and ecosystem service development or protection are more likely to provide support (either in terms of resources, support, or prioritization). Where governments or communities are evaluated as inflexible, strategies to gain support for climate-smart projects can be developed that acknowledge and potentially mitigate constraints to flexibility (e.g. through communicating of alternative options[131].

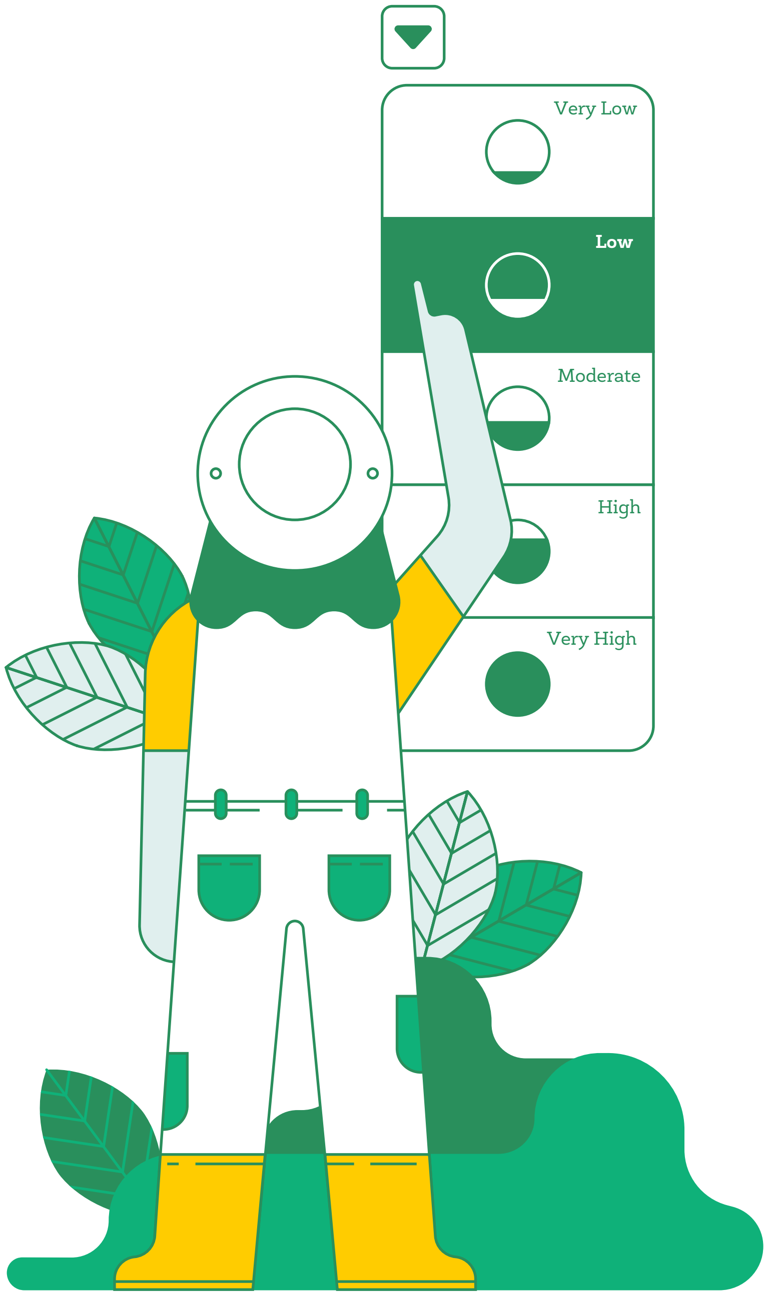
Resources

Evaluation of Flexibility can use local knowledge of stakeholders flexibility. Local social scientists may have knowledge of flexibility of different stakeholders including government (national, provincial, local) and may provide important insights for evaluating the potential success of mangrove conservation or restoration and planning for their maintenance with climate change.

131 Thinda et al. 2020.

Vulnerability Rankings

Use the table below to rank vulnerability based on local conditions. While using this tool could help summarize data and discussions and prioritize sites, it may not finalize decisions about actions to reduce vulnerability, which may be decided using qualitative approaches. Ranking in the table is specific to each characteristic of climate threats, sensitivity and adaptive capacity and broadly fits into the following ranking criteria.

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Very Low

Sites for restoration of conservation that rank as very low for the vulnerability characteristic being assessed are less likely to be impacted climate change. For example, where vulnerability to sediment supply is ranked as very low, this means that the supply of sediment to the mangroves is likely high and stable, and therefore not considered a characteristic of concern for management, conservation, or restoration. Characteristics ranked very low can be viewed as a positive for a conservation, management, or restoration, and activities at these sites should harness the benefits of these aspects within the project.

Low

Low vulnerability rankings, as with those ranked very low, are of lesser concern for consideration in a project or at a site. It should be acknowledged that low does not mean no vulnerability or risk of impacts from climate change.

Moderate

Components of vulnerability that are ranked moderate are those where the sensitivity, exposure, or adaptive capacity aspect of the site means that there is the potential for positive impacts for conservation and restoration. Where components of vulnerability have been identified as moderate there is opportunity to focus actions for the project to reduce vulnerability and there is the potential for these characteristics to have the greatest impact in terms of success. Establishing the costs and effectiveness of potential interventions is an important step in the decision process.

High

Characteristics that are ranked as having high vulnerability should be identified and be given high level of consideration. It is important to understand whether any intervention or influence on the aspect ranked as high is possible, and if it is, establish the costs and effectiveness of potential interventions (see Assessing Priority).

Very High

Very high vulnerability characteristics indicate those that are extremely vulnerable to climate change and special consideration can be given during project planning and site assessment. As with high vulnerability characteristics, special consideration must be given to understanding whether any intervention or influence is possible, and if it is, establish the costs and effectiveness of potential interventions (see Assessing Priority).

Assessing Priority

When identifying the various characteristics of a project or site and ranking the vulnerability of those aspect to climate change impacts, consideration must be given to whether interventions or actions are likely to be successful and what they may cost to implement. The potential to influence or change levels of vulnerability will help determine which aspects should be prioritized[132].

Where vulnerability ranking results in a moderate, high, or very high score for certain characteristics, a project could focus on specific actions that have the potential to influence to reduce the vulnerability. However, there are some characteristics that, where the vulnerability assessment is very high it may not be possible to adequately implement management actions or activities to reduce vulnerability.

In the tool criteria for prioritization include:

- Importance: "Does anyone care?" – A measure of how much support there is likely to be. Social and cultural importance (including charisma).
- Feasibility: "How easy is this to achieve?" – An assessment of the difficulty associated with this action of suite of actions. Logistical and political, source of funds, community attitudes.
- Benefits: "What good will it do?" – A measure of how much good will result from the project. For example, will there be a reduction in extinction risk, increase in population size of important species, provision of valued ecosystem services (e.g. timber, carbon).
- Costs: "What will it cost?" – An assessment of the relative economic costs of the project (or gains). In this criterion there are both positive and negative components which must be weighed against each other. Components to consider are direct and indirect costs of the project, direct and indirect social and economic costs and benefits that will flow from the project.
- Urgency: "Can it be delayed?" – A measure of whether the projects are time-limited, or whether it can be delayed. For example, habitat for important species may be lost, or there is high potential for loss of opportunity if the project is delayed.
- Chance of Success: "Will it work?" – An assessment of whether the project will work. Will it meet its specified objectives?

In cases where the vulnerability ranking is very high and it is determined that interventions are largely unlikely to be successful or prohibitively costly, then several additional strategies could be discussed that might include additional transformation pathways[133].

132 Mace et al. 2007 at https://www.academia.edu/19526475/Prioritizing_choices_in_conservation

133 Colloff et al. 2021; Mach and Sider 2021. https://www.science.org/doi/full/10.1126/science.abh1894

Management Actions

Rehabilitation/ Restoration

There are many documents to guide restoration of mangroves. Where rehabilitation or restoration of mangroves is desirable, one of the first steps is to assess whether the hydrology is suitable for mangrove growth, and whether there are connected patches of mangroves that can supply propagules so that mangroves can recover naturally. In this case management might focus on improving hydrology, reducing threats and enrichment planting.

If hydrology is unsuitable to support mangrove growth e.g., tidal water is too deep or inundated for >50% of the time (the site is lower than mean sea level) or waves prevent seeding establishment then repairing hydrology could be considered, if possible (see Hydrological Interventions to restore tidal flows).

If there are limited propagules present, then assisted dispersal, where propagules are collected from elsewhere and scattered over the site, or enrichment planting could be considered. Projects would need to know the correct timing of propagule production of a range of species to time collection activities and knowledge of how to determine collected propagules that are mature.

Some projects may wish to plant seedlings. Rhizophora species are often used for planting because they can be easily collected and planted, but they are not always the best species choice (see below). For some species a nursery may need to be established to grow seedlings to the size where they can survive under field conditions.

Information on mangrove nurseries can be found here (link to manuals). Engagement with local scientists or those with local knowledge of the mangroves can be helpful.

Species selection for restoration and rehabilitation

Species selection for rehabilitation or restoration projects: Some species of mangrove trees are more susceptible to damage by storms than others. For example, Rhizophora species tend to suffer greater levels of mortality during storms than those of Avicennia or Sonneratia (or other species). This is largely because Avicennia and Sonneratia can regrow from their stumps or from damaged trees (they can coppice), while Rhizophora has limited capacity to resprout and often dies after extensive canopy damage. When selecting species for mangrove restoration in areas affected by intense storms species other than Rhizophora should be considered[134]. It is useful to assess the local natural forests to determine which species might be most suitable.

Some species of mangrove trees are more tolerant of highly saline conditions than others. Success is more likely if the salinity tolerance of species selected for use in restoration are matched to the salinity conditions of the site. Table 9 provides indication of the tolerance of different mangrove species of porewater salinity, levels of inundation and temperature. Avicennia marina and A. germinans. are tolerant of hypersaline conditions.

134 Salmo et al. 2013

Tradeoffs depending on the goal of your project - Mangroves with low canopy heights and low mature biomass occur in highly saline and inundated sites. These kinds of mangrove communities are highly tolerant of suboptimal environmental conditions and provide a range of ecosystem services, but they store less carbon in their biomass. Tradeoffs among ecosystem services could be considered in climate-smart projects. The goals of restoration can be clearly stated (see SERA or other manuals[135]) so that trade-offs associated with species selection are clear. For example, restoring for high biomass for carbon projects (e.g., with taller R. apiculata) may not be the best strategy for achieving high levels of resilience where storms are common, or for achieving high levels of biodiversity, and instead a mix of lower biomass species that are better able to recover from storm damage may be selected for restoration.

Planning restoration projects

Techniques for restoration and rehabilitation of mangroves are well developed[136]. Guidance is provided in a range of sources for different nations. At a regional scale the IUCN ROAM process[137] can be used to assess restoration opportunities. The ROAM process can accommodate planning for climate-smart restoration in many of its steps, including definition of objectives, outputs and scope (see Figure 22). The most important elements for planning restoration using ROAM are:

1. Define the problem and objectives
2. Engage key partners: find an institutional home for the project, establish a team to coordinate and lead
3. Define the outputs and scope of the project
4. Establish rules and stratify the project area – how will you divide up the site into more homogeneous areas for assessment and restoration?
5. Identify potential restoration options/interventions/actions
6. Identify assessment criteria and indicators – include success criteria here too
7. Identify the data and capacity needs
8. Plan for stakeholder engagement
9. Prepare for an inception workshop

The data collection and analysis phase are the core phase of the IUCN ROAM process and includes:

10. Stakeholder prioritization of restoration interventions
11. Restoration opportunities mapping
12. Restoration economic modelling and valuation
13. Restoration cost-benefit carbon modelling
14. Restoration diagnostic of presence of key success factors
15. Restoration finance and resourcing analysis

Phase 3 of ROAM takes results from the scoping phases to recommendations. This includes:

16. Organizing a validation workshop
17. Testing the perceived relevance of strategic institutional and policy options with local-level government
18. Identifying finance options for implementing the restoration opportunities
19. Taking recommendations to implementation

These phases and steps are broken down in step-by-step detail in the ROAM user guide.

135 https://www.seraustralasia.com/standards/National%20Restoration%20Standards%202nd%20Edition.pdf
136 Restoration Guide (Howard et al. 2022)
137 Guide to using the IUCN ROAM can be found at https://portals.iucn.org/library/node/44852

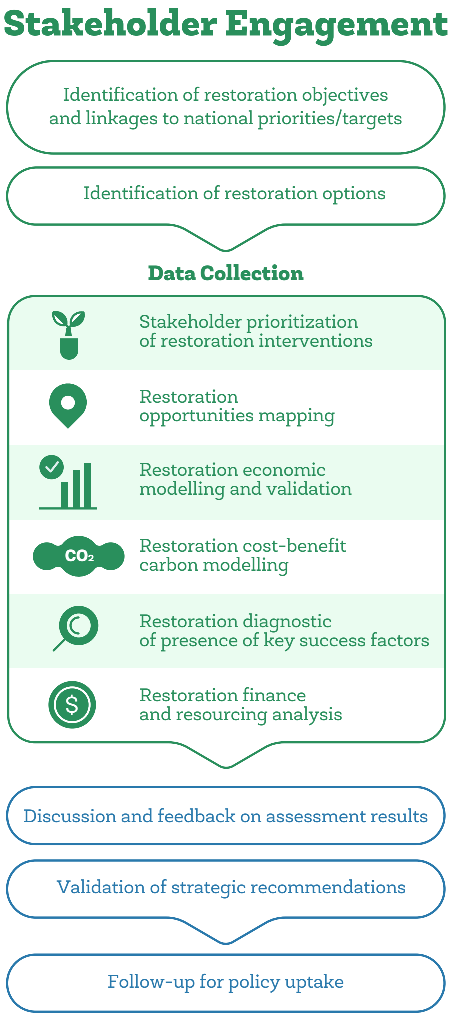

Figure 22 *Key steps in a typical IUCN ROAM process*[138]

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138 Extracted from the IUCN ROAM guideline

Catchment management and sediment supply

Sediments suspended in water can be trapped in mangroves and contribute to elevation, which is important for mangroves to maintain a favorable position for growth in the intertidal zone. Sediment supply is an issue that is often managed at the scale of catchments of rivers. For example, forest clearing in catchments can lead to erosion and high sediment loads that may be reduced with limitations on land clearing. Construction of dams lowers sediment supply as sediments and water are held behind dam walls. While communities and project teams may have limited direct influence on upstream catchment management and catchment processes, projects can evaluate the influence of catchment processes on mangroves in connected estuaries and in response develop strategies to influence catchment management if needed.

Local controls on sediment supply are also possible. For example, in some saltmarshes in the USA sediment is dredged and sprayed on the marsh to increase site elevation[139]. However, this is costly and often difficult to achieve at large scales, although it may be suitable for high value sites. In Mexico adding sediments has been used to make elevated islands so plants can establish where sediments have subsided after mangroves have died.

139 Ford et al. 1999

Where sediment sources and supply can be managed on site, such as with the removal of local weirs or barriers in waterways, consultation with regulatory authorities, stakeholders, and local landowners may be required to understand the purpose of the barriers, the potential risks associated with removing them, and the potential impacts of climate change with barrier removal.

Once sediment sources and changes (or potential changes) in availability are identified then some actions to consider are:

- Engage in dialogue of regional planning for river management, including influencing implementation plans for building of dams and avoiding reductions in sediment supply.
- Assess the elevation of the mangroves relative to mean sea level and contributions of sediment to elevation gain to further assess components of the vulnerability of the mangrove to sea level rise.
- Plan interventions, including evaluating the risks of interventions.

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Plan and implement landward migration

Landward migration of mangroves enables the maintenance of mangrove cover with sea level rise. In some cases landward migration of mangroves may result in an increase in mangrove cover if losses of mangroves on seaward edges (due to sea level rise or storm associated erosion) are limited. Land use planning can facilitate future landward migration of mangroves. Land use planning might include designating areas where building infrastructure and housing landward of mangroves is not permitted or permitting land uses that could easily transition to mangrove when needed (e.g., agriculture or forest land).

Planning for landward migration requires land use planning that focuses on change in land use, from current land use which maybe agriculture, urban (infrastructure) or natural vegetation to mangroves or other coastal wetlands. Knowledge of natural coastal wetlands and their arrangement over intertidal gradients will help to understand the type of changes in vegetation that may occur as sea level rises.

Land-use planning is complex and requires inputs and agreements from many stakeholders. Processes for land-use planning include:

- Engage with stakeholders (e.g., landowners, government, industry) in a participatory planning process that takes into consideration the aspirations of local people and regulatory frameworks. Land use planning might include designating areas where building infrastructure and housing landward of mangroves is not permitted or permitting land uses that could easily transition to mangrove when needed (e.g., agriculture or forest land).
- Maps and models of the land elevation, infrastructure that influences tidal inundation of land (if present) and the likely impacts of sea level rise on current land-uses can be used to understand the potential extent of the changes that will be experienced in the future (e.g., using models) (see Figure 23).

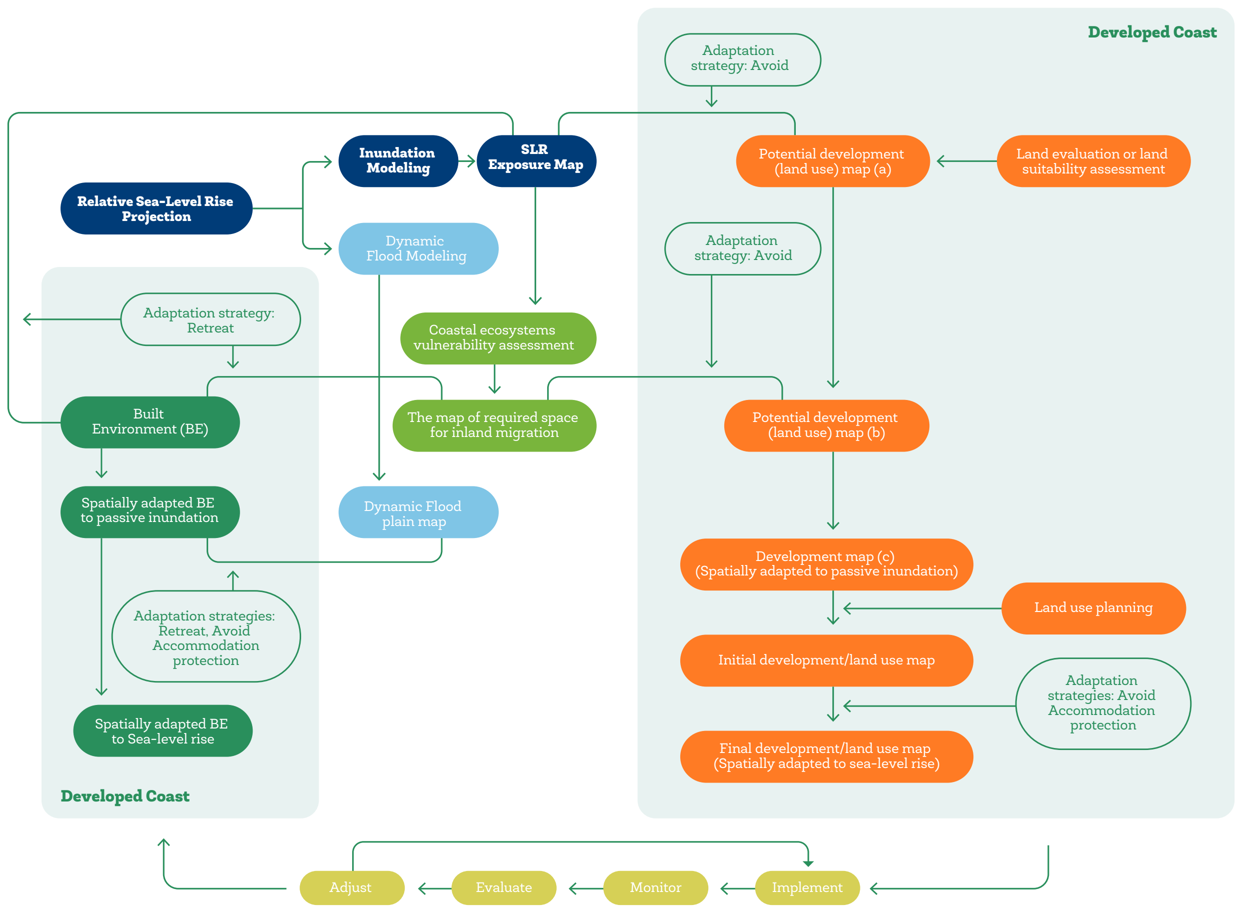

Figure 23 *Spatial Integrated Sea Level Rise Adaptive Management Plan Framework*[140]

- Analysis of the costs of interventions (loss of agricultural production, engineering) and ways to finance change in ways that support the community (e.g., blue carbon, biodiversity credits) can be explored and collated to support the planning process.

Implementation of landward migration may include governments allocating land for mangrove expansion (in a planning process), or the purchase of land for mangrove migration (see Table 12). For private land holders incentives to change land-uses, which may include offering payments for ecosystem services (carbon sequestration or blue carbon, biodiversity, nutrient removal or coastal protection) could support landward migration. Payment for ecosystem service schemes for mangroves and other wetlands are available in many countries. Payment for ecosystem service schemes have potential benefits but also risks for communities and guidelines for best practice are available (IUCN Standards for Nature-based Solutions https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf and best practice guidelines for high quality for blue carbon projects https://climatechampions.unfccc.int/wp-content/uploads/2022/11/HQBC-PG_FINAL_11.8.2022.pdf

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140 From Davar et al. 2021

Table 12 *Strategies to manage coastal risk through land management*[141]

Objective	Measure	Benefits	Limitations
Protect (reduce the likelihood of the hazard)	Build/maintain hard defences	• Proven to be effective at preventing damage to infra-structure during extreme events. • Well-established engineering guidelines and certainty under certain margins.	• Displacement of beach and associated amenities. • Maintenance costs once infrastructure is established. • Lack of flexibility and the potential for lock-in. • Risk of infrastructure failure in the future. • Can create a sense of security for communities which inadvertently. discourages the adoption of other risk-reduction measures.
	Beach nourishment and dune restoration	• Preserves beach amenities and associated tourism activities. • Is reversible and can be easily modified to the actual rate of sea-level rise.	• Expensive to continue in the long term. • In some cases, can be environmentally damaging to continually dredge new sand. • Effectiveness is expected to decrease over time as beaches become more unstable.
	Replace/reinforce shoreline protection with "living" shorelines - through planting vegetation, etc.	• Reduces negative effects of protective infrastructure (downdrift erosion). • Maintains beach habitat in enclosed areas.	• Requires more planning and materials than traditional protection. • Not suited for high-wave energy areas such as open beaches. • Implementation and monitoring of success is not as advanced as other strategies.
Accomodate (reduce vulnerability)	Change building codes and design standards to account for sea-level rise, e.g. in building elevation and foundation design	• Provides flexibility to manage future coastal inundation and flooding. • More incremental change than other options.	• Adds upfront development costs. • Only applicable for new buildings or refurbishments. • Requires a high degree of co ordination between planning and implementing agencies.
	Encourage the use of property-level measures for both new and existing properties	• Flexible and easily combined with other measures. • Raises household awareness of risks.	• Property-level technology still underdeveloped.
	Emergency management	• Mitigate loss of life and assets from coastal flooding.	• Uncertainty of storm-surge predictions within early warning systems. • Significant financial cost for evacuation of people.
Avoidance and planned retreat (reduce exposure)	Prevent new development in areas at risk of flood or erosion through land-use regulation/zoning	• Flexible to address different conditions and needs within a community. • Provides opportunity for additional access to waterfront area. • Reduces potential for coastal squeeze.	• Removing existing zoning rights can be a slow process that requires compensation. • Only applicable for new development compensation.
	Physical relocation of people and critical assets, including removal of existing hard protection	• Protects existing and creates new intertidal habitats, which are a natural form of flood protection. • Can save communities from future costs of flood protection.	• Often substantial financial cost if existing property owners need to be compensated. • Direct impact on those living in affected properties.

141 OECD – Responding to Rising Seas: OECD Country Approaches to Tackling Coastal Risks

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Hydrological interventions to restore tidal flows

Hydrological interventions could include on-site works that facilitate the reinstatement or creation of tidal flows that are suitable for mangrove growth. For example, in some instances deposition of sediments or debris during storms can block tidal flows and lead to ponding of water or hypersaline conditions that can kill mangroves. Therefore, hydrological interventions could involve unblocking tidal channel. In other cases, hydrological interventions could involve removal or modification of tidal gates, or blocking or modification of drainage channels (e.g., plugging drains).

Planning hydrological interventions are site and situation dependent[142]. They require a thorough knowledge of site hydrology. Sometimes it is very difficult to diagnose whether hydrological interventions are needed, but changes in water levels and loss of mangrove heath are key indicators[143].

Planning hydrological interventions may require the development of hydrological models that allow for evaluation of interventions/solutions before they are enacted. Evaluation is important to identify potential risks to adjacent properties and assets, including biodiversity. It is important to understand the long-term impacts of hydrological modifications given expected sea level rise and to communicate these potential changes to stakeholders. For example, removal of tidal gates and

142 Van Loon et al. 2016
143 Examples are demonstrated in Lopez-Portillo et al. 2017

introduction of tides may lead to change in adjoining freshwater ecosystems, that could be highly valued.

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Engineering interventions to reduce wave attack on shorelines

Engineering interventions are those that require engineering designs of infrastructure to limit wave attack on shorelines and therefore reduce erosion and potentially contribute to shoreline accretion and mangrove establishment. These kinds of interventions might include the building of groynes or seawalls of some sort[144].

Many of these engineering of interventions are experimental. For example, fences have been used to trap sediment on eroding shorelines[145].

Engineering interventions may be costly (design, on-ground works, and maintenance) and may become ineffective over time as sea level rises. Any engineering interventions should be comprehensively costed to include maintenance costs with clear understanding of who bares the cost into the future.

Factor	Spatial scale	Temporal scale	Direction of change	Predictability
Water flow	Local	Short	↓	***
	Regional[a]	Medium	?	
Sediment grain size	Local	Short	↓	***
Sediment organic content	Local	Short	↑	**
Detritus	Local	Medium	↑	**
Water quality	Local	Short to medium	↓	**
Soft-bottom habitats	Local	Short	↓	***
	Regional[a]	Medium	↓	***
Soft-bottom species richness	Local	Short to medium	↑↓	**
	Regional[a]	Long	↑↓	*
Hard-bottom substrata	Local	Short	↑	***
	Regional	Medium to long	↑	***
Hard-bottom species richness	Local	Short to medium	↑	***
	Regional	Long	↑↓	*
Fish and mobile fauna	Local	Short to medium	↑	***
	Regional[a]	Long	↑↓	*
Productivity	Local	Short to medium	↑	**
	Regional[a]	Medium to long	↑↓	*
Ephemeral and muisance species	Local	Short to medium	↑	***
Non-native species	Regional	Medium to long	↑	**
Dispersall barriers	Regional	Medium to long	↓	*
Habitat fragmentation	Regional	Medium to long	↑	*

Both direction of change (↑ =increase, ↓=decrease, ? =not known) and estimates of the current ablity to make predictions (*=low, **=moderate, ***=good) are indicated. For detailed explanations, see text.
[a] Indicates impacts expected from the proliferation of structures over whole coastlines.

Figure 24 *Summary of main impacts expected from the construction of hard defense structures with respect to the "do nothing" alternative, and relevant scales (spatial and temporal) of each impact*[146]

144 Examples in Beck et al. 2022
145 Example from Germany by Eichmanns et al. 2021, Winerwerp et al. 2020

146 Table extracted from Airoldi et al. 2005

Figure 25 *Examples of different types of sediment trapping fences used in mangrove projects*[147]

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147 From Germany by Eichmanns et al. 2021

Monitoring

Monitoring is critical to support adaptive management. Through monitoring, the effects of management actions can be understood and corrected if need be. Monitoring is vital for measuring success, adapting, and adjusting aspects of the project to enable positive and successful outcomes, and for providing adequate and robust data for informing both the project outcomes and future decisions that may be made for other projects in the region.

When designing monitoring programs, setting monitoring targets and objectives early in the planning phase can ensure that monitoring activities are appropriate to the objectives of the monitoring, and that they are achievable (and within the budget). There are several manuals and guidelines for measuring and monitoring mangroves available for various geographical regions and areas. SPREP has developed a manual for mangrove monitoring in the Pacific Islands that includes measuring growth of mangroves[148]. The Tropical Forestry Handbook[149] also contains a chapter on conducting mangrove management, assessment, and monitoring.

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148 SPREP Manual for Mangrove Monitoring in the Pacific Islands Region https://www.sprep.org/attachments/Publications/Manual_Mangrove_Monitoring_PICs.pdf
149 Tropical Forestry Handbook – Mangrove Management, Assessment and Monitoring https://doi.org/10.3390/ijerph18020590

Reduce Local Pressures

Resilience to climate change can be enhanced by reducing pressures on mangrove health. Pressures include unsustainable harvest, nutrient or other pollution, and altered hydrology. Pressures can be identified and their reduction prioritized.

Pressures will be unique to each site and project. Once they have been identified and their management determined, efforts can be focused on working with local stakeholders, communities, government, and/or land managers as appropriate to mitigate impacts where possible. Some pressures are linked to system-wide problems. For example, over harvest of mangroves can occur because alternative fuels are not available. While introducing new fuel sources could be beyond the resources of projects, the introduction of efficient cook stoves, or solar food preservation systems, or adoption of community forestry practices[150] may be components of a solution. Questions to consider are:

- What are the pressures directly impacting the mangroves?
- Which pressures can be controlled or mitigated?
- Does management of pressures require stakeholder engagement, planning interventions, land management adjustments or policy change?

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150 FAO 2019 http://www.fao.org/3/ca4987en/CA4987EN.pdf

Community Awareness and Education

Community education programs can enhance interest in conservation and restoration projects and empower people to achieve their conservation goals. Community education programs can increase community cohesion. Activities that focus on mangroves e.g., field schools for aquaculture producers or farmers. community or school art, photography programs, or visits to mangroves that might include activities like monitoring or tree planting can be developed. Examples include:

- Mangrove Action Project Art Contest[151]
- International Day for the Conservation of the Mangrove Ecosystem events and awareness sessions[152]
- World Mangrove Day community events[153]
- Regional Mangrove Program, such as DEALS[154]
- School-aged children awareness field trips and education programs[155]

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151 https://mangroveactionproject.org/childrens-calendar/
152 https://www.unesco.org/en/days/mangrove-ecosystem-conservation
153 https://wildlife.org.au get-involved-on-world-mangrove-day-26-july-2021/
154 https://www.livingoceansfoundation.org/education/mangrove-education-and-restoration/mangrove-deals/
155 https://panorama.solutions/en/building-block/mangrove-awareness-field-trips-and-education-schools

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Appendix A
Literature Review

A Decision Support Tool for Conserving and Restoring Climate-Smart Mangroves

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Introduction

Mangroves are especially susceptible to the impacts of climate change due to their geographic position along coastlines and their specific biological needs for survival. Tidal inundation, sea level rise, coastal erosion, storm surge, increase sea and air temperatures, and land use conflicts are some examples of the threats to mangroves globally. Conservation and restoration can provide protections for mangroves that ensure they can survive, thrive, and provide environmental, social, and economic ecosystem services that coastal communities around the world are and will become more dependent on.

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In developing mechanisms for the conservation and/or restoration of mangroves, climate change and its associated impacts must be considered to ensure resources are being appropriately allocated and that projects are successful. A climate-smart decision support tool to assist WWF field teams in Madagascar, Mexico, Colombia, and Fiji is being developed to provide a mechanism to choose and develop conservation and/or restoration projects with the impacts of climate change in mind.

The development of the tool has been staged as follows:

- Literature review (this document)
- Flow chart development
- Draft decision support tool
- Field testing
- Finalization of the decision support tool

Purpose of the Literature Review

The literature review stage of the project aims to develop a comprehensive understanding of the risks to mangroves from climate change, other methodologies or tools that exist and are used to assist in the development of conservation and/or restoration projects, and examples of projects that have either integrated climate-smart principles or have been impacted by climate change. By reviewing the available literature, the findings can be summarized and used to guide the development of the framework and, ultimately, the decision support tool itself.

Methodology

The literature review has been conducted using two main methods of searching:

- Academic publication searches using Google Scholar and the Web of Science, accessed through the University of Queensland online library.
- Grey literature and reports provided by WWF-US and field office teams in Madagascar, Fiji, Mexico, and Colombia.
- Published reports from intergovernmental and non-government organizations, such as the Convention on Biological Diversity Knowledge Hub.
- Information from online resources, such as the Global Mangrove Alliance.

Searches focused on key word hits and were limited to the first page of results for each key word to limit the scope of review. Key words used were: “Mangrove+Conservation”, “Mangrove+Restoration”, “Mangrove+Climate Change”, “Mangrove+Sea Level Rise”.

Results of these searches were collated using Mendeley and reviewed for insights into the following questions:

- What are the key climate change factors impacting the success of mangrove conservation or restoration?
- What kinds of mangroves appear more/less susceptible to climate change impacts?
- What actions (if applicable) are likely to be successful in conserving and/or restoring mangroves in areas particularly impacted by climate change?
- What national policy/strategy actions have been implemented that are enabling success?

The answers or insights found were then summarized below in the next section.

Impacts to Mangroves – A Review of Literature

Exposure: Climate Change Factors Affecting Mangroves

Climate change has the potential to impact mangroves significantly. There are several factors associated with climate change that may alter processes and result in both positive and negative impacts. Table 1 details factors and processes of mangroves that can be affected by climate change.

Table 1 *Factors and Processes of Mangroves Affected by Climate Change (adapted from Ellison (2012) and Lovelock and Ellison (2007)*

Factors	Processes
Rising sea level	Mangrove health, productivity, and recruitment impacted. Sedimentation rates and inundation periods altered. May result in mortality, dieback from the seaward edge, migration landward.
Extreme storms	Mangrove productivity, recruitment, and sedimentation rates affected. May result in mangrove damage or destruction, ground elevation change, erosion, or sediment smothering.
Increased waves and wind	Sedimentation rates and recruitment affected. May result in changes to mangrove coverage located higher in the intertidal zone.
Increased air and sea temperature	Respiration, photosynthesis, and mangrove productivity may be affected. May result in reduced productivity at lower latitudes and increased winter productivity at higher latitudes.
Increase carbon dioxide	Affects photosynthesis, respiration, biomass allocation, and mangrove productivity. May result in increased productivity and soil elevation gain.
Increased rainfall	Impacts sediment inputs, groundwater quality, salinity, and productivity. May result in increased sediment availability, rate of accretion and soil surface elevation gain, volumes of groundwater, diversity, productivity, and recruitment, although flooding can result in mortality.
Reduced rainfall	Sediment inputs, groundwater, and salinity may be affected. May result in loss of surface elevation through subsidence, reduced sediment supply, migration landward, reduced availability of groundwater, increased salinity and reduction in photosynthesis and productivity, species turnover, and reduced diversity.
Reduced humidity	Photosynthesis and mangrove productivity may be affected. May result in reduced productivity, species turnover, and reduced diversity.

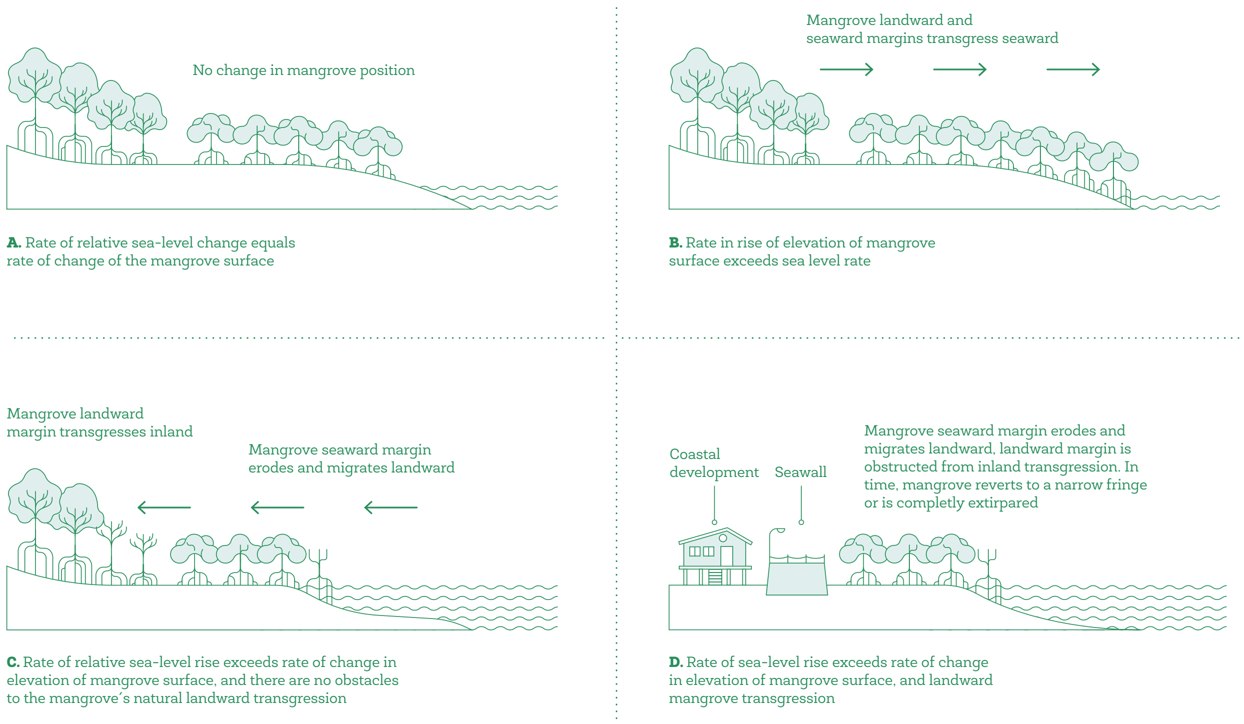
Uncertainty in projects and impacts from climate change is an issue when considering threats and adaptations at a global scale. There is a high level of uncertainty in the impact of climate change factors on mangroves (Oppenheimer *et al.*, 2019) because of the high spatial variation in likely climate change impacts and because of strong interactions with human use of mangrove landscapes.

Sea level rise is widely acknowledged as the greatest long term threat to mangroves from climate change (Field, 1995; Mcleod and Salm, 2006; Lovelock and Ellison, 2007; Gilman *et al.*, 2008; Ellison, 2012; Munji *et al.*, 2014; Lovelock, Cahoon, *et al.*, 2015; Sasmito *et al.*, 2016; Ward *et al.*, 2016; Schuerch *et al.*, 2018). While anthropogenic impacts, such as land clearing and deforestation, have been greater threats, it is expected that relative sea level rise and erosion will result in substantial reductions in areas of mangroves and other intertidal wetlands in the future (Goldberg *et al.*, 2020). Ward *et al.* (2016) note in a review conducted to identify the impacts of sea level rise on mangroves that the principal factors are:

- Declining plant productivity
- Increased erosion
- Insufficient sediment supply
- Increased inundation depth and duration, resulting in mangrove drowning (mortality and recruitment failure)
- Salinity (both increased from rising sea levels, and decreased from freshwater inundation caused by increased rainfall and flooding)

Sea level rise can alter inundation frequencies and duration, salinity, and potentially result in mangrove mortality (Ward *et al.*, 2016). Increased flooding can affect the deposition and establishment of mangrove seedlings, with tides either washing seeds inland or out to sea, limiting local reestablishment and reproduction which in turn can impact the conservation effort (Munji *et al.*, 2014). However, mangroves can be resilient to sea level rise where their ability to enhance surface elevation processes (through accretion of sediments and root growth) and inland migration is not impeded (Ward *et al.*, 2016; Woodroffe *et al.*, 2016). Inland flooding could disperse propagules and enable mangrove migration and recruitment inland, facilitating natural retreat of mangroves (Munji *et al.*, 2014). Enabling inland retreat is an effective method for conserving mangroves (Gilman *et al.*, 2008) – see Figure 1.

Figure 1 *Rates of sea level rise and rate of change to mangrove surface (Gilman et al., 2008)*



Increased flooding associated with sea level rise may encourage the inland migration of mangroves in some places (Nicholls *et al.*, 2007, Schuerch *et al.* 2018). However, the type of flooding, fluvial flooding (i.e., freshwater) or storm surge (i.e., saltwater), can differentially impact the ability for mangroves to establish or reestablish. For example, if mangroves are comprised of freshwater species, they may be negatively affected by increased salinity during storm surges.

Mangroves in high intertidal positions (relative to mean sea level) are likely to be less negatively affected by sea level rise while those lower in the intertidal zone are more likely to be affected (Cahoon *et al.*, 2019).

Those higher in the intertidal are less affected because they may experience decades of sea level rise before they reach the level of mean sea level and therefore become vulnerable to drowning, while mangroves that are currently at mean sea level may be overwhelmed by sea level rise if they have limited accretion, particularly if combined with increasing wave energy or storm surge (Woodroffe *et al.*, 2016; Rogers, 2021).

Storms (winds and waves), increasing storm intensity, and resultant surge present direct threats to mangroves and can cause significant damage that can take years to recover (van Hespen *et al.*, 2021). Sea level rise can enhance the impacts of storm surge as waves can penetrate further into mangroves (Blankespoor, Dasgupta and Lange, 2017). Flooding and delivery of sediments pulses that cover aerial roots following storms can cause mangrove mortality and present a significant threat to mangroves (van Hespen *et al.*, 2021).

Changes to precipitation are being highlighted as a significant symptom of climate change by the IPCC (Oppenheimer *et al.*, 2019), which is likely to be further complicated by changes in temperature (Ward *et al.*, 2016). Changing temperature and rainfall patterns will likely alter the distribution of mangroves, their extent, and their ability to grow and reproduce (Gilman *et al.*, 2008; Ellison, 2012). Greater rainfall variability can slow growth which can in turn slow accretion, limiting mangroves' ability to keep pace with sea level rise (Ellison, 2012). Where precipitation increases, there is the potential for increased sedimentation in mangroves and adjacent coasts as a result of terrestrial run-off that may facilitate mangrove expansion, whereas drier regions may experience greater loss where fluvial sediment sources become reduced (Ward *et al.*, 2016).

Rising temperatures affect mangrove species differently; however, it is understood that generally mangrove growth is somewhat inhibited outside of a range of 15 to 25°C (Mcleod and Salm, 2006; Osland *et al.*, 2017). Warming temperatures increase growth and reproduction at the latitudinal edge of the mangrove range, which can lead to expansion (Saintilan, Rogers and McKee, 2018).

Extreme changes in temperature, such as high temperatures associated with extreme drought, can also lead to large scale mangrove mortality (Sippo *et al.*, 2018; Krauss and Osland, 2020). High temperatures are associated with high leaf to air vapor pressure deficits which cause stomatal closure and loss of productivity in some species (Lovelock *et al.* 2016).

The impact of climate change on mangroves and human adaptation to climate change can interact to increase the negative impacts of climate change on mangroves. An indirect threat from climate change to mangroves is also the relocation of human communities as part of the 'retreat' process. As people begin to retreat from the coast to save their properties and settlements, mangroves also become targets for land reclamation. Where coastal flooding is becoming increasingly problematic in some areas, mangrove deforestation for the purposes of supplying raw building materials to rebuild properties inland is increasing (Climate Crowd, 2021).

Sensitivity: The Resilience of Mangroves to Sea Level Rise

Mangroves can be resilient to sea level rise (Lovelock *et al.* 2015) although there are thresholds to the persistence of mangroves (Saintilan *et al.* 2021) and that resilience is determined by a range of interacting factors. For example, in settings where there is limited sediment supply (coral atolls in Tahiti and Belize, for example), models suggest that mangroves are likely to be resilient to low to moderate sea level rise (Buffington *et al.*, 2021). While specific to the Pacific Islands, there is historical evidence available in other studies that show historical adaptation by mangroves to past variation in sea level and climate (Alongi (2015, Saintilan *et al.* 2021).

Maintaining Mangrove Soil Surface Elevation in the Intertidal Zone

The maintenance of mangroves position in the intertidal zone is critical to their plant growth and persistence and thus maintaining their elevation and the capacity to maintain soil surface elevation within the intertidal zone through vertical accretion and lateral movement is key to the survival and success of mangroves in the face of sea level rise.

Knowledge of the elevational range of mangroves at a site, as well as estimating local sea level rise along with potential sediment accumulation at a chosen restoration site will be key to determine whether mangrove restoration will be climate-resilient (Sasmito *et al.*, 2016). Tidal range is also a key consideration when considering sea level rise, as tidal range may vary with sea level rise and local management of hydrodynamic processes. Mcleod and Salm (2006) note that mangroves occurring in macrotidal, sediment-rich environments are more likely to survive sea level rise. Conversely, carbonate islands, such as atolls, are extremely vulnerable to sea level rise as they are without sediment supply or space for retreat (Mcleod and Salm, 2006).

Mangroves have the capacity to hold their position in the intertidal zone or maintain their surface elevation relative to sea level rise through processes that contribute to vertical accretion of the sediment. If the rate at which mangroves can accrete sediment is equal to the rate of sea level rise, the mangrove will survive and remain stable over the long term. If the rate of accretion is slower than rising sea levels, the mangrove will eventually drown seawards and landward expansion of the mangrove will be important for persistence (Alongi, 2015). Recent evidence suggests that mangroves will not survive in locations where they do not have space to migrate landward or the bio-physical means to adapt, such as low-lying islands where mangroves are positioned at mean sea level and where there are limited sources of sediments, or in river deltas where sediment sources are being significantly reduced through human activities (Alongi, 2015; Woodroffe *et al.*, 2016). In these cases, adaption of mangroves to sea level rise and maintenance of aerial cover requires landward migration of wetlands and management of coastal squeeze (Schuerch *et al.* 2018).

Regional and local variation in changes in surface elevation must be considered when assessing the potential for sea level rise impacts to mangroves (Alongi, 2015; Lovelock, Adame, *et al.*, 2015; Saintilan *et al.*, 2020). Surface elevation of wetlands can be impacted by several factors, but for mangroves, variation in sediment availability (Sasmito *et al.* 2016) and factors that result in subsidence (e.g. mangrove mortality, Cahoon *et al.* 2004) are the two main processes that affect the ability of mangroves ability to maintain their position in the intertidal zone with sea level rise.

The maintenance of functioning hydrologically connected landscapes enables sediment accretion, mangroves are more likely to be able to produce roots, and therefore are more likely to trap more sediments and enable establishment of mangroves (Sasmito *et al.*, 2016; Climate Crowd, 2021). The maintenance of sediment supply (upstream sediment sources) and their reliability is important in determining whether mangroves are likely to continue to survive and thrive in certain areas. Where sediments are being impeded by manmade activities or structures, it should be determined whether sediment supply can be restored by additional engineering works or the removal of such structures to ensure continued supply (Spalding *et al.*, 2014). However, it is important that suitable hydrological networks allow for sediment distribution and continuous open channel access to provide environments where mangroves can continue to survive (Woodroffe *et al.*, 2016).

Areas that are subject to subsidence, either from natural erosive processes, mangrove mortality or from human activities like water extraction, are likely to have difficulty reestablishing compared with limited subsidence and where natural accretion and sedimentation (increasing elevation) have occurred (Sasmito *et al.*, 2016). However, as noted in Woodroffe *et al.* (2016), sediment accretion and elevation change rates occur more rapidly at lower elevations, and this should be considered when assessing the impacts of sea level rise on existing mangroves and those to be restored.

Structure of Mangroves

The size, structure, density, and even the species of mangrove tree can vary the resilience of mangroves to flooding and storms (van Hespen *et al.*, 2021). Species that tend to grow closer to the sea (i.e., open coastal or seaward mangroves), such as *Sonneratia apetala* and *Avicennia marina* were found to have stronger branches than the landward species (*Acanthus ilicifolius*, *Aegiceras corniculatum*, and *Kandelia obovata*), suggesting that strong-branched, more compact species are more resilient to withstanding mechanical forces from wave and surge energy (van Hespen *et al.* (2021).

Species that were found to experience a greater drag-force – i.e., those with larger, less flexible branches – were more likely to experience significant damage than those that were more flexible, compact, had smaller branches (van Hespen *et al.*, 2021). Additionally, the structure of mangroves may also provide evidence of resilience to climate change (Spalding *et al.*, 2014). For example, a mangrove that includes a range of smaller younger trees with older larger trees, root systems that support epibiont communities such as oysters or sponges, and mangroves abundant with mature reproductive trees are more likely to be resilient and provide sources of propagules for future colonization (Mcleod and Salm, 2006).

Variation in Species Adaptability

Certain species have also been found to have greater potential to adapt (resistance) to increasing levels of inundation. Studies reviewed by Alongi (2015) suggest that *A. marina*, for example, have a high degree of tolerance to prolonged inundation than other species. Other studies also suggest that species selection can play a significant role in determining the potential for mangrove restoration success with climate change. For example, species that are more tolerant of salinity may be more successful in areas where freshwater sources are reduced (by drought, for example) or where sea level rise or tidal inundation is likely to be more profound and mixed species stands have been found to be more resilient to impacts of storms than monospecific stands (Salmo, Lovelock and Duke, 2014).

Assessing Mangrove Vulnerability to Climate Change

Vulnerability assessments for specific areas of mangroves can be useful in determining the risks of management intervention (conservation or restoration). The IPCC (AR6 2022) elaborates vulnerability as a function of three key elements: exposure, sensitivity, and adaptive capacity.

Exposure relates to extrinsic factors and the magnitude of such factors that will impact a mangrove community. It examines issues related to climate change and the speed at which change is likely to occur (Ellison, 2012).

Sensitivity describes the characteristics of the species or system itself, determining how tolerant it is of changes to factors such as rainfall, temperature, humidity, inundation, or drought.

Mangroves show response to these factors through declines in condition, stability, productivity, and biodiversity (Ellison, 2012). Adaptive capacity is the ability for the species or system to adapt to or accommodate changes with minimal disruption. Resilience refers to the ability of mangroves to respond to and recover from impacts of climate change, whereas resistance relates to its ability to withstand changes and continue to survive and function (Ellison, 2012).

Earlier assessment of vulnerability defined a range of variables that distinguished variation in vulnerability to sea level rise in mangroves (Mcleod and Salm. 2006) Table 2:

Table 2 *Assessing Mangrove Vulnerability to Sea Level Rise (Adapted from Mcleod and Salm, 2006)*

Vulnerability	Local Conditions	Details
Most Vulnerable	Low relief islands	Restricted sediment source/accretion, subject to drought and wave erosion, likely to experience flooding, soil salinity increases, and inundation
	Areas without rivers	Lack of sediment or freshwater source inputs
	Carbonate environments	Landward migration limited, restricted sediment sources
	Areas experience subsidence (tectonic activity, groundwater extraction, underground mining)	Greater impacts from sea level rise, inundation a threat
	Micro-tidal environments starved of sediments	Lack of sediment inputs, inability to naturally accrete with sea level rise, problems establishing species diversity, changes to geographic distribution of mangroves
	Mangroves with landward edge limited by coastal development or steep topography	Inability to move landward with sea level rise, no space for retreat
Least Vulnerable	For islands, mangroves in deeper sediments on high-lying islands or in deltaic settings	Structurally stronger and less vulnerable to storm surges than those on low-lying islands or in shallow sediments; higher islands better adapted to survive climate change with larger surface areas, more reliable freshwater sources, more fertile and structurally diverse soils, and more diverse resources
	Riverine mangroves	Larger, more reliable source of sediments, higher nutrient concentrations available
	Macro-tidal sediment rich environments	More reliable sources of sediments, strong tidal currents to distribute sediments
	Mangroves with room to move landward	Areas backed by low-lying, undeveloped areas or salt flats provide space for mangroves to retreat inland with sea level rise
	Mangroves in remote areas	Limited stresses from other anthropogenic sources (e.g., exploitation, deforestation, etc.) and more likely have room to retreat where not impeded by development
	Mangroves surrounded by high quality dense forests	Communities that are surrounded by dense mangroves have greater and more reliable sources of seeds and propagules for reproduction

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Vulnerability of coastal communities can be assessed by examining three criteria: the hazards – waves, storms, erosion, sea level rise – that communities are exposed to; the exposure – population and infrastructure proximity to low-lying coastal areas; and vulnerability – the susceptibility of the community to damage and its capacity to adapt or cope (Spalding *et al*., 2014). Where existing mangroves have the potential to attenuate waves, reduce the impact of storm surges, mitigate erosion, or protect coastal areas from sea level rise, they can help reduce the vulnerability of communities to climate change (Spalding *et al*., 2014). In such cases, while land availability and long-term anthropogenic threats unrelated to climate change still need to be determined, the conservation and/or restoration of these mangroves may be prioritized to providing insurance against climate change impacts. A range of indicators have been developed to assess landscape scale vulnerability to climate change (Nguyen *et al*., 2016), as well as specific indicators of the condition of mangroves (Yando *et al*., 2021). A list of indicators from 63 studies were summarized by Ngyuen *et al*. (2016) (Table 3) that may be useful to adapt to provide potential indicators of vulnerability of mangroves.

Table 3. *Physical and Social Vulnerability Ranges Used for Coastal Vulnerability Indices from 63 Studies of Coastal Vulnerability Indicators*

	Rank				
	Very Low	**Low**	**Moderate**	**High**	**Very High**
Physical Variable					
Relief (m)	>/= 30.1	20.1 – 30.0	10.1 – 20.0	5.1 – 10.0	0 – 5.0
Sea level rise (mm/yr)	<0	0 – 1.5	1.6 – 4.0	4.1 – 6.0	>6.1
Tidal range (mean, m)	<0.5	0.5 – 2	2 – 4	4 – 6	>6
Wave height (max, m)	0 – 2.9	3.0 – 4.9	5.0 – 5.9	6.0 – 6.9	>/=7.0
Flood depth (m)	<0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	> 2.0
Salinity (ppt)	<1	1 – 2.5	2.5 – 3	3 – 4	>4
Shoreline displacement (m/yr)	>2.0	1.0 – 2.0	-1.0 – 1.0	-1.1 – -2.0	<-2.0
Social Variable					
Population density (inhabitants/km^2)		<500	500 – 1000	>1000	
Land use patterns	Water	Minimal use, nature conservati on, potential agriculture	Livestock grazing, irrigated horticulture, woodland	Residential	Transport and comms
	Protected Area	Unclaimed	Settlement	Industrial	Agricultural
	Rocky / Cliffs	Scrub	Beach, sand, dunes, forest, rough	Agricultural, fairways, amenity grass	Urban, residential, car parks, greens
	Forest / Sea	Agricultural land	Living and tourism	Industry and transport	
	Limited Use	Low impact, bare land	Middle impact, water/ wetland, grassland	High impact, forest, farmland	Built up
Local income level (USD/capita/yr)		>USD 375	USD 150 – 375	USD 150	

Recognizing the limited data in some settings (e.g., Indian ocean) a mixture of global, regional, and local data could be sourced to assess the climate change vulnerability of mangrove sites which may link to management actions.

Actions for Success

Assisted adaptation of mangroves to climate change may be the most effective way of conserving and restoring areas vulnerable to change. Adaptation actions can be summarized into three broad categories:
1. reducing non-climate related stressors, 2. active adaptation actions, and 3. monitoring and evaluation to guide adaptive management (Ellison, 2012). Non-climate related stressors may include pressure from development, deforestation, overexploitation of resources, pollution, or land management practices (adjacent and local). These can be managed through establishing strategic protected areas, improving legislation, rehabilitating degraded mangroves, improving local management, ensuring mangroves are considered in urban and spatial planning considerations, and implementing buffer zones and green belts (Mcleod and Salm, 2006; Ellison, 2012). Active adaptation can include planning for inland migration, assisted restoration of existing mangroves and restoring fringing areas of mangroves, managing for accretion in mangroves, and managing upstream sources of water, sediments, and local hydrology (Mcleod and Salm, 2006; Ellison, 2012; Enwright, Griffith and Osland, 2016). Monitoring and evaluation is discussed in more detail in the next section.

Selection of sites that have the capacity to support mangrove expansion with sea level rise is important for planning for resilience. For example, in a study conducted by Enwright, Griffith and Osland (2016), it was found that landward migration of coastal wetlands were particularly successful along the US Gulf of Mexico coast where hydrological and land management conditions and methods are compatible with coastal wetland expansion. For example, where freshwater inflows are extensively interrupted, or the geology influences the potential for saltwater inundation of groundwater, the success of landward migration will vary (Enwright, Griffith and Osland, 2016). Therefore, where the space is available and conditions are suitable, enabling landward migration as a conservation strategy can be effective. Where the topography restricts inland retreat, for example in landscapes characterized by steep cliffs, mountains, or human infrastructure, landward migration of mangroves may be limited to river channels, and as such, these features will become critical for climate-smart conservation and management success (Buffington *et al.*, 2021). Where land use limits wetland migration then local land use planning to consider mangrove conservation with sea level rise will be important.

Mangroves are also subject to significant anthropogenic pressures and therefore the success of any climate-smart conservation or restoration will be largely also dependent on local socio-economic settings, including government (i.e., regulatory frameworks and policy) and community engagement and buy-in. Areas that are more remote and under less stress from people are more likely to thrive and survive under climate change where they have fewer pressures and room to retreat (Mcleod and Salm, 2006). However, conservation and restoration of mangroves in populated areas may provide greater benefits to communities.

Mcleod and Salm (2006) summarize ten strategies that may assist managers in protecting, conserving, and maintaining mangroves through climate change and potentially increase their resilience:

1. Apply risk-spreading strategies to address the uncertainties of climate change
2. Identify and protect critical areas that are naturally positioned to survive climate change
3. Manage human stresses on mangroves
4. Establish greenbelts and buffer zones to allow for mangrove migration in response to sea level rise and to reduce impacts from adjacent land use practices
5. Restore degraded areas that have demonstrated resistance or resilience to climate change
6. Understand and preserve connectivity between mangroves and sources of freshwater and sediment, and between mangroves and their associated habitats, such as seagrass and coral reefs
7. Establish baseline data and monitor the response of mangroves to climate change
8. Implement adaptive strategies to compensate for changes in species ranges and environmental conditions
9. Develop alterative livelihoods for mangrove-dependent communities and a means to reduce mangrove destructions
10. Build partnerships with a variety of stakeholders to generate the necessary finances and support to respond to the impacts of climate change.

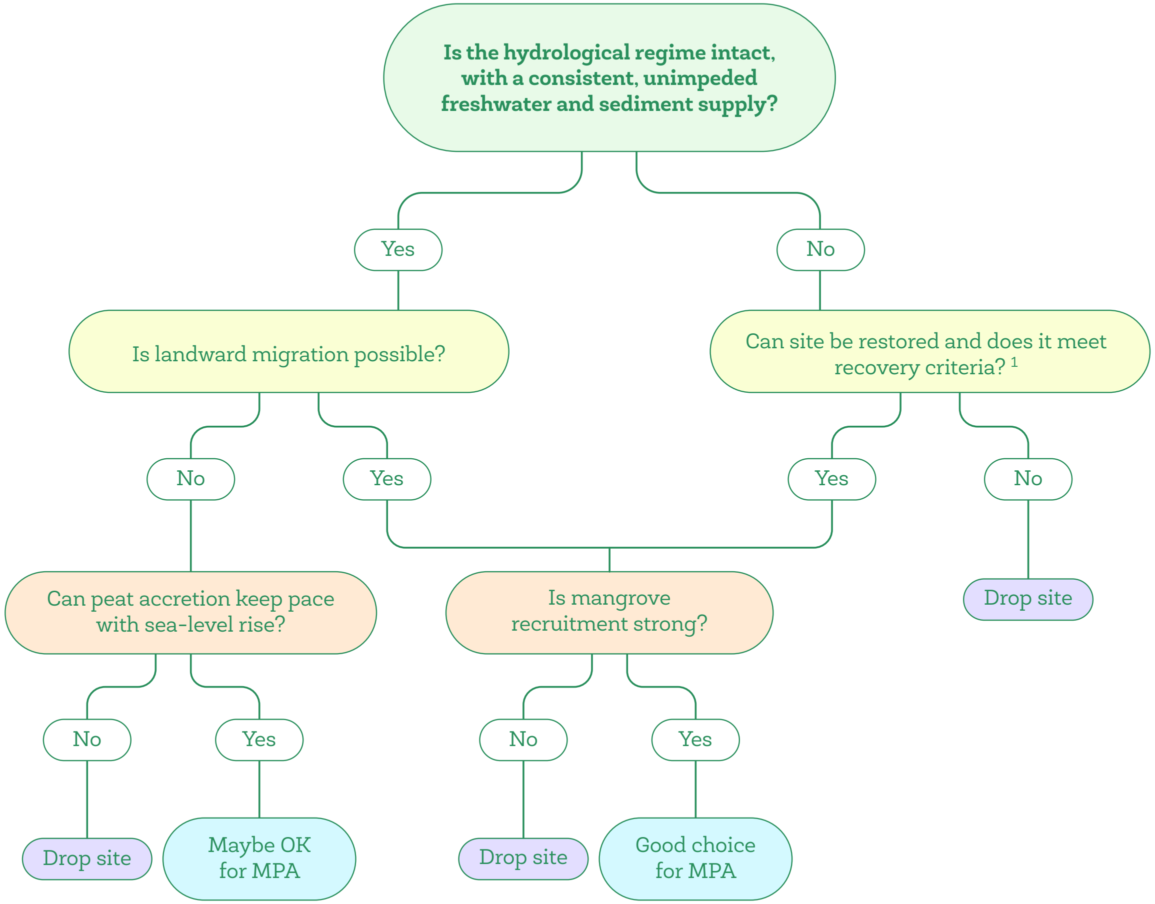
(Extracted from Mcleod and Salm, 2006).

The decision tree developed by Mcleod and Salm (2006) in Figure 2 was to aid decisions on selecting areas for Marine Protected Areas (MPAs). They focus on the benefits of protecting landscapes with unmodified hydrology. Similar approaches could be further developed to provide guidance of how to made decisions that support climate resilient mangroves within hydrological modified or other landscapes that may provide potential for conservation and restoration under climate change.

Alignment with Domestic Policy and Strategy

Actions for successful mangrove conservation and restoration can be viewed within a larger suite of measures aimed at climate change mitigation and adaptation. Integrating mangroves into coastal defense strategies, coupled with hard engineering methods where appropriate, has shown to provide effective mechanisms for managing the impacts of climate change on coastal communities (Spalding *et al.*, 2014). However, there are no standalone methods for establishing mangroves within coastal defense strategies.

Regions with Integrated Coastal Zone Management (ICZM) plans and strategies designate areas for preservation, conservation, restoration, development, and other uses with climate change in mind (Nicholls *et al.*, 2007). Mangroves could be an integrated part of ICZM and areas where existing mangroves can be prioritized for protection or restoration as a result of their potential to provide climate-related ecosystem services could be specifically highlighted (Spalding *et al.*, 2014)



* This decisión tree should be applied once andidate sites of high biodiversity have been selected using biological criteria

1. See Mcleod and Salm 2006 (Box 1) for factors that indicate strong recovery potential.

Figure 2 Decision tree to aid resilient site selection for mangroves (Mcleod and Salm, 2006)

Management and Maintenance

Mangrove conservation and restoration are ongoing practices that do not have a specific set end date; therefore, it is important to consider maintenance, monitoring, and ongoing management requirements to enable mangroves remain resilient and responsive to climate change. While interventions should be minimal as mangroves become well-established and healthy, external factors should be managed to prevent stressors and impacts from anthropogenic sources aside from climate change. Anthropogenic stressors are likely to increase with climate change as communities seek to adapt and build resilience themselves. This may include reclaiming land and constructing seawalls or revetments, which could inhibit mangrove retreat and lateral growth, particularly landward (Mcleod and Salm, 2006). Mangroves that are to be restored or rehabilitated should be monitored and evaluated before, during and after to determine the appropriate local conditions as they relate to the restoration works, and follow up monitoring to determine whether define success criteria for restoration have been met (Dahdouh-Guebas and Cannicci, 2021). Mangroves located in close proximity to urban areas may experience greater stressors than those in more remote locations from factors such as the urban heat island effect, pollution, channelization and dyking associated with agriculture, deforestation, and coastal development; therefore it is important that management is implemented to mitigate impacts where controllable (Mcleod and Salm, 2006). Ongoing monitoring of mangrove areas will also inform the performance of mangroves with regards to their resilience and adaptation to climate change.

Implementing monitoring programs will be key to informing adaptive management strategies for mangrove conservation and restoration (Mcleod and Salm, 2006).

In their "Six Principles for Climate-smart Conservation Strategies" information sheet (2020), World Wildlife Fund details that conservation strategies should be deliberate and focus on managing specific climate change risks, consider the socio-economic needs of people in a changing climate, integrate actions for climate change risk management into the overall conservation strategy rather than creating a stand-alone focus, ensure they are flexible and adaptable, connect strategies and actions to policy, and include mitigation actions that seek to more broadly tackle climate risks through nature-based solutions.

Key Findings and Summary

Mangrove conservation and restoration can benefit from an assessment of the vulnerability of the area to climate change. By assessing the exposure, sensitivity, and adaptive capacity of mangroves, the vulnerability can be determined. Where sites are particularly vulnerable to climate change impacts, further assessment on how risks can be managed to enhance successful mangrove conservation and restoration can then be recommended. There are a range of indicators of vulnerability that may be adapted for the development of a restoration tool which could be linked to potential actions to reduce climate change risks.

Site characteristics are key to determine where mangrove conservation or restoration efforts are likely to be successful with climate change. Identification of exposed areas of the coast where storm surge and wave energy have the potential to cause significant damage will be critical. Determining areas where mangroves have the space to retreat landward with sea level rise is also important and could be prioritized. Areas subject to significant drying trends or temperature increases, where terrestrial sediment sources may be reduced by creeks and rivers becoming ephemeral with lowered precipitation should also be identified such that management can be designed to inform expectations for conservation and restoration.

Site selection should be informed by factors that will enable mangroves to establish, reproduce, and function. These are summarized below.

Potential for accretion of sediments: co-location within drainage systems (rivers and creeks as sources of freshwater and sediments), sediment rich macro-tidal environments with currents to distribute sediments, actively prograding coasts, estuaries, or deltas, and protected coastal features (bays, estuaries, barrier islands, etc.) that reduce wave erosion and storm impacts.

Sediment supply with changing precipitation should be considered in locating mangrove restoration or conservation efforts. Sites that are likely to maintain or have increasing sediment supplies because of climate change (i.e., in estuaries and deltas that are unlikely to experience drought or drying) are more likely to be successful under changing climatic conditions.

Landward migration: mangroves backed by low-lying, undeveloped areas allowing for retreat in suitable environments (such as salt plains, marshes, and coastal flats), remote locations distant from human settlement and industry, mangroves in "brownfield" areas that provide opportunity for restoration and remediation, areas subject to natural disasters that prohibit development (such as tsunami-prone areas, flooded fields, etc.).

Sediment distribution and propagule dispersal: tidal creeks with free-flowing pathways, areas with large tidal ranges, permanent strong currents, areas where flows are not seasonal or likely to become seasonal with climate change (i.e., drought prone areas).

Intact and connected mangrove sites: areas of existing diversity in species and with clear spatial zonation across elevation (from intertidal to dry land), size and maturity range diversity with young recruits to mature reproducing trees, tidal creeks with banks already densely populated by mangroves, areas of continuous mangroves, existing established healthy mangrove systems in areas that have demonstrated resilience to climate driven sea level rise or tectonic subsidence. Species selection in restoration activities will be an important factor in increasing the overall resilience of mangroves. Using stronger and more compact species in open-coastal areas or areas that are likely to be subject to increasing storm surge and wind energy will provide a buffer for other species. Therefore, due consideration should be given to species composition of the mangrove.

Strong recovery potential: access to a supply of healthy propagules, strong recruitment evidenced by the presence, variety and abundance of existing propagules, proximity to healthy established stands of mangroves, access to sediment and freshwater, limited influence of human activities, natural or easily restorable hydrological regimes, areas subject to existing protections and management practices or where these could be readily established (i.e., not subject to dredging, harvesting, industry, or agricultural adaptations).

Depending on particular climate vulnerabilities a **range of actions** to reduce risks and enhance mangrove resilience are possible. These could include managing extraction and other stressors, landward land-use and catchment processes. Given the uncertainties associated with climate change impacts, adaptive management is key.

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Appendix B

Glossary of Terms

Glossary of Terms

Adaptation – the adjustments made in ecological, social, or economic systems in response to actual or expected changes to the climate and the associated impacts or effects (as defined by UN Climate Change).

Climate-smart – an approach that guides actions to mitigate or manage impacts to mangroves that specifically consider climate change as the driver. Ensuring climate-resilient practices are considered.

Conservation – the careful preservation and protection of an aspect of the environment that is specifically planned and measured.

Extreme Climatic Events – relative to normal baseline conditions, these are unexpected, severe, or unusual weather events that are driven by climate change.

Intertidal Zone – the area between approximately mean level sea level and the highest astronomical tide, although this may vary with local conditions.

Long-term Sustainability – improved chances of survival or success in the future by ensuring that impacts can be self-managed through adaptation.

Resilience – the ability of mangroves to adapt and recover from environmental change (i.e., climate change or extreme events).

Rehabilitation – the process of reinstating ecological function on degraded ecosystems where restoration is not feasible.

Restoration – the assisted recovery of an ecosystem that has been degraded, damaged, or destroyed (as defined by the Society for Ecological Restoration).

Risk – the result of the likelihood and consequence of a hazard or impact occurring and causing significant damage or change.

Risk-based approach – using an understanding of the key and critical risks to change and negative impacts to drive and determine best approaches to management and control.

Tidal inundation – the process by which sea water is driven up and over land that is normally semi-dry or dry because of rising sea levels, tsunamis, or tidal surge created by storm activity.

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