Climate Change Adaptation Guide for Practitioners

Natural Environment Risks and Solutions

On behalf of:

Federal Ministry
for the Environment, Climate Action,
Nature Conservation and Nuclear Safety

of the Federal Republic of Germany

IKI INTERNATIONAL CLIMATE INITIATIVE

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

CLIMATE ANALYTICS

As a federally owned enterprise, GIZ supports the German Government in achieving its objectives in the field of international cooperation for sustainable development.

Published by
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

Address
GIZ Office East Asia
Tayuan Diplomatic Office Building 2, 16th floor
14 Liangmahe Nanlu, Chaoyang District
100600 Beijing, PR China

Email: climatechangechina@giz.de
For more information on the project and IKI in China please refer to climatecooperation.cn

Project Description
This report is an output of the Sino-German Cooperation on Climate Change – NDC Implementation project, a bilateral initiative by the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) in partnership with the Ministry of Ecology and Environment of the People's Republic of China (MEE) carried out by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH together with China's National Centre for Climate Change Strategy and International Cooperation (NCSC).

The project is implemented on behalf of the International Climate Initiative (IKI) of the Federal Government of Germany. Within the Federal Government, the IKI is anchored in the BMUKN. Selected individual projects are also the responsibility of the Federal Foreign Office (AA).

Project Director
Paul Recknagel

Authors
Andrés Ángel, Zachary Zeller, Winnie Khaemba and Rosanne Martyr (Climate Analytics)

Reviewers
Melania Guerra (Climate Analytics)
Xing Lianghui, Julia Berndt, Ren Yingying (GIZ)

Design
Beijing Zhuochuang Advertising Co., Ltd

Photo credits
https://pixabay.com
https://699pic.com

Beijing, December 2025

Contents

Foreword

Dr. Ben Fitzpatrick

Leader Coastal and Marine Specialist Group, Commission on Ecosystem Management, International Union for Conservation of Nature and Natural Resources (IUCN)

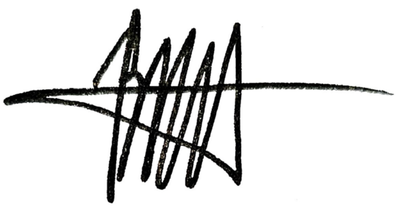
Climate change is accelerating risks to ecosystems worldwide, threatening not only biodiversity but also the services natural systems provide: water regulation, coastal protection, food security, cultural identity and economic opportunities. As climate pressures intensify, so does the imperative to advance climate adaptation strategies that are grounded in science, tailored to local contexts, and capable of delivering co-benefits for both people and nature.

This report brings together international best practices for understanding and addressing climate risks to the natural environment. Grounded in the latest scientific research and supported by illustrative case studies from across the globe, the report is designed as a practical guide for decision-makers, practitioners, and planners working at the nexus of climate adaptation and ecosystem management.

What makes this guide particularly valuable is its emphasis on actionable insights. From risk identification and analysis to monitoring, evaluation and learning, it outlines step-by-step methodologies that can be adapted to local contexts. It highlights the role of enabling policy, financing mechanisms, and institutional capacity in translating assessments into meaningful outcomes. And it champions the critical role of communities, Indigenous peoples, and local knowledge systems in shaping adaptive responses that are both equitable and enduring.

As climate impacts grow more severe and complex, cross-sectoral collaboration and shared learning become increasingly essential. I hope this report not only supports practitioners in designing and implementing effective adaptation measures but also fosters greater international cooperation toward a climate-resilient future. The path ahead demands urgent, informed, and sustained action. By investing in our natural systems, we not only buffer against climate risks but also safeguard biodiversity, strengthen livelihoods, and uphold the ecological foundations of sustainable devel-opment.

I thank the contributors to this report and look forward to seeing its insights applied across geographies and governance levels in the years to come.



Foreword

XU Huaqing

Chief Scientist,

National Center for Climate Change Strategy and International Cooperation

Natural environments worldwide are increasingly vulnerable to climate change. Shifts in temperature and precipitation patterns, along with more frequent extreme events, affect forests, wetlands, rivers, and coastal zones, as well as the ecosystem services they provide. These risks manifest at different scales: some are local, such as droughts or floods affecting specific river basins, while others can trigger cascading impacts that extend far beyond their point of origin. As a result, ecosystems are under growing threat, with consequences for biodiversity and the livelihoods and resilience of people worldwide.

China is already experiencing these challenges. Mangrove forests in the coastal areas are under pressure from rising temperatures, more frequent heatwaves, and sea level rise, which reduce habitats and intensify ecological degradation. Extended hot and dry periods in summer and autumn increase vulnerability to pests and diseases, expanding the areas of damage. In the country's mountain regions, greater variability in precipitation and more localized extreme rainfall heighten the risks of floods, droughts, and geological disasters. These developments illustrate how climate risks can unfold in diverse ecosystems, affecting both nature and people.

To address the adverse impacts and risks of climate change, the Chinese government released the National Climate Change Adaptation Strategy 2035 which strengthens monitoring, early warning systems and risk assessments, while embedding adaptation into planning and governance. The strategy also emphasises the protection and restoration of forests, grasslands, wetlands, rivers, and coastal ecosystems to harness their ecosystem service functions and enhance the country's overall capacity to adapt to climate change.

As part of a series of Climate Change Adaptation Guides for Practitioners, this report offers practical orientation for professionals working to protect natural environments and address the growing threats to ecosystems and the services they provide. It includes case studies, toolboxes, and international best practices for disaster risk assessment, identifying adaptation options, and strengthening governance. I hope this guide will serve as a valuable reference for practitioners in China and around the world, supporting joint efforts to protect ecosystems, enhance resilience, and build a sustainable future for all.

Executive Summary

Purpose and Scope

Climate change and environmental degradation are altering the dynamics of the planet at an alarming pace and the risks for communities and for the natural environment on which they base their livelihoods are increasing. Global warming is projected to exceed 1.5°C within the first half of the 21st century, significantly increasing the likelihood of severe, widespread, and irreversible, impacts. Global warming beyond 1.5°C will significantly increase the risk of ecosystem collapse and accelerate biodiversity loss, increasing species extinction and the disruption of critical ecological functions that support life on Earth. Therefore, understanding the risks and solutions related to it is crucial for informing strategies that enhance both natural and social sustainability.

The present report provides a conceptual basis of risk management in natural environments, including an overview of international best practices from an integrated approach and toolboxes for practitioners to apply them. It also provides international case studies with an emphasis on solutions in different ecosystems, including mangrove and high plateau areas, with the aim of informing decision makers about options they can adopt. As a synthesis of information, sources on data and analyses options, the report can be used as a basis for planning, implementing and monitoring initiatives in different contexts.

In terms of scope the report covers risks that are relevant in different ecosystems, how these can be assessed and analysed via examples and tools that can be applied. It also presents methodologies that can be used for risk assessments, as well as available tools that can provide information for decision making and prioritization. Additionally, it addresses climate adaptation options in the natural environment. It references how policies and governance frameworks can support the entire continuum of addressing risks in the natural environment emphasizing the role of stakeholders such as communities and indigenous peoples, vertical and horizontal collaboration including across borders among others.

Climatic and non-climatic drivers play a role in the shaping of both primary and secondary climate hazards. Recognizing both the type of driver –i.e. if it directly relates to changes in the climate system or not– and in the type of hazard –i.e. if it is either direct and immediate or derived from pre-existing hazards– is essential to effective assessments. As with any public policy, risk management plans and programs need continuous assessment. We recommend a continuous and iterative Monitoring, Evaluation and Learning (MEL) framework based on Key Performance Indicators (KPIs) to track progress, assess effectiveness and adapt strategies.

An integrated approach to climate risk management must be cross-sectoral and multi-level and involve mitigation and adaptation. Limiting warming to 1.5°C through ambitious mitigation efforts substantially improves the effectiveness of adaptation strategies, reducing climate-related risks with less effort and investment compared to higher warming. The IPCC found with high confidence that the consequences of climate change for adaptation can be significantly reduced with warming limited to 1.5°C whereas at 2°C warming, adaptation becomes more challenging, costlier, and less effective. An integrated approach to climate risk management also recognizes the interrelatedness of the social, environmental and economic spheres. It is crucial to understand that key risks to the natural environment may be multi-scalar, cross-systemic between the geosphere, biosphere, hydrosphere, cryosphere and the atmosphere, and can entail synergetic relations that might not always be evident, such as teleconnections, is crucial. Global literature contains several examples of risk assessments in components of the natural environment such as forests, wetlands and mountain regions.

Adaptation strategies and solutions should ideally combine three characteristics: Low cost, high effectiveness, and entail as many co-benefits to society as possible. Solutions that rely on the services that natural systems provide, a.k.a. Nature-based Solutions (NbS), generally combine these attributes and are therefore desirable. Applications related to forests, mangroves, coral reefs and agricultural systems are presented in this document. Technological approaches are also discussed and corresponding examples are provided. These include the use of artificial intelligence, multi-hazard early warning systems and construction of infrastructure are outlined.

For the process of risk management in the natural environment, the following steps are encouraged:

1. **Setting the scene:** Defining the context and scope.

2. **Assessing risks:** Applying qualitative and quantitative methods to substantiate risk, vulnerability and hazards, considering synergistic effects between different types.

3. **Using attribution science:** Considering scenarios with different factors to materialize their corresponding influence, as well as acknowledging the associated uncertainty.

4. **Integrating methods:** Combining strategies and perspectives to produce a holistic view of an issue.

5. **Analyzing potential solutions:** Conducting feasibility and risk assessments for all factors involved, undertaking multi-criteria decision making processes as well as considering multi-scale interactions while acknowledging epistemological diversity is key to choosing optimal responses. Evaluating against Sustainable Development Goals (SDGs) can also be very informative on the adequacy of the solution.

Governance and policy frameworks are key in addressing risks in the natural environment as they provide frameworks which stakeholders, including government policymakers at local level, can use to develop and implement initiatives funded either by their own resources or from the central government, private sector, communities or other stakeholders, including international climate finance sources. For example, different countries have set in place various policies on nature-based solutions that can enable protection of the natural environment as well as systematic implementation of nature-based solutions.

Monitoring and evaluation play a significant role in the review, evaluation and update of initiatives under implementation to ensure the realization of optimal outcomes. Key performance indicators, analyses such as counterfactual analyses, among others, can be used as a way of tracking progress. It is also imperative that a whole-system approach is embraced to consider how risks affect not only the natural environment, but also people, especially the communities that live directly off these systems and the arising socio-economic implications.

Some best practices of what has worked in different contexts are included for application and adaptation by users of this report. To be successful, these have to be contextualized with consideration of the risk assessment, evaluation and prioritization, as well as other aspects highlighted in this report for optimal outcomes.

This report on Natural Environment Risks and Solutions is part of a series of three Climate Change Adaptation Guides for Practitioners that can be accessed here.

The other two reports focus on Urban Environment Risks and Solutions, as well as the Adaptation Policy Cycle.

Key Findings

The box below highlights some major risks and the proposed solutions that can be implemented to address the identified risks.

Ecosystem	Major Risks	Proposed Solutions
Coastal and marine ecosystems	• Sea-level rise • Ocean acidification and heating • Storm surges • Coastal erosion • Biodiversity decline	• Management of coastal defense, such as mangroves • Designation of protected areas • Fishery management • Erosion protection
Mountains and plateaus	• Landslides • Glacier melt • Flooding • Erosion	• Reforestation in degraded areas • Use of local and indigenous knowledge • Integrated water management practices
Forests and grasslands	• Droughts • Floods • Wildfires • Deforestation • Biodiversity loss • Habitat fragmentation	• Monitoring and management of invasive species • Designation of protected areas • Establishment of wildlife corridors • Reduction of illegal logging, poaching, and agricultural conversion
Agricultural landscape	• Droughts • Floods • Pests & disease outbreaks • Temperature extremes • Decline of pollinators	• Water management, irrigation • Agroforestry and agroecology • Improved crop varieties

Recommendations

It is imperative that policymakers and other decisionmakers **strengthen existing policy and governance frameworks** around the natural environment, so that they are better able to deal with existing climate risks, as well as emerging ones. Some examples discussed in this report include the designation of protected areas and nature reserves/parks, the incorporation of nature-based solutions in local and national policies, etc. It is also important that climate risks are mainstreamed across all sectorial plans, strategies and policies, so as to ensure synergy and coordinated approaches in addressing the risks. This has to go hand in hand with the incorporation of local and indigenous knowledge, which is not only important in conserving natural environments but also vital for addressing risks.

Financing is a critical aspect, as resources are required to implement the solutions outlined in this report. Stakeholders have to allocate their own resources, sources for domestic resources and through private sector and international partners to be able to implement solutions that safeguard natural environments.

Resilience building measures are critical to safeguard natural environments, which face multiple climate risks. This can be achieved through deployment of adaptation options discussed in this report, as well as addressing non-climate factors, such as pollution and other forms of environmental degradation, like biodiversity conservation. It is also important for actors to note that different ecosystems and contexts require different approaches to ensure efficiency, effectiveness and optimal outcomes.

Research, innovation and continuous monitoring and evaluation are critical, thus stakeholders have to forge partnerships with academia and organizations that produce novel scientific data and knowledge. In parallel, they should set up robust monitoring, evaluation and learning mechanisms to not only support decisionmaking but also generate information for further analysis and foster better understanding about the interlinkages between natural environments and climate risks.

Awareness creation amongst the public is also a key recommendation, which can support policy makers and decisionmakers to get public adoption and facilitate implementation of solutions. Awareness and access to information can also foster increased participation of citizens in co-creation of solutions, as well as active mobilization in initiatives such as mangrove planting and reforestation, among others. Such public involvement can enhance compliance with policies or measures, such as those concerning protected areas and fragile ecosystems.

Key Definitions

Adaptation - Process of adjustment of human systems to actual or expected climate and its effects, in order to moderate harm and/or exploit beneficial opportunities (based on IPCC, 2023).

Climate change - Persistent change in the state of climate, identifiable by performing statistical tests on the variability of climate parameters. These changes typically last decades or longer and can be attributed to internal processes and/or external forcings (IPCC, 2023).

Feedback loop - Interaction between a perturbation in one climate factor that causes a change in a second, and change in the latter causes an additional change in the first, in the same direction (Calvin et al., 2023). Example: An increase in temperature melts snow and ice (factor 1), which leads to reveal darker surfaces, reducing Earth's albedo and increasing radiation absorption (factor 2), which in turn lead to temperature increase and more snow and ice melting.

Maladaptation - Result of an intentional adaptation policy or measure directly increasing vulnerability for the targeted and/or external actor(s), and/or eroding preconditions for sustainable development by indirectly increasing society's vulnerability (Juhola et al. 2016).

Mitigation - Actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere. (IPCC, 2023)

Related concepts such as mitigation measures and mitigation scenarios are respectively defined as: 1. Those technologies, processes or practices that contribute to mitigation efforts (examples are waste minimisation, renewable energy technologies and habits change) and 2. Plausible descriptions of future implementation of mitigation measures and policies, and the response of the corresponding systems

Nature-based Solutions - 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 (UNEA, 2022).

Teleconnection - Calvin et al., (2023) define this term as "Association between climate variables at widely separated, geographically fixed locations related to each other through physical processes and oceanic and/or atmospheric dynamical pathways". They can also be conceptualized as "linkage[s] of seemingly unrelated climate anomalies over great distances" (Z. Liu & Alexander, 2007) or "remote connections between components of the complex climate system [which] reflect the transportation of energy or materials on global scale" (T. Liu et al., 2023).

1 Introduction

1 Introduction

1.1 Context of Climate Change

The continued consumption of fossil fuels, coupled with disruptions to ecosystems and natural systems, have led to the emission of large amounts of carbon into the atmosphere, driving anthropogenic climate change. In turn, this has caused noticeable changes to Earth's dynamics and harmful impacts on human and natural systems. This process manifests itself primarily as changes in the intensity and frequency of extreme weather events at a global scale as well as continuous increases in global mean temperature.

Although it is too soon to tell, 2024's average temperature exceeding 1.5°C, could be the first of the 20-year average that, according to the Paris Agreement's measuring methodology, would confirm the passing of the 1.5°C average global warming threshold (Bevacqua et al., 2025).

Such overshoot would have several implications for the natural environment and could compromise valuable ecosystem services like those provided by mountainous regions (water provision, etc.) and mangroves (coastal protection from erosion, habitat for species,) which are discussed in further sections of this report.

1.2 Adaptation vs. Mitigation

There are two primary and interrelated ways that climate risk can be reduced; mitigation and adaptation. Climate mitigation decreases risk by reducing or reversing carbon emissions, thereby limiting the impacts of climate change and reducing climate hazards. Whereas mitigation works by reducing climate impacts from the source, adaptation works by adjusting and responding to impacts and limiting their detrimental consequences (thereby reducing exposure and vulnerability). Reducing climate risk comprehensively, requires appropriate integration of both adaptation and mitigation measures.

Adaptation and mitigation may be best implemented at different scales and with different instruments. Since emissions from one region will have consequences distributed globally, mitigation is an important and overarching theme that should be prioritised at the national and international levels, with an emphasis on global cooperation and coordination of policy measures. Alternatively, adaptation is largely a local and regional process, highly dependent on site-specific contexts and complexities, given that climate change does not manifest uniformly across space and time. Adaptation strategies may therefore require integration of local knowledge with available resources.

While the general association of adaptation with local scales and mitigation with global scales is helpful, it does not capture the full reality of these processes. Indeed, while adaptation is a localised process, it often requires funding, knowledge, resources and guidance from higher levels of governance. Additionally, regions and nations may wish to coordinate large scale adaptation efforts to promote security, socio-economic development, and risk reduction. Similarly, top-down mitigation strategies should work alongside and in cooperation with the local level, since large-scale efforts to reduce emissions still largely rely on individual actors. Furthermore, certain localities may have heightened capacity for mitigation, such as ecosystems with high carbon-sequestration potential or regions with large renewable energy capabilities. In these locations, high prioritisation of mitigation potentials can contribute significantly to global impacts.

It is not possible to focus solely on mitigation efforts and exclude adaptation. This is because even under the most ambitious decarbonisation strategies and scenarios, global temperatures will still require decades to come back down, and some impacts of climate change today are irreversible for centuries to come. On the other hand, focusing solely on adaptation while ignoring carbon emissions is short-sighted and self-defeating, since many adaptation strategies diminish in effectiveness under increased climate change.

Many solutions to climate change have synergies with both adaptation and mitigation, resulting in win-win scenarios. This is especially the case for conservation and restoration of natural environments, which provide a host of co-benefits in addition to carbon sequestration and storage. In cases of conflicts between adaptation and mitigation, decision makers should consult a variety of stakeholders and work to balance tradeoffs equitably and sustainably. The following section will introduce potential solutions and strategies that can reduce risk through mitigation and adaptation.

1.3 Importance of Natural Environment Adaptation

Natural environment adaptation is critical for maintaining a balance that sustains both nature and humans (IPCC, 2022; Pearce-Higgins et al., 2022). Specifically, it contributes to human well-being where people benefit from their interaction with the natural environment. For example, the natural environment serves as a valuable repository for indigenous knowledge and cultural preservation.

The IPCC reports that impacts on the natural environment have increased in both frequency and intensity (IPCC, 2022), Thus adaptation is important for ecosystem services, biodiversity and resilience. These three are inextricably linked since healthy ecosystems support biological diversity which in turn supports the proper functioning of ecosystems. Resilience on the other hand, supports ecosystem services and biodiversity in responding to disturbances and long-term changes, strengthening their capacity under climate change stressors (Pearce-Higgins et al., 2022).

Ecosystem services in this case include: provisioning services such as food, water and medicine; supporting services such as cycling of nutrients; regulatory services like coastal flood regulation by mangroves and water filtration by wetlands; and, cultural services including recreation and sacred and spiritual sites (Muhammad et al., 2025). Natural environment supports biodiversity by ensuring diversity in the genetic pool and ecosystems and the survival of species. Adaptation in the natural environment enhances resilience by enabling systems to adjust to rising temperatures and other climate extremes, to recover from these extremes and to support human resilience (Beck et al., 2025; IPCC, 2022; Pearce-Higgins et al., 2022).

Adaptation in the natural environment includes preservation and conservation, application of indigenous knowledge practices and continuous monitoring among others. Threats to the natural environment that also impact adaptation capacity include deforestation, urbanization, biodiversity loss, pollution, among others. These interdependences are made even more complex by compounding and cascading climate risks and hazards (Chen et al., 2011; IPCC, 2022). Adaptation has been shown to contribute to resilience, food security and reduction of disaster risks and associated climate hazards (Asmamaw et al., 2015; Muhammad et al., 2025; Munang et al., 2013; Nyathi et al., 2025).

2 Risk Management

2 Risk Management

Risk is defined by Calvin et al. (2023) as "the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems".

Climate risk can also be conceptualized as an emergent property of a dynamic socio-ecological system arising from the interactions between its elements. In established risk frameworks, a risk's magnitude depends on the interplay of three properties: the hazard, the exposure and the vulnerability. It is therefore useful to establish the definitions of these elements.

2.1 The Integrated Approach

Key definitions

Hazard

"The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources"*

Exposure

"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"*

Vulnerability

"the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt"*

**Calvin et al., 2023*

The relation between the factors can be expressed mathematically in the following manner:

$$Risk = Hazard \times Exposure \times Vulnerability$$

The expression above contains the standard definition used more generally, in which risk is the product between hazard, exposure and vulnerability. These components are dynamic in time and space. Taking the vulnerability of a community as an example, it is determined by its adaptive capacity, governance structures, social cohesion, access to resources and similar factors. These are implicit in the vulnerability term and therefore already considered in the estimation of risk, albeit not explicitly in the equation above nor the figure below. When combined, these factors can be recognized as collectively capacity, which is formally defined as "[readiness] of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure" (Calvin et al., 2023). Therefore, the more capacity a system has, the less vulnerable it is. A graphic depiction of the interaction between the three original factors is IPCC's propeller shown below (see Fig. 1).

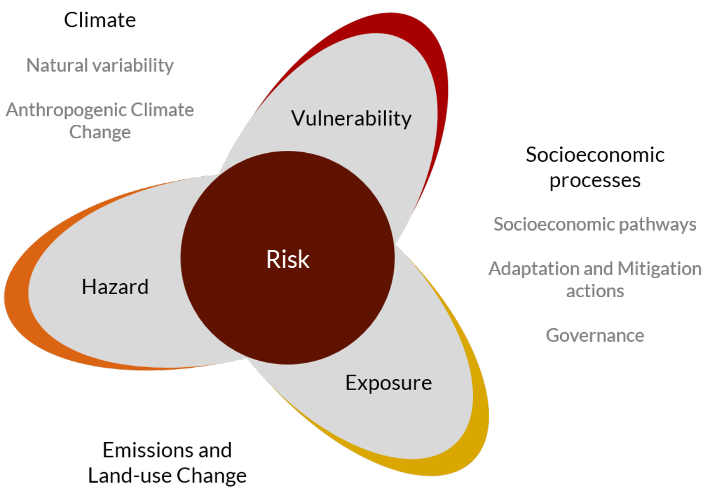


Fig. 1. Risk Propeller
Source: Prepared by the authors based on IPCC (IPCC), 2023b)

The general term that describes all activities conducive to coping with adverse consequences of climate change is Climate Risk Management. This is a large area of study and it is composed of subsidiary processes or stages, such as risk assessment and risk treatment (see fig. 2). Risk assessment refers to a multi-step process in which climate-related risks are identified, analyzed and evaluated, while risk treatment refers to any actions oriented to mitigation of those risks. A third instance can sometimes be included in the frameworks, which accounts for the ex-post assessment of the implemented measures to determine their effectiveness.

Exposure in particular can be divided into natural and human, referring to that pertaining to ecosystems and communities respectively. In each context, relevant case-specific indicators must be selected to properly account for the presence of people, assets, infrastructure or economic activities in areas subject to climate hazards. There is also a strong interdependence between the two typologies: Healthy ecosystems provide services that may reduce the exposure of populations to hazards and conservation efforts from communities help enhance the resilience of the ecosystems. An example of the use of indicators from both typologies, namely population density and forest cover, to assess risk can be consulted in Thomas et al. (2020).

There are multiple risk management terms and frameworks and they tend to share the same basic elements, although the arrangement may vary slightly among them. This section briefly presents two illustrative examples of risk assessment frameworks: one from the Organization for Economic Cooperation and Development (OECD, 2021), which outlines four key steps, and a more generic three-step approach (Identification, Analysis, and Evaluation or IAE) proposed by the consulting firm CRI Group (2025). The correspondence of the steps in both frameworks shown in Figure 2 and the OECD framework will be discussed further in relation to the GIZ approach later in the report.

While this section mainly refers to the IAE framework, its three steps, namely Risk Identification, Analysis, and Evaluation, closely align with OECD's four key steps, even if not mentioned explicitly. The process begins with Risk Identification. This step involves recognizing the existence of potential adverse events while understanding their causes and mechanisms. The second step, Risk Analysis, involves the further characterization of the identified risks, for example by estimating the likelihood of occurrence, identifying contributing factors, and assessing the potential nature and magnitude of consequences. Finally, Risk Evaluation uses the results of the analysis and contextual information to determine which mitigation actions should be taken. In the IAE framework, decision-making and the implementation of measures are both embedded within the evaluation stage.

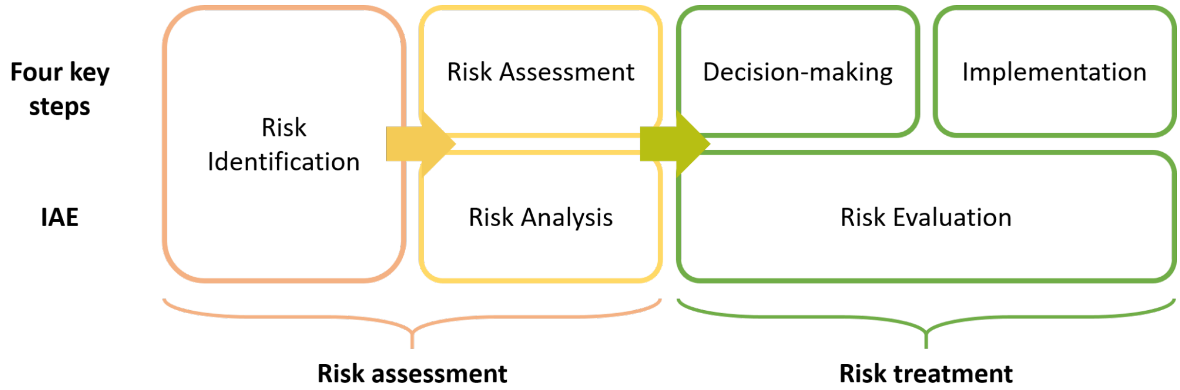


Figure 2 Key steps of Risk Management
Source: Produced by the authors based on (OECD, 2021) and (CRI Group, 2025).

More general Climate Risk Management (CRM) frameworks like GIZ's 6-step methodology can also be found in the literature (GIZ, 2021). This methodology adds and emphasizes certain aspects, separating them as prior or posterior, unlike IAE's more integrated approach on risk identification, analysis and evaluation. Therefore, it is worth describing it further to assess the potentially useful additional steps:

1. Analysis of status quo - information needs and objectives: Diagnose of the current state of knowledge and context information (profiling of institutions, climate change risks, stakeholders, regulations and frameworks in place and systems of interest such as regions, sectors or others).

2. Hotspot and capacity analysis of system of interest: Characterization of the object of study (region and sector) and of adaptation and risk management gaps.

3. Development of a context-specific methodological approach: Description of the potential quantitative and qualitative methodologies to describe risks and impacts in the particular case of study as well as necessary adjustments. Additionally, an assessment of available information is to be made in this step.

4. Qualitative and quantitative risk assessment: Analysis of existing risks, projected climate change impacts, socio-economic trends response to measures and hazard, vulnerability and exposure indicators selection.

5. Evaluation of Risk Tolerance: Determination of the level exhibited by the communities, sectors, etc. and their level (acceptable, tolerable, intolerable).

6. Identification of feasible options to avert, minimise and address (potential) losses and damages: Recognition and characterization of potential response strategies, their costs, scope and constraints.

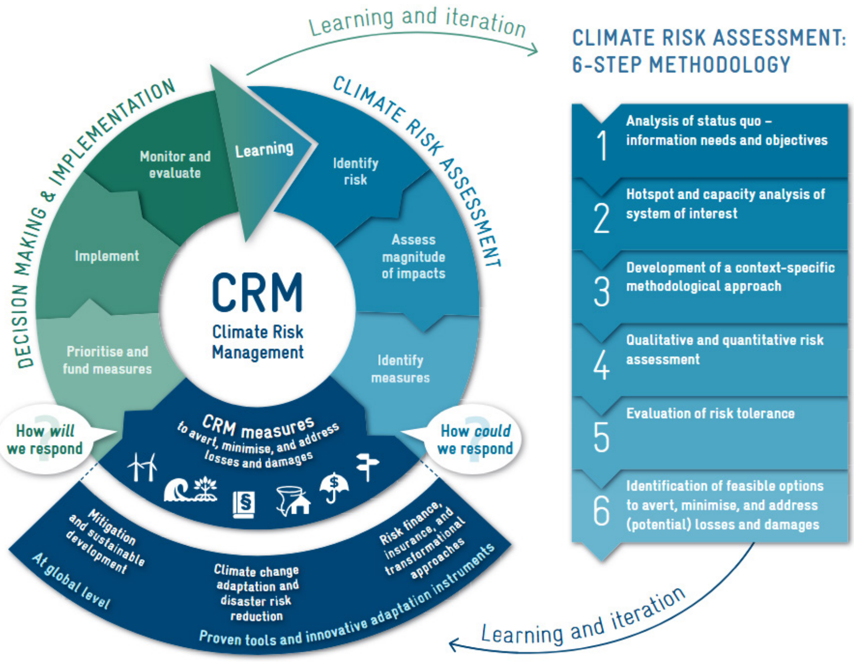


Fig. 3. CRM framework and 6-step methodology

Source: GIZ (2021)

The Importance of an Integrated and Iterative Approach

Each of the steps described in these frameworks must be conducted carefully and provide information for the next. Failing to do so, for example by misidentifying a risk, will result in innocuous measures or even an erroneous decision to not take any measures, which could prove very costly in the case that a risk materializes. Errors in the Risk Analysis stage may lead to inaccurate likelihood estimates, underestimation or overestimation of consequences and maladaptation. If an error propagates up until the decision-making and implementation stages and these become ineffective, it could lead to misallocation of resources, materialization of the risks and consequences like loss of life, property damage, etc.

Insufficient or even counterproductive risk management from flawed identification and analysis increases the risk itself, especially at smaller scales. A study by Bressan et al. (2024) observed that lack of information at an adequate scale on specific physical risks to assets exposed to chronic and acute impacts, could result in losses of up to 70% in value of such assets. The case study analyzed by Bressan was specifically on mines, processing facilities, power plants, liquefaction and regasification facilities in Mexico and the hazard of interest were tropical cyclones, however the observation about the importance of the quality of information can also be applied to physical risks, to diverse ecosystems and to other natural elements across a variety of hazards.

Risk management is a process inherently based on incomplete knowledge (IPCC, 2020) and therefore, it must be iterative, meaning that it evolves over time, through which the information generated by past processes can inform and improve future actions, in a series of decision-making cycles that ideally mitigate risk more efficiently through every new iteration. It is therefore important that the institutions in charge of risk management are robust enough and have the capacity to adapt and learn from past experiences.

More information on further risk classifications and typologies and focuses on new (emerging) risks can be found in OECD's Working Paper on Public Governance No. 78. It is useful to complement the risk management framework contained in the IPCC documents. A more succinct Public Governance Policy Paper on this framework is available here.

2.2 Risk Identification

2.2.1 Key Risks to the Natural Environment

Climate risks are diverse and can manifest themselves in different ways. Due to their nature and magnitude, some risks can manifest at a global scale while others may only be initially relevant at specific locations. Nevertheless, given the complexity and interconnectedness of the Earth System, teleconnections between local impacts may trigger global tipping points in the planetary system.

Once these tipping points are reached, positive feedback loops can exacerbate impacts on Earth subsystems, such as the geosphere, biosphere, cryosphere, and hydrosphere. One example of this is deforestation in the Amazon basin, which could eventually lead to an interruption of the atmospheric moisture flows generated by evapotranspiration (Boers et al., 2017), potentially leading to water stress in the biome with catastrophic consequences and collapse of the remaining rainforest ecosystem.

Additionally, climate change does not manifest homogeneously across the Earth system, with some regions experiencing more intense impacts. This is evident, for instance, in polar regions. High latitudes in the northern hemisphere show stronger warming than the global average due to a phenomenon known as polar amplification (Intergovernmental Panel On Climate Change (Ipcc), 2023a). This process leads to the accelerated melting of glaciers and ice sheets, contributing to sea level rise. Permafrost thaw in the northern hemisphere also has a significant influence on arctic river dynamics since riverbank erosion is expected to increase dramatically as this process continues (Geyman et al., 2024), posing a major threat to the habitats and infrastructure of the region.

Climate change risks to the hydrosphere are also significant. From a global perspective, a warmer climate favors ocean temperature stratification, preventing oxygen-rich surface water from mixing with deep waters. Moreover, higher atmospheric CO2 concentrations lead to increased dissolution of the gas in ocean water, forming carbonic acid that breaks into bicarbonate and hydrogen ions, decreasing the oceans' average pH (Intergovernmental Panel On Climate Change (Ipcc), 2023a). This combination of low-oxygen and acidic conditions threatens a wide range of ocean life. Freshwater resources are also highly threatened under climate change. For example, rising sea levels can infiltrate freshwater aquifers in coastal areas, introducing salt into water supplies. Increasing drought conditions and lack of rain reduce the availability of freshwater, while in other parts of the world, quickly melting glaciers result in a loss of otherwise steady freshwater for human consumption and agriculture.

Reduction in freshwater resources has resulting impacts on other sectors, such as agriculture. The combination of extreme temperatures during the growing season and a lack of water can lead to reduced productivity, or even crop failure. Another extreme involves flooding and storms caused by climate change, which leads to physical damage of crops. Extreme temperatures may also affect labor productivity, not to mention, in extreme cases, climate-induced displacement and migration of populations, resulting in abandonment of agricultural land.

2.2.2 Drivers of Risks

Climate risk does not depend only on the nature of the hazard, but on the specific exposure and vulnerability. It is therefore key to understand how social and natural systems evolve through time. Considering that the changes through time of non-climatic factors can be particularly difficult to predict, there are certain scenario analysis tools, such as IPCC's Shared Socioeconomic Pathways (SSPs), which contain the assumptions that later feed Integrated Assessment Models (IAMs), Energy–Environment-Economy (E3) models and similar. It is important to understand that these scenarios are built on observed data on energy consumption, trade, sectoral trends, demographic changes, etc. A comprehensive overview of models used is available at UNFCCC.

Extreme events, as well as progressive changes and decrease in the environmental quality of ecosystems, can be exacerbated by anthropic interventions, such as land-use changes including wetland drainage, urban sprawl, expansion of agriculture or cattle ranching; changes to the hydrological system, such as dam construction, channelisations and diversions; water and soil pollution due to discharges; and disturbances due to resource extraction (mineral and oil & gas).

In this regard, we can distinguish two types of hazards: primary and secondary, and two types of drivers, climatic and non-climatic, which will be explained in more detail below.

Hazards refer to both the continuous long-term trends (such as sea-level rise) and discrete events (such as floods) that can cause damage or disruption to natural and human systems. A distinction between primary and secondary hazards can be made based on how it manifests in natural systems. The former refers to the potential for direct and immediate consequences of a climate-related event such as a flood after heavy rainfall, high winds due to a hurricane, storm surges fueled by a cyclone or a drought due to prolonged lack of precipitation in an area, while the latter describes the resultant effects from primary hazards, such as riverbank erosion due to flooding, infrastructure collapse due to permafrost thawing of famine after prolonged drought.

On the other hand, a climatic (or climate) driver is “a changing aspect of the climate system that influences a component of a human or natural system” while non-climatic (or climate) driver refers to an “agent or process outside the climate system that influences a human or natural system” (IPCC, 2023b). Thus, climatic drivers are directly related to and influenced by global climate trends while non-climatic drivers are often human-induced and can mitigate or exacerbate climate-related hazards or effects.

Examples of climatic drivers are rising temperatures, sea level rise, changing precipitation and hydrological droughts. Examples of non-climatic drivers include land-use changes, the generation -and subsequent transport- of pollutants, etc.

2.3 Risk Analysis

2.3.1 Risk Assessment of Natural Ecosystems

Climate risk assessments (CRAs) are comprehensive and systematic analyses that consider the likelihood of negative impacts due to climate change. In particular, CRAs consider how hazards, vulnerability, and exposure interact to generate risks on populations, assets, natural resources, and wildlife. These assessments provide the basis for risk management, policy direction, and informed decision-making across sectors and among stakeholder groups.

The completion of a CRA elucidates how climate change will manifest across environmental, economic, and social dimensions. Environmental impacts of climate change include loss of biodiversity, collapse and transition of ecosystems, and changes to geological and hydrological cycles. Since the economy is dependent on Earth’s resources and natural processes, environmental changes will necessarily have economic impacts. These include a loss of ecosystem services such as water filtration, carbon sequestration, and erosion prevention along with reduction of natural resources like timber, freshwater, fisheries, etc. These losses can result in further social impacts, such as food and water insecurity, loss of livelihood/income, disruption of essential supply chains, and displacement of local people.

Understanding how such impacts can manifest in the future is the first step in addressing and reducing climate risk. The foundation of a strong CRA is based on integration and analysis of various data sources. Methodologies for CRAs can include a variety of approaches, such as geospatial mapping and remote sensing, analysis of historical records, and statistical modelling. In general, the integration of multiple types and sources of data along with various methodologies increases the ability of a CRA to understand the particular system or region studied. The end result of a CRA is the quantification of risk based on hazard, exposure and vulnerability.

Important considerations must be accounted for by those with direct understanding of the system assessed. The magnitude of a risk depends on aspects such as likelihood and severity of impacts, and the manageability of consequences. There is no one-size-fits-all solution to climate risk, thus local experts and practitioners should consider the tradeoffs associated with various risks. For example, a low-likelihood risk with low impacts and high manageability may be less immediately important than a high-likelihood risk with high impacts and low manageability. Since risk assessment is context- and location-specific, there is no universal guidance. Nevertheless, the IPCC provides a general framework with guidance on the conceptualisation of risk, which is widely useful for science and policy applications.

Considering the diverse topography and ecosystems in China, vulnerable habitats, such as mangrove forests and mountainous regions may be particularly at-risk due to the severity of impacts under future climate change, accompanied by high vulnerability and exposure. Strong understanding of risk, informed by robust CRAs, has allowed for local governance to better manage and mitigate risk. The progress made in risk management will be showcased in chapter 5, with examples from Sichuan and Guangxi provinces.

2.3.2 Examples of Risk Assessments

Forests

Relevant examples of general risk assessments can be found in the literature. These contain specific thematic areas and are very useful to understand how other countries are managing these risks. One of such examples is Germany's Climate Impact and Risk Assessment 2021 (Umweltbundesamt, 2021), which examines and evaluates the future risks for Germany due to climate change, with a particular focus on forests and tree health.

The assessment cites increasing drought and heat as a major threat to forests and plant health. These conditions also create secondary hazards by increasing the probability of wildfire and favoring the proliferation of pests, which is best illustrated by the dramatic impacts of Bark Beetle outbreaks in Spruce forests. Extreme weather, such as storms, can also result in increased windthrows, affecting larger trees and compromising entire tree communities. Federal States in Germany like Baden-Württemberg have produced detailed vulnerability maps for current conditions and under climate scenarios out to 2080 (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, 2025). These are good examples of complex assessments synthesized in readily available products for decision-makers.

In this case study, the future suitability of tree species is assessed with respect to three different groups of tree species, namely main species, secondary species and all others, each with a specific diagnostic tool. The methodology considers groups of so-called climate influence factors. Among others, they include such categories as: Temperature and Precipitation (mean annual temperature, length of the vegetation period, annual precipitation, rainfall distribution and winter frost); Extreme Weather Events (drought, hot days/ periods, hurricanes, large precipitation events); and Climate Effects (species and habitat vulnerability, late frost, mass propagation and increase in harm potential of native insects, pathogens and wood diseases, etc.). Based on these climate influence factors, the climate risk per species can be estimated.

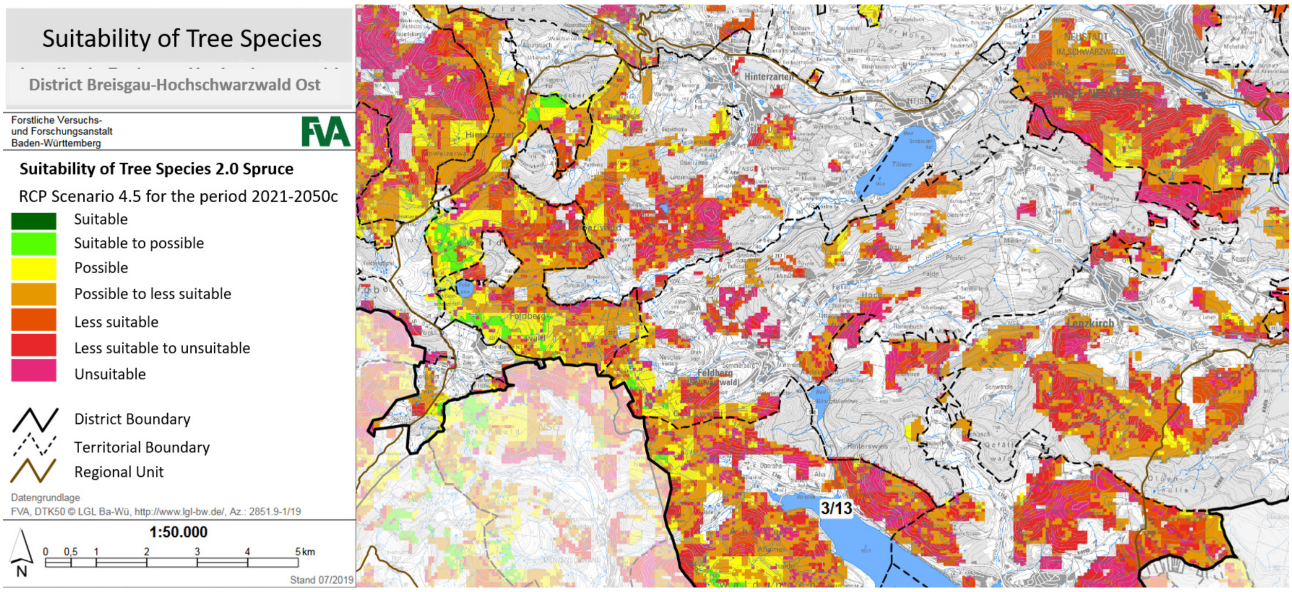


Fig. 4. Excerpt of the Tree Species Suitability Map under scenario RCP4.5 for the period 2021-2050 in the district of Breisgau-Hochschwarzwald Ost, Federated State of Baden-Württemberg, Germany.
Source: Modified from Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg (2025)

Finally, it is also important to discuss the adaptive capacity regarding forest systems. As a commodity, climate change may increase wood prices due to increasing scarcity. Institutions from the public and private sector may not be able to identify and react to new climate change-related challenges. Companies may suffer or even disappear and regulators may be unprepared to design and implement tools to help fight pests or other threats timely. Public support for investing in forest management may also decrease as these lose their capacity to provide ecosystem services such as recreation, creating a detrimental feedback loop regarding the attitudes to them (Umweltbundesamt, 2021).

The Food and Agriculture Organization of the United Nations (FAO) created a framework methodology to help identify and describe elements in the process of assessing the vulnerability of forest ecosystems and forest-dependent people. It contains good practices, lessons learned and principles for effective vulnerability assessments, among other useful tools (Meybeck et al., 2019).

Wetlands

From a global perspective, wetlands play a significant role regulating methane ($CH4$) emissions. Their state of conservation and maturity determines whether they behave as carbon sinks or sources, therefore these aspects of their lifecycle are very relevant. On the local level, wetlands provide ecosystem services such as carbon sequestration and storage, drinking and irrigation water supply, water regulation and recreational and cultural services (Secretariat of the Convention on Wetlands, 2021). Additionally, IPCC highlights with high confidence the role that these elements play in decreasing flood risks and urban heat (Calvin et al., 2023).

According to the Secretariat of the Ramsar Convention, both arctic and montane wetlands are at special risk due to the impacts of climate change. Changing weather patterns will increase the risk of water stress due to both flooding and drought and stresses the urgency of wetland restoration and management for mitigation and adaptation (Secretariat of the Convention on Wetlands, 2021). It is worth recognizing that the Aichi Targets 5, 9, 10, 11 and 15, in their aspects related to wetlands, were not completely achieved (Secretariat of the Convention on Biological Diversity, 2020).

Risk assessments such as "Managing Climate Risks in Wetlands. A Practitioner's Guide" (GIZ, 2023), offer a practical approach to risk assessment and adaptation options for wetlands. It offers a highly participatory and rapid methodology suited for local-level discussions based on impact and vulnerability assessment, adaptation planning and, finally, implementation and feedback. It presents an Integrated Management Plan including, among others, the following processes: Wetlands Description, Assessment of Ecological Character, Diagnostic of Threats, Institutional Analysis, Establishment of a Management Framework, Drafting of Monitoring and Evaluation, and Action Plans and Budgeting and Activity Phasing.

TOOL - VULNERABILITY SCORING MATRIX

		Impact				
		Very Low Inconvenience (days)	**Low** Short disruption to system function (weeks)	**Medium** Medium term disruption to system function (months)	**High** Long term damage to system property or function (years)	**Very High** Loss of life, livelihood or system integrity
Adaptive capacity	**Very Low** Very limited institutional capacity and no access to technical or financial resources	Medium	Medium	High	Very High	Very High
	Low Limited institutional capacity and limited access to technical or financial resources	Low	Medium	Medium	High	Very High
	Medium Growing institutional capacity and access to technical or financial resources	Low	Medium	Medium	High	Very High
	High Sound institutional capacity and good access to technical or financial resources	Low	Low	Medium	Medium	High
	Very High Exceptional institutional capacity and abundant access to technical or financial resources	Very Low	Low	Low	Medium	High

Fig. 5. Example of a vulnerability scoring matrix included in GIZ's report.
Source: (GIZ, 2023)

Although this framework was designed for India, it is not context-specific, so it can be implemented in other countries. It is also very detailed, so practitioners can use it as a step-by-step guide for conducting assessments. Flow charts and process planning charts, lists of factors, scoring protocols and matrices and tables with different categories and examples are available for consultation.

Mountain Regions

Not only montane wetlands are experiencing the impacts of climate change, but also mountain glaciers. According to the IPCC, (2023b) a general decline has been observed in low-elevation snow cover, glaciers and permafrost in recent decades (high, very high and high confidence respectively) and this has in turn altered the frequency, magnitude and location of natural hazards, increasing the exposure of growing populations to related hazards (high confidence).

There are limited existing cases of risk assessments in mountain regions and high-plateau areas. These settings are, nevertheless, at high risk due to their high levels of warming and large gradients of elevation. Additionally, mountain slopes are at high risk of resulting in erosion and landslides, effecting low lying areas.

Risk assessments of these ecosystems should consider that changes in the climate will also displace the ecological niches of several species causing large-scale contractions in montane ecosystems (Helmer et al., 2019) and affect the phenological cycles of plants, especially those located in tropical biomes (Numata et al., 2022) causing further stress on species that depend on them which could lead to catastrophic consequences in trophic chains.

The IPCC (2023b) also highlights the impacts of glacier retreat and snow cover changes on communities dependent on their run-off. These factors have contributed to the decrease in agricultural yields and water availability in regions like the Hindu Kush and the Tropical Andes (medium confidence). Glacier retreat may result in summer run-off increase in the short-term, but it will inevitably mean less water availability in the medium- and long-term.

Risk assessment and management efforts should incorporate not only these high-elevation regions, but also the downstream effects on nearby communities. The IPCC has produced a cross-chapter paper (Cross-Chapter Paper 5, 2022) focusing on unique risks facing mountain regions, which can provide a basic understanding and summarization of current knowledge on these settings.

Agriculture

Run-off seasonality and amount has changed with corresponding changes in snow and glaciers in snow-dominated basins (The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change, 2022), therefore, agricultural practices, livelihoods, socioeconomic activities and sectors in areas that depend on run-off from glacier-fed rivers are especially threatened by climate change. Moreover, the agricultural sector absorbs 82% of drought's economic impacts (The Impact of Disasters and Crises on Agriculture and Food Security, 2021).

A holistic view is necessary when assessing climate risks to agriculture. Therefore, factors such as the state of agriculture itself and the tensions with ecological conservation have to be considered. There are examples of policies trying to tackle these intersectional aspects, such as China's Grain for Green (退耕还林) program, introduced in 1999 after a period of grain surplus in the country. Designed to tackle deforestation, ecological degradation, soil erosion and cultivation on excessive slopes, the program provides subsidies to farmers that convert sloping and marginally productive lands to grasslands or forests.

Studies have found that this type of subsidy promotes afforestation and reforestation while benefiting the farmers themselves (World Bank, 2022). Such efforts can contribute both to climate mitigation – by increasing carbon storage capacity through forestation – as well as adaptation – by increasing natural ecosystem services and reducing the risk of erosion.

Events such as the COVID-19 pandemic and the Russian invasion of Ukraine highlighted the importance of having food sovereignty in a country. However, to ensure the success of both programs, it is indispensable to consider the farmers' economic situation, the ecologic vulnerability and to have, in general, a holistic view of the food security-ecology-rural development nexus. Key actions to guarantee success are:

- to protect the achievements of the Grain for Green program,
- to increase transparency in local afforestation databases,
- to ensure diversification of grain supply strategies,
- to conduct detailed soil assessments and
- to align with the farmers' preferences and practices while offering viable job opportunities. (Sino-German Agricultural Centre, 2023).

Global Risk Assessment - Mangroves

Typically climate risk assessments for ecosystems are conducted within a defined geographic scope. However, in 2024 the IUCN conducted the first-ever global assessment for an entire ecosystem. Utilising the Red List of Ecosystems framework, they mapped out the health of the world's mangrove ecosystems, finding that 50% were at risk of collapse, with rising sea levels being the greatest threat.

The Red List of Ecosystems framework is a global standard to assess ecosystem health and completed ecosystem assessments following this guideline are made available on the Red List of Ecosystems database.

2.4 Monitoring, Evaluation, and Learning

Monitoring, evaluation and learning (MEL) is a systematic approach used to track progress, assess effectiveness, and adapt strategies in projects, programs, or organizations, each of MEL's steps are key aspects when thinking about natural environment risks. MEL is important in terms of helping enhance understanding, designing strategies and interventions, implementation and updating to ensure intended outcomes (IISD, 2024). It supports decision-making by assessing data and information and adjusting interventions. Various approaches are used for MEL normally dependent on various factors such as the scale, resources available, technical capacity and duration among others and can be especially important in disaster risk management.

COP 28's UAE Framework for Global Climate Resilience provides a way in which adaptation can be tracked. There are other monitoring platforms in use to look at risks. Various countries have adopted different approaches on MEL with some developing comprehensive tools for this. The report National Monitoring, Evaluation, and Learning Systems for Climate Change Adaptation: A Comparative Analysis of Nine Countries (IISD, 2024) provides an overview of practice in select countries on this topic. The authors contend that while frameworks and tools are in place, oftentimes learning is not fully integrated in this process.

Natural environmental risks being unpredictable especially with climate change means that the role of MEL is even larger as this can help respond to fast changing scenarios and varying dynamics. MEL tools can help foster accountability and be used as a tool for stakeholder engagement thus enhancing ownership (OECD, 2021).

The environmental social safeguards are sometimes used as part of MEL processes where the safeguards are tracked to ensure that these remain in place during implementation of strategies and interventions (OECD, 2021). Noltze et al. discuss various approaches to MEL for climate risks including the risk management approach, adaptive pathways approach, dynamic policy approach and a dynamic adaptive policy pathways approach. Some of these such as the adaptive pathways approach considers tipping points, looking at different adaptation pathways, lock-ins and dependencies (Hasnoot et al, 2012) and later the Dynamic

Adaptive Policy Pathways (Hasnoot et al, 2013). These can be utilized as tools and approaches for ensuring effective MEL.

Key Performance Indicators (KPIs) are critical tools within the MEL framework, as they provide measurable values to evaluate success and inform decision-making (OECD, 2021; Enenkel et al., 2022). When combined, MEL and KPIs create a robust system for achieving goals, improving performance, and ensuring accountability.

KPIs act as markers of progress and for evaluation with clear targets that are quantified and leading towards set objectives. They also act as benchmarks for reference. KPIs have to be aligned to set objectives, measurable and defined within a given timeframe for easy tracking (IISD, 2024; OECD, 2021). The table below shows some examples of key performance indicators.

Table 1: Examples of Key Performance Indicators

	Strategy	Example of Key Performance Indicator
1.	Enhanced resilience and adaptive capacity e.g. to coastal flooding	• Percentage/acres of mangroves restored in three years • Number of flood defenses (natural and technological) installed in one year
2.	Strengthening of climate services and DRM	• % of effectiveness of early warning systems in one year • Number of people utilizing climate services
3.	Increased access to climate finance	• Amount of funds received in past year • % of received funds disbursed in the past year
4.	Policy strengthening	• Number of policies in place to address climate risks • Number of strategies implemented to address climate risks in the past year
5.	Capacity building	• Number of people trained on climate risks assessment in the past year • % of population with increased understanding of climate risks and their impacts
6.	Research and development	• Number of research outputs on climate risk in one year • Number of innovative approaches to addressing risks in the past three years

Since results for adaptation are often not apparent in the short term MEL frameworks for climate risks have to have a long-term outlook and be robust enough for indicators that can be modified, reviewed and updated for use over time. They should also consider path dependencies so as to avoid lock-in and maladaptation (Noltze et al, 2021). Selected indicators need to be SMART1, dynamic and the entire process iterative to ensure that learning is incorporated. Counterfactual analyses[2] that estimate risk under conditions without climate change

1 The acronym S.M.A.R.T. refers to indicators that have all of the following characteristics: Specific, Measurable, Achievable, Relevant and Time-bound.

2 According to Bull et al, 2020 'counterfactuals are a type of reference scenario that captures an alternative possible trajectory of a dynamic system

or without adaptation, may also be a useful tool in MEL to ensure that updates and reviews to the MEL framework are incorporated to address climate risks.

These analyses seek to provide alternative scenarios, e.g in when no action is taken, that can help to make decisions. Bull et al (2020) state that it is possible to have multiple counterfactuals that can help estimate the gap between action and inaction, thus helping decision makers and policymakers in making decisions. Therefore, MEL frameworks need to be applicable across levels thus addressing both vertical and horizontal levels relating to the climate risk.

The NAP Global Network has developed a MEL toolkit that can be used for national adaptation planning

in the absence of a given intervention'.

3 Adaptation Strategies and Solutions

processes including climate risk assessment. Some national case studies include the Rwanda KPI's and a cross-section of indicators compiled by the UNFCCC from various countries that can be useful for seeking collaboration as well as peer-to-peer learning and exchange. Additionally, there are tools and approaches such as the Greenpass in Elagiry et al with a case study of Segrate.

3 Adaptation Strategies and Solutions

Climate risk assessments identify and quantify emergent impacts of climate change, paving the way for solutions to reduce impacts. When determining which solutions to pursue, it is preferable to prioritise solutions that combine both mitigation and adaptation, are low cost and highly effective, and offer various co-benefits to society. Solutions to reduce risk can vary from aspects such as physical infrastructure, protection of nature, technological implementation and behavior changes.

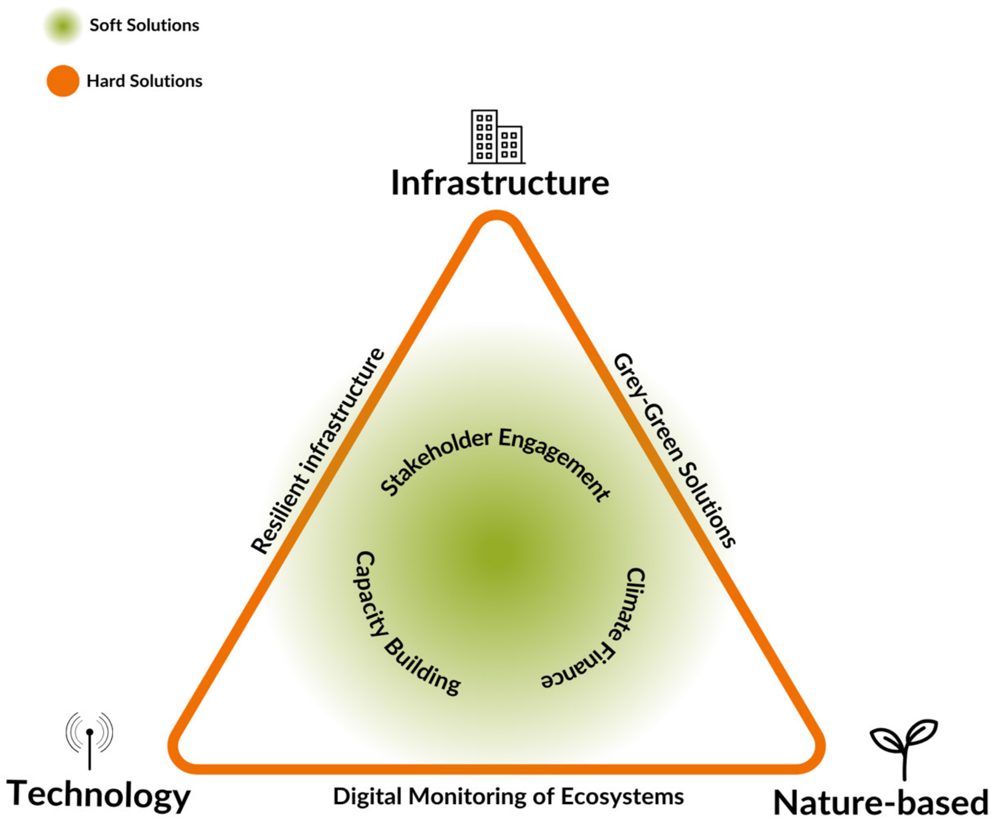


Figure 6 Adaptation goals can be achieved and enabled through a variety of interrelated and supporting solutions. Source: Authors of the report

3.1 Nature-based Solutions

Nature-based solutions (NbS) have the potential to promote both mitigation and adaptation at a relatively low cost compared to mechanical and engineered solutions, while promoting a host of co-benefits for humans and nature. For settings in rural and natural ecosystems, where there is less intense land-use pressure, NbS have a high potential for implementation and maximisation.

NbS rely on the services that natural systems provide to humans and nature. These services can take the form of improved water management, reduction of disaster risk, food production, biodiversity support, and carbon storage, to name a few. Often, the use of NbS promotes multiple services at once, working synergistically to enhance ecological and social outcomes. NbS can be implemented by protecting, managing, and restoring natural ecosystems, as well as creating hybrid solutions involving integration with traditional infrastructure, in 'green-grey' approaches. Below we introduce some examples of NbS and what benefits they may offer. While not exhaustive, these examples demonstrate how various ecosystem types in different geographies may be useful as climate solutions.

Forests

Forests are a common 'go-to' NbS, as there is widespread attention around their importance in storing carbon, providing habitat for wildlife, and filtering water, not to mention their role in supporting indigenous communities and national economies. Protection of existing forests is generally more effective than reforestation when it comes to carbon storage, biodiversity protection, and cost. However, there exists great potential for restoration of deforested lands, and reforestation can still provide cost-effective climate mitigation and adaptation. In the United States alone, there are approximately 60 million hectares of land available for reforestation, which could capture 535 million tonnes of CO2 per year. Reforestation can take the form of more active tree planting initiatives, or simply allowing trees to regrow in a process known as 'natural regrowth'. Natural regrowth may be particularly advantageous when resources are limited, as this method can reduce costs by 77%. Additionally, forests also reduce and prevent natural hazards, particularly in mountainous regions, making them effective tools in Ecosystem-based disaster risk reduction (Eco-DRR). In Mountainous regions, gravity-related hazards (i.e. landslides and avalanches) and flooding can be mitigated by healthy forest habitats, protecting low-lying areas at the base of the mountain.

In Brazil, where some 60% of the Amazon rainforest resides, forest conservation and management is crucial to protect biodiversity and maintain functioning ecosystem services. In 2002, the Amazon Region Protected Areas Program (ARPA) was established as the world's largest tropical-forest conservation initiative, with an initial goal of protecting 60 million hectares by the year 2039. The project was developed in a series of phases. Starting in 2003, phase I involved the creation of 23 million hectares of protected land. During phase II, from 2010-2017, additional existing protected areas were consolidated under the ARPA program. By 2017 the program had surpassed its initial conservation goal, at 60.8 million hectares of land under protected status. The program, which was launched by the Brazilian government and coordinated by the ministry for the Environment, incorporates both public and private funding from a variety of foundations and international NGOs. IN 2014, the Transition Fund was established, with a goal to gradually establish full public financing by 2039. In addition to large-scale conservation, biodiversity protection, and carbon sequestration, ARPA also offers local benefits to farmers and indigenous populations that rely on ecosystem services from the Amazon. Involvement of local governments, training local conservationists, and facilitating public-private partnerships have been attributed to the widespread success of the initiative.

Mangroves

Mangroves are powerful NbS, offering coastal protection, biodiversity support, contribution to local livelihoods and large carbon storage in the form of 'blue carbon'. Mangrove forests provide fishing stock for both local and indigenous people, as well as commercial fisheries. Mangroves also contribute to supporting local people and economies by protecting populations and assets from sea level rise, storms, and coastal erosion. In China, for example, mangrove forests are estimated to protect more than 8.5 billion USD in assets and more than 500,000 individuals during average annual storms. Due to high productivity of these ecosystems and low carbon turnover in waterlogged soils, mangrove ecosystems can sequester and store up to 5 times the amount of organic carbon as tropical upland forests, providing mitigation benefits.

In Djibouti, a joint program with the United Nations Environment Program (UNEP) worked to restore mangrove habitat and promote resilience to climate change. By combining hard infrastructure (levees, gabion walls, drip irrigation) with local mangrove species, the project employed a 'green-grey' approach to adaptation that was locally targeted. Additionally, local people were directly involved, through education, training, and employment. For example, local community members were hired to clear debris from mangrove habitats, manage mangrove nurseries, and plant mangroves. Local community members were also provided with fishing equipment and training on sustainable fishing practices. Cooperative fishing associations were established to improve knowledge on mangrove protection and fishing. Women benefited from direct involvement in a woman's fishing association, and by selling handicrafts as a result of eco-tourism. In addition to increasing income from fishing, the project resulted in more than 2,000 hectares of restored mangrove habitat and 800+ hectares of mangrove rehabilitation. The project reported that integration of the local community, understanding of on-the-ground conditions, and long-term planning were key to the success of the initiative.

Best Practice

Different types of ecosystems such as forests, wetlands and coral reefs, can work synergistically across a landscape, offering habitat connectivity and edge effects, supporting biodiversity and ecosystem services. Conservation of entire landscapes as opposed to single ecosystems can enhance NbS effectiveness.

Coral Reefs

Coral reefs are crucial habitats that provide coastal protection, habitat for wildlife, and opportunities for ecotourism and conservation. Similar to mangroves, coral reefs protect coastal communities by reducing wave energy by an average of 97%, protecting an estimated 100 million people. This protection holds both for low-frequency storms, and daily wave events, protecting against coastal erosion. In the United States alone, coral reefs are estimated to provide 1.8 billion USD in hazard risk reduction benefits annually. These habitats have been shown to be as effective as artificial wave attenuation structures, and in tropical environments, restoration of coral reefs is significantly cheaper than mechanical alternatives. Coral restoration involves a variety of approaches, such as growing coral off-site and replanting in reefs, increasing genetic diversity through artificial fertilisation, and providing structural support to protect against disturbances.

On the island of Guadeloupe, a Caribbean territory of France, the development of an ecologically designed mooring system aimed to protect local coral reefs, while providing infrastructure for boat docking. In the bay of Deshaies, a hotspot of marine biodiversity and conservation, boat anchors were causing mechanical disturbances to local coral reefs. A policy prohibiting anchoring was implemented in the bay and accompanied by the installment of eco-mooring devices, where boats could be alternatively secured. In addition to reducing mechanical disturbances, these eco-mooring devices were designed to replicate the natural conditions of local sites, attracting coral larvae to grow on the structures. A total of 40 mooring blocks were constructed and monitored to evaluate successful colonisation over time. After 6 years, the Bay of Deshaies saw return of coral and seagrass species, with more than half of the local coral species growing successfully established on the eco-mooring blocks, providing habitat for 43 species of fish. Notably, the eco-mooring devices survived the 17 meter high waves of super hurricane Irma in 2017, protecting most of the mooring-established corals. This success story highlights the possibility of integrating NbS with conservation policy and active restoration.

Despite innovative solutions, current coral restoration efforts are constrained by high costs, small scales, and low success rates. This is concerning especially when considering that coral reefs are especially vulnerable to human activity. According to CORDAP, over 60% of Earth's corals have already been lost, and 75%-90% of the remaining coral reefs could disappear in the next two decades. There is a need to increase research and development in coral reef restoration as well as to establish networks for knowledge sharing in restoration and conservation, as has been done in Florida, USA, and small islands in the South Pacific Islands. Since coral reefs provide high value to tourism and fishing industries, there are opportunities for these sectors to collaborate with restoration and conservation efforts. For example, in Fiji, a hotel resort partnering with the Reef Resilience Network sponsored the training of 15 local residents to become coral gardeners, eventually hiring two of the gardeners as full-time staff to work on local coral reef conservation.

Agricultural Nature-based Solutions

The integration of NbS into agricultural systems has the potential to reduce environmental tradeoffs associated with food-production while enhancing benefits to farmers. A variety of NbS have been utilized in agricultural production to improve carbon storage in soils, promote biodiversity, and enhance water management. One common agricultural NbS involves the integration of trees on farmland (agroforestry) and pasture (silvopasture). Particularly in the tropics, even small patches of trees integrated in pastures have been shown to significantly reduce local temperatures, which can limit the evaporation of water and protect cattle and farmworkers from hot temperatures. These trees provide additional co-benefits, such as habitat for wildlife, carbon sequestration and storage, and diversified tree crops for humans and livestock.

In Colombia, a silvopasture education program trained more than 4,000 farmers across 87 municipalities to promote silvopastoral practices. This involved planting trees and shrubs in and around pastures, as well as the establishment of 'conservation corridors' to promote wildlife conservation and habitat connectivity. Prior to this intervention, many farmers removed trees on their land due to the belief that they competed with production. However, as a result of these measures, farmers reported a 20% increase in beef and milk production alongside reduced fertiliser use. The results of this project have led to a reduction of 1.5 million tons of greenhouse gas emissions. Some farmers even received financial compensation for conservation efforts through a payment for ecosystem services (PES) scheme. In tropical regions, where land use conversion is driven largely by farmland expansion, agricultural NbS can play a significant role in promoting conservation and restoration while providing co-benefits to farmers.

Implementation and Prioritisation

NbS are promising solutions because, with proper implementation, they can deliver simultaneous climate adaptation and mitigation. At the global level, the most cost-effective terrestrial mitigation potential comes from forests (particularly tropical forests), followed by inland wetlands, then coastal wetlands, and grasslands. The 'natural climate solutions (NCS) hierarchy' complements this ecosystem hierarchy by prioritising protection of in-tact ecosystems first, followed by land management, and finally ecosystem restoration. This is largely due to the long-term carbon storage and high biodiversity found in existing ecosystems, which take much longer to establish in newly constructed ecosystems. Furthermore, the protection of longstanding ecosystems (particularly old-growth forests) offer the most co-benefits for biodiversity, local communities, and climate adaptation. Tools such as the interactive naturebase platform (figure 7), developed by the Nature Conservancy, provide emissions reductions potentials of various NbS for different countries, regions, and subregions.

Climate Benefit Estimate by Pathway (tonnes CO_2e/yr)

☐ Calculate totals across selected areas

Name ↑↓	China (940,246,000 ha) ↑↓	Brazil (852,303,000 ha) ↑↓
Increased Soil Carbon in Croplands	254,074,000	95,216,000
Reforestation	25,126,000	706,098,000

Climate Benefit Estimate by Pathway (tonnes CO_2e/yr)

☐ Calculate totals across selected areas

Name ↑↓	Sichuan Province (49,468,000 ha) ↑↓	Inner Mongolia Autonomous Region (114,446,000 ha) ↑↓	Heilongjiang Province (44,882,000 ha) ↑↓	Guangxi Zhuang Autonomous Region (24,771,000 ha) ↑↓
Avoided Peatland Conversion	4,379,000	4,768,000	2,172,000	0
Cropland-based Agroforestry	4,099,000	590,000	5,272,000	1,907,000
Grassland Restoration	1,695,000	15,686,000	399,000	0
Increased Soil Carbon in Croplands	16,168,000	10,177,000	30,720,000	7,403,000
Increased Soil Carbon in Grazing Lands	7,899,000	38,882,000	1,116,000	604,000
Reforestation	137,000	539,000	884,000	6,848,000

Figure 7. The naturebase platfrom allows users to compare different types of NbS and their climate mitigation potential across different countries and subnational levels.
Source: Naturbase.org

According to the naturebase platform, China and Brazil are the countries with the highest potential for emissions reductions using NbS. However, this potential varies depending on the type of NbS implemented. Furthermore, a comparison of the most promising regions for carbon sequestration in China (Sichuan, Inner Mongolia, Heilonjiang, and Guangxi) shows that potential varies based on ecosystem type (cropland, forest, peatland, grazing land) and intervention method (restoration, protection, or management).

While there are certainly optimal approaches and ecosystem types at the global level, the potential of NbS to deliver beneficial outcomes depends on local conditions, available resources, and capacity. Therefore, local understandings of ecology, land-use patterns, and socio-ecological systems should be considered before deciding on NbS to implement. In general, existing ecosystems in a particular region are highly adapted to local conditions, and the creation of new ecosystem types or introduction of new species can threaten the ecological health of a region. For example, mass reforestation based on monocultures of fast-growing trees may offer initially high carbon mitigation, but can harm local biodiversity, introduce new pests and disease, and reduce water storage capacity. Afforestation, particularly in high-latitude regions, can also lead to significantly reduced land surface albedo, causing increased temperatures and potentially outweighing the benefits of carbon assimilation.

Additionally, the 'natural climate solutions (NCS) hierarchy', which prioritises conservation over management and restoration, depends largely on the land-use conversion of a region. For example, in areas where deforestation is low, conservation may have limited potential as compared to improved management or restoration of ecosystems. As a result, the implementation of NbS is highly dependent on local conditions.

As solutions that depend on natural processes and ecological principles, the effectiveness of NbS vary depending on local-ecological contexts. A 'one size fits all' approach is not appropriate and may reduce the effectiveness of NbS or lead to maladaptation. Since NbS are specific and context-dependent, it is difficult to provide universal guidelines. However, there are some principles that attempt to address common shortcomings while also allowing for broad implementation and conceptualisation across regions and habitats.

Toolbox for Practitioners Nature-based Solutions		
Benefits: Relatively low cost, co-benefits for nature and society, mitigation potential	**Considerations:** Limited effectiveness under continued high emissions, understanding of local ecology required for successful implementation	**Policy Opportunities:** Species and landscape conservation Rural development planning Agricultural, forestry, and fishery management
Guiding Frameworks: IUCN Global Standard for Nature-based Solutions Natural Climate Solutions Hierarchy		
Supporting Tools and Data: Global Mangrove Watch – Access data on mangrove ecosystems worldwide Global Forest Watch – Explore forests and land use across the world Allen Coral Atlas – Find risk data for coral hotspots Nature-based Solutions Evidence Platform – Determine and compare benefits of NbS Naturebase – Evaluate natural climate solutions at national and subnational scales		
Communities of Practice: NetworkNature Reef Resilience Network The Mangrove Alliance IUCN CORDAP		

3.2 Digital Technology

Emerging technology can be a solution to climate risk, by providing up-to-date, data-driven and on-the-ground information and forecasts, leading to better ability to reduce hazards and impacts in real time. As technological innovation increases, there is opportunity to harness its capabilities for adaptation.

Early Warning Systems

One technological solution that is particularly promising are Early Warning Systems (EWS), which can mitigate risk by reducing exposure ahead of time. The United Nations Environment Programme (UNEP) reports that providing just 24 hours of notice of an impending hazard can reduce damages by 30%. Approximately 20% of disasters can be classified as 'multihazard', i.e. cascading and interacting hazard events that result in unique impacts. These multi-hazard disasters contribute 59% of global economic losses. Multi-Hazard Early Warning Systems (MHEWS), have been introduced to effectively streamline identification and warning for one or more hazards. At the 2022 UNFCCC COP27, the UN Secretary-General's established the Early Warnings for All Initiative (EW4All), which set forward a four-pillar approach to implementing MHEWS based on knowledge management, observation and forecasting, dissemination, and response preparation.

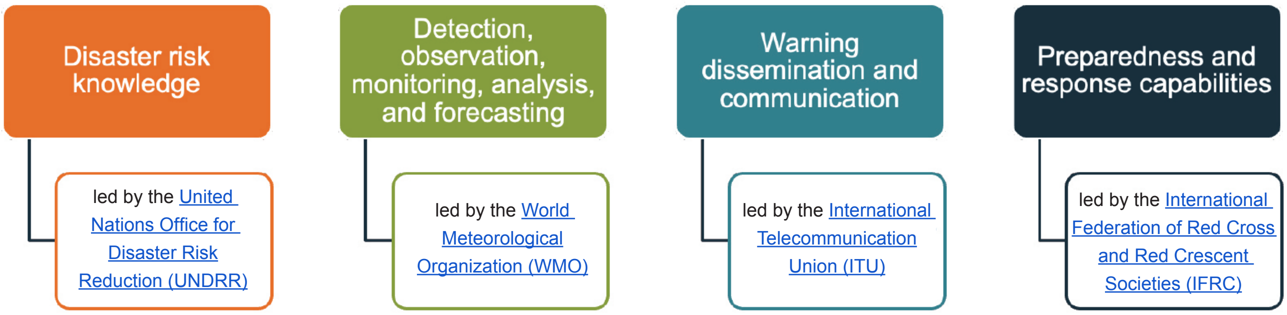


Fig 8: EW4All Framework

Source: Prepared by the authors based on EW4All

These four pillars are each overseen by an international governing body and must be coordinated across sectors and levels of governance in order to be fully effective. Furthermore, these MHEWS comprise 'end-to-end' services, starting with robust knowledge management and concluding with emergency response services. Integrated climate risk assessments play an important role in informing the risk knowledge management pillar by providing essential research on sectoral and geographic risk. Furthermore, many of the methods and data used to assess risk in the first place can also be incorporated in observing and forecasting hazards, providing a unique bridge between one-off risk assessment and continuous monitoring and forecasting.

While the first two pillars of the EW4All framework highlight the role and importance of data, knowledge, and preparedness, pillars 3-4 involve delivery of this information to relevant sectors alongside necessary support services. The EW4All urges that MHEWS must have a 'people centered approach' which is accessible and inclusive. Vulnerable groups (including women, rural and indigenous people, migrants, illiterate and people with disabilities) are at a higher risk during disasters and may have reduced ability to access or understand warnings and alerts. As a result, stakeholder involvement in the development of these systems can inform ways to better ensure their efficacy and access. Initial risk assessment should also consider underlying social vulnerability factors (such as literacy rates, access to internet and cellular service, primary language spoken, etc.) that may affect the uptake and success of MHEWS.

Monitoring rainfall and landslides in Peru

Peru is one of the most hazard-prone countries in the world, particularly affected by heavy rainfall, flooding, and mudslides in mountainous areas. In 2011, the NGO Practical Action partnered with the National University of Cusco to help monitor for conditions that would lead to mudslides, installing low-cost monitoring stations in mountains on the outskirts of Lima. These monitoring stations send near-continuous photos of water levels and soil saturation graphs to municipal authorities. In case of detected mudslides, community leaders are alerted via text message, who then can alert their community and begin evacuation. In addition to providing early warnings to rural communities, the project also developed small yet effective solutions to reduce the impacts of flooding, such as digging drainage ditches around key structures.

This approach, which integrated the community, local authorities, and research institutions, has allowed the region to better prepare for disaster. Additionally, the utilisation of low-cost methods such as 3D printing, solar-powered monitoring systems, and on-site electronic assemblage has allowed for the project to operate under relatively low cost.

Source: Practical Action

Agricultural Early Warning Systems

Besides informing human populations of impending hazards, EWS can also assist in management of assets and decision making across sectors. One sector of significance, particularly in developing countries, is agriculture, which is especially susceptible to drought. Unlike many other disasters, drought conditions can be forecasted on a longer time scale and larger geographical area, making ground measurements inadequate and untimely. Using satellite-based remote sensing data, the Food and Agriculture Organization of the United Nations (FAO), together with the Flemish Institute for Technological Research (VITO) and the Joint Research Centre of the European Commission developed the Agricultural Stress Index System (ASIS). The ASIS detects agricultural areas with a high likelihood of drought and water stress, providing hotspots of global concern every 10 days. Geospatial data is simplified into agricultural indicators that can be interpreted by agricultural stakeholders with limited technical knowledge and is open to the public. Past records are also provided since the year 1984. While the original ASIS provides global insights, country-specific platforms have been developed to provide more accurate results based on national data. These country-specific platforms can directly strengthen national EWS and inform policies around food-security, agricultural management, and economic impacts.

Emerging Technologies

The Internet of Things (IoT) is another technology that can provide solutions to reducing climate risk. This technology works by embedding physical objects and settings with sensors, which exchange data via the internet, allowing for real world processes to be digitally monitored. While there is overlap between IoT and EWS, allowing for unique opportunities to expand observations and forecasting, IoT goes beyond predicting hazards for early warning, but offers continuous data that can inform decision-making. Monitoring soils and plants in agricultural fields allows for more efficient resource use and avoiding loss of crops. In rainforests, the IoT has been used to pick up on the sounds of chainsaws, firearms, and vehicles, to identify and pinpoint illegal logging and poaching. In mangrove forests, IoT has been used to measure soil moisture, humidity, and temperature to help inform management decisions and quickly respond to threats. The IoT may be particularly useful in managing and monitoring rural and natural environments by covering vast areas where there is a lack of human resources available.

While IoT allows for continuous real-time data collection and monitoring, digital twin technology further utilises this data, creating a virtual replica of a real world object, setting, or process. Digital twins differ from traditional simulations and models in that they incorporate real-life changes and patterns, based on constant updates from their physical counterparts. The integration of real-time data with historical records allows a more realistic understanding of how systems operate.

Digital twins can be used to replicate, monitor, and assess ecosystems, habitats, agriculture, infrastructure, human settlements, water bodies, and farms, to name a few. The Digital Twin of Alps is a decision-support tool created to integrate multiple models with remote sensing to support water resource management and disaster risk management. Furthermore, the project provides a roadmap for the development of future digital twins of the Alps region. The European Commission has developed Destination Earth, a flagship digital twin of the Earth system, which provides insight into land, marine, atmosphere, biosphere and anthropogenic processes. The European Commission is also developing a Digital Twin Ocean, which will provide greater insight into ocean processes, which will be further integrated into the Destination Earth platform. Digital twins are also being considered for evaluating and monitoring NbS. For example, a digital twin framework has been developed for seagrass NbS in reducing storm surges. Although research in this field is nascent, utilising digital twins for NbS may be particularly valuable, as they can more accurately evaluate the inherently dynamic processes of natural systems.

Artificial Intelligence

A cross-cutting technology that has garnered increased attention is Artificial Intelligence (AI). With the ability to simulate human learning, comprehension, problem solving, decision making, creativity and autonomy, AI can more effectively and quickly make sense of climate risk data in various contexts while providing recommendations and solutions. Financial institutions, for example, have already made use of AI in climate risk analysis. The Bank for International Settlements (BIS) developed Project Gaia in order to standardise and coordinate vast amounts of climate risk data across various reporting frameworks and regions. As a result, the once-difficult process of comparing assessments across different jurisdictions and frameworks has been streamlined for financial analysts to better understand climate risk in the financial system.

One application of AI technology is Machine Learning (ML), which allows models to understand complex patterns and learn from it. ML is useful in modelling habitats, ecosystems, and natural processes by making sense of complex non-linear and multivariate datasets. This may be particularly relevant when trying to understand normally unpredictable processes or hazards. For example, wildfire is a multi-factor process, dependent on a range of local and climatic conditions. To account for the various factors influencing fire development, the European Centre for Medium-Range Weather Forecasts (ECMWF) developed a fire-prediction model called Probability of Fire (PoF) in order to better forecast wildfires. As a relatively low-cost and high-resolution (1 km) model, PoF provides warnings of fire outbreaks up to 10 days prior, on a global scale. The model was developed by using ML to analyse vast amounts of historic satellite imagery, which would otherwise be difficult for scientists to accomplish by themselves. The ECMWF utilises the PoF to provide fire predictions for a variety of regions around the world. Conservation efforts can also benefit from ML approaches. A study to understand the future habitat distribution of a local bird species in Utah, United States, relied on ML to integrate climate projections with species distribution modelling (SDM). Researchers found that the coupling of SDM with ML could effectively predict future wildlife implications, and better inform current conservation measures.

Considerations for Technical Solutions

As with NbS, a variety of approaches and methods can work synergistically to improve the efficacy and co-benefits of technological solutions. For example, monitoring of ecosystems required in MHEWS can be integrated with IoT. The coupling of real-time data from IoT with analysis of past historical records using ML may foster new insights and understanding of natural systems and processes. These insights can then be used in models and digital twins to allow analysis of various policy and management options under current and future conditions. Furthermore, AI can then be used to understand and evaluate solutions. Together, these technologies can underpin and strengthen useful applications for disaster and resource management, such as MHEWS and agricultural EWS. In China, a digital twin of the Yangtze River has been developed to model the entirety of the river basin, including weather, ecology, shipping, and flooding. With data sourced from some 2,700 water-level monitoring stations, 37,000 rainfall stations, and hydropower monitoring sites, the digital twin integrates various sectors and facilitates collaboration. With relevant insights all in one place, stakeholders can make decisions, develop early warning systems, and conduct contingency planning.

Technological solutions are accompanied by important ethical and security questions. For example, open data sharing is complicated by the need to protect private personal data, which is typically governed by national and regional policies and can vary across jurisdictions. Furthermore, the use of emerging technologies, such as AI, can come with concerns about environmental impacts, such as massive energy and water consumption in the development and running of its models. It is essential to ensure that technology-based solutions are developed, operated, and decommissioned sustainably and ethically. Additionally, it is recommended to consider the cost-benefit of a particular technology and whether or not its use will have a net positive impact on climate change mitigation and adaptation.

Toolbox for Practitioners

Digital Technology

Benefits:	Considerations:	Policy Opportunities:
Provides up-to-date information and guidance, data-driven insights	Ethical, environmental, and legal consideration required, importance of cooperation, data sharing, and involvement of vulnerable groups	Innovation, research & development Disaster response Education and training Data management & governance

Guiding Frameworks:

UNDRR EW4ALL

Common Alerting Protocol

Supporting Tools and Data:

FAO Agircultural Stress Index System – detect global drought areas every 10 days

Destination Earth Digital Twin – monitor the Earth system and environmental change

WhatNow Message Portal – access a platform for early warning messages and dissemination

Communities of Practice:

The International Federation of Red Cross and Red Crescent Societies (IFRC)

IoT Community

3.3 Infrastructure and Energy

Climate change threatens energy systems and built infrastructure through long-term continuous exposure (such as increased temperatures, and sea-level rise) and sudden hazards (cyclones, floods, wildfire). Since human populations rely on infrastructure for essential services (health, energy, sanitation, transport, communications), disruptions to these systems can lead to cascading risks far beyond the initial impact. An analysis of more than 700 hazard events across 30 countries found that cascading failures to infrastructure accounted for 64-89% of service disruption, spreading the impact to regions beyond the initial hazard in 75% of cases. As a result, disruption to essential services surpassed physical impacts by a factor of 10. Furthermore, the building, operation, maintenance and eventual decommissioning of infrastructure is responsible for 79% of all greenhouse gas emissions (namely in the energy, buildings, and transportation sectors). Infrastructure also comprises 88% of forecasted adaptation costs, largely in the water sector. As a result, there is great opportunity to proactively address mitigation and adaptation by strategically developing infrastructure under a climate risk management framework.

Low-Carbon Climate Resilient Infrastructure

Low-Carbon Climate-Resilient Infrastructure (LCCRI) is an approach to reconcile both the high emissions and vulnerability of the infrastructure sector, delivering win-win solutions that contribute to sustainable development. One example of LCCRI is public transportation that is resilient to future climate impacts (such as flooding). Investment in public transportation can improve development by providing affordable and reliable service to the population, while also reducing emissions and pollution associated with individual car use.

For natural environments, agriculture, and rural settings, certain LCCRI may provide unique opportunities to mitigate risks, protect natural assets, and support local communities. In coastal areas, measures such as breakwaters and seawalls have been used to protect shorelines from tides and storm surges. Dikes and levees are structures used to protect land against flooding and water intrusion. In cities at or below sea level, such as Miami, USA, a multi-pronged approach has been implemented to strengthen flood-prone areas. The reconstruction of roads and buildings on higher land has been coupled with a robust system of canals, sewers, and water pumps to reduce the impacts of extreme precipitation, storm surges, and sea level rise.

Green-Grey Solutions

There is a great opportunity to combine traditional built infrastructure with NbS to create hybrid 'green-grey' approaches. These approaches often deliver similar co-benefits associated with traditional NbS, while providing an extra level of mechanical protection against natural hazards. Taking the combination of mangrove and seawall implementation as an example, can illustrate the synergies of both approaches. As mentioned previously, mangroves provide extensive protection to coastal areas, specifically by buffering storm surges, waves, and wind. However, by themselves and in extreme situations, mangroves may be insufficient, with most benefits coming from large areas of fully-grown mangrove forests that may take a long time to establish. Built infrastructures such as seawalls, on the other hand, can provide immediate protection, but have high maintenance costs and lose effectiveness over time. In Guyana, coastal mangrove forests were found to significantly attenuate wave height, reducing the required height of coastal sea walls, and thereby reducing overall building costs. To establish habitat and encourage further mangrove growth, additional low-tech infrastructure, such as permeable sediment-trapping units made from locally available bamboo, were built. This additional infrastructure to facilitate mud-bank formation also contributed to wave attenuation, highlighting further co-benefits between grey and green approaches. In fact, coupled green-grey approaches may offer more effective and affordable approaches, especially when considering the entirety of the life-cycle. One study found that a hybrid approach could save 94% of life cycle costs associated with

Best Practice

Integrating NbS into traditional infrastructure may provide long-term savings and additional co-benefits. When developing interventions, do a cost-benefit comparison between grey-green solutions and traditional infrastructure, considering multiple payback horizons.

traditional grey infrastructure.Another study done on green-grey solutions in a residential neighborhood of Nanjing, China found that the payback period for a green-grey runoff system could significantly be reduced from 4 years, to less than 1 year with the presence of green building subsidies. The World Resources Institute put out a guide detailing how to assess the cost and benefits of green and grey infrastructure for water supply systems.

Renewable Energy and Decarbonisation

Naturally, the single most important way to reduce climate risk is to eliminate greenhouse gas emissions, and drastically develop renewable energy capacity. Renewable energy will play a key role in contributing to sustainable development while limiting climate impacts. This should be accomplished alongside a variety of technological developments that will aid in this transition, such as improving energy efficiency, modernising energy grid infrastructure, developing energy storage technologies, and exploring clean fuel sources for sectors that can not be electrified.

The large amount of energy required to offset fossil fuels will require an expansion of renewable energy infrastructure in different settings, requiring dedicated land use particularly in areas that are more rural and less desired for other land uses (such as urban settings and prime agricultural land). Existing energy technologies such as wind, solar, hydroelectric, and geothermal are promising solutions in different contexts. For example, wind energy is effective in areas with consistently windy conditions, and geothermal energy is only currently feasible in locations where geothermal reservoirs are easily accessed. Future conditions may change the availability of certain natural characteristics that make an area favorable for energy production. One such example of this is hydropower.

The prevalence of drought and the melting of ice and glaciers, particularly in mountainous regions, may alter current hydropower systems and management. In Switzerland, for example, Alpine hydropower production relies on glaciers that are increasingly vulnerable to climate change. Under continued warming, current hydropower production in Switzerland is expected to fall by 1.0 TWh yr−1 by mid-century. However, changes to hydropower production vary by context. In some regions, increased melt could lead to greater hydropower potential, requiring proactive adaptation to future conditions.

Case Study: Hydropower in Iceland

Almost three quarters of Iceland's electricity comes from hydropower. Due to melting glaciers, the amount of water inflow is expected to increase by 15% by mid-century and then decrease to 1990s levels by the year 2080. In order to fully utilise the additional inflow, existing infrastructure would need to be retrofitted to increase hydroelectric turbine capacity as well as reservoir storage. The national power company of Iceland along with a consortium of Nordic research institutions worked to produce hydrological models to project future water flow under climate change. These modelling results, which are amended every 5 years to account for updated climate developments, form the basis of reservoir management. Furthermore, they also contribute to the building of new hydropower infrastructure and retrofitting of existing plants.

Already, modelling results informed the increased capacity of the Búrfell Hydropower Plant from 70 MW to 100 MW. Similarly, the Búðarháls plant was increased from 80 mW to 95 MW. The success of this project has been attributed to strong cooperation with other power companies and institutions as well as consistent calibration of hydrological models based on monitoring results.

Source: Landsvirkjun

A review of the threats facing hydroelectric power considered major regions of significance across the globe. They found that climate change will impact hydropower capacity differently based on locality. The region of Northeast Asia, for example, in which most hydroelectric plants are located along the Yangtze and Yellow river, is expected to experience future changes due to melting glaciers, while the impacts of altered precipitation are not yet clear. They note that in Northeast Asia, additional runoff volume can likely be managed through adjusted reservoir management, although anthropogenic factors may also reduce water volume.

Addressing Land-Use Conflicts

There is great concern that new renewable energy projects will require large amounts of land (particularly for photovoltaic and wind energy), which may threaten existing habitats. This contradiction between conservation and energy production is concerning, considering that both conservation and renewable energy are essential mitigators of emissions. However, this contradiction can be reconciled by following best practices on renewable energy development, such as choosing ecologically-degraded sites and avoiding regions of high ecological significance. Increasingly, international efforts are being undertaken in order to facilitate dialogue between conservationists and renewable energy advocates. In 2015 the UN Convention on Migratory Species established an energy task force in order to align best practices and facilitate stakeholder dialogue. Tools such as The Nature Conservancy's Site Renewables Right Tool, and AviStep, highlight the importance of ecologically-informed site planning for renewable energy.

Ecovoltaics

In some cases, renewable energy production can be integrated into ecological systems. Ecovoltaic systems utilise solar panels to provide shade and cooling to vegetation growing beneath, reducing evapotranspiration and promoting habitat for biodiversity. These systems can also be integrated with agricultural systems to provide enhanced grazing and crop growing opportunities. This is the case for the Big Lake agrivoltaics project located in Minnesota, USA, where an array of solar panels are spaced out on farmland. The panels provide a megawatt of clean electricity while shade-tolerant crops and honeybees grow below. The farm is managed to involve community members and provide training to emerging farmers, who produce vegetables and honey.

Big Lake is one of the many agrivoltaic projects that the Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) project is studying. In order to facilitate greater research and policy implementation in this field, InSPIRE has compiled case studies and data for various agrivoltaic systems around the world.

Source: Great Plains Institute 2024

Win-win solutions that integrate solar power generation into local ecology or natural assets (such as irrigation and agricultural landscapes) may offer a host of co-benefits for agriculture, biodiversity, and water management. In particular, the use of solar panels as a physical barrier to prevent excess heat and evapotranspiration for canals, plants, and grazing animals, could play an important role for agriculture and water sectors in the future and be seen as an adaptation measure. However, as with all solutions, the efficacy of this type of approach depends heavily on local conditions and ecology.

Over-canal solar

Another example of solar generation that reduces land-use pressure is over-canal solar. This approach involves mounting solar panels over waterways and irrigation canals. Here, solar panels provide shade and evaporative control, reducing water loss and algae growth. Conversely, the water below cools solar panels which improves overall efficiency. Over-canal solar was first piloted by the Indian state of Gujarat in an attempt to bring electricity to rural farms lying along irrigation networks. Currently, the idea is being replicated for the more than 6400 kilometers of canals across California, USA. A feasibility study found that the financial benefit of water savings, improved panel efficiency, and avoided aquatic weed mitigation outweighed the additional cost of suspending panels above the water. In fact, the net present value of over-canal solar exceeded conventional panel installation by 20-50%.

The innovative approach of integrating solar power over canals demonstrates a unique opportunity to address adaptation at the nexus of energy and water infrastructure, especially considering that water-related adaptation costs are expected to be some of the highest of all infrastructure types.

Source: UC Merced 2021

Researchers have established an ‘Ecovoltaics’ framework, in an attempt to reconcile solar power infrastructure with ecosystem conservation. This approach relies on 5 pillars to ensure that a net-positive outcome for biodiversity is achieved, focusing on properly siting, designing, and managing park sites with a wide range of stakeholder and ecological input.

Toolbox for Practitioners

Infrastructure and Energy

Benefits:	Considerations:	Policy Opportunities:
Mitigation potential, co-benefits for economic and social development	Biodiversity and conservation considerations	Infrastructure planning Energy subsidies Land-use and development Industrial policy

Guiding Frameworks:

IUCN Guidelines on Mitigating biodiversity impacts associated with solar and wind energy development

Ecovoltaics framework

Practical Guide to Implementing Green-Gray Infrastructure

Supporting Tools and Data:

Site Renewable Right – determine biodiversity-safe areas for renewables in North America

AVISTEP – plan energy projects with consideration of bird habitat (select geographies)

Coastal green-gray cost-benefit analysis tool – compare costs and benefits of green-gray adaptation

InSPIRE data portal – Access datasets and case studies for agrivoltaics across the U.S

Communities of Practice:

Global green-gray community of practice

Green-gray infrastructure accelerator (Sub-Saharan Africa)

3.4 Adaptive Capacity

So far we have seen examples of various technical approaches to mitigate climate risk. However, managing climate risk also entails ‘soft’ approaches that reduce vulnerability by increasing knowledge, providing resources for adaptation, and more effectively utilising financial opportunities. According to the UNEP’s 2024 Adaptation Gap Report, there is a bias in adaptation efforts towards ‘hard’ approaches, leaving key enabling factors under utilised. These solutions typically rely on utilising behavior changes, policy, and financial mechanisms to promote and facilitate adaptation.

Education and Capacity Development

Despite best efforts to mitigate climate risk through technical solutions, unavoidable impacts will persist, affecting and altering organisations, sectors, populations, and individuals. These impacts may alter livelihoods, health outcomes, social cohesion, and interactions with the natural world. There is a need to raise awareness about the impacts of climate change both through public awareness campaigns and targeted messaging for at-risk populations and sectors, paying close attention to how these impacts will affect essential processes for health, safety, and livelihoods. Under the Paris Agreement, the UNFCCC includes Action for Climate Empowerment (ACE) which outlines climate education and public awareness as key elements.

In addition to raising awareness, affected groups and organisations will need to be provided with the tools, knowledge, opportunities, and resources to respond to these impacts in a process known as capacity building. Capacity building can take many forms, such as formalised education (mostly through schools and universities), specialised trainings (such as courses and webinars), networking opportunities (workshops, sharing platforms, and other means of knowledge sharing), technical assistance (such as the EU's 'Twinning' instrument) and, in cases of high risk and low capacity groups, direct intervention and assistance (often through aid and development).

Women in the informal sector, India

The Self Employed Women's Association (SEWA) is a trade union supporting low-income and self-employed women across India. More than 3 million informally-employed women are members, with the majority working in agriculture as smallholder farmers, sharecroppers, and agricultural labourers. With increasing climate hazards such as monsoons and drought and limited social safety and financial protections, many informal agricultural workers have had to bear the costs of climate change. SEWA's Agriculture Campaign works to reduce vulnerability and build resilience among rural women. SEWA has initiated a program to develop "Green Technicians", with the goal of disseminating sustainable practices to more than a million households. Some of these initiatives include developing composting businesses to create additional income for women and promote sustainable farming practices, establishing tool and equipment libraries, educating farmers on agricultural risk and the need for rainfall insurance, and installing solar-powered water pumps and irrigation, saving water and energy.

Recently, SEWA created a 'Climate School', which educates members about climate change, specifically targeting scientific terms and concepts to those who have limited formal education. The Climate School trained 28 educators to disseminate the curriculum to women in rural villages and propose innovative solutions, access finance, and implement solutions. As a result of this process, adaptation to climate change can be effectively disseminated to those who lack formal education, employment, and access to traditional legal and financial mechanisms.

Source: Coady Institute 2023

Increasingly, capacity development efforts are being scaled up and made freely accessible to the public, regardless of geography. Online, self-paced, and free educational courses are available through platforms such as UNCC e-learn, and the SDG academy, with courses ranging from adaptation policy, NbS, and climate finance. Targeted courses for specific sectors, such as GIZ's series on Climate Smart Agribusiness can be particularly useful for entrepreneurs to better integrate risk into their enterprises. In addition to online courses, the UNFCCC Capacity-Building Portal provides a centralised location for various resources to be shared, including case-studies, webinars, projects, and tools. The platform allows for further selection based on specific topic, geographical region, country and language. Similarly, the UN Climate Technology Centre & Network (CTCN) provides a platform for technology transfer, technical assistance, and international collaboration tailored to the needs of individual countries. These technical solutions cover multiple sectors including forestry, water, EWS, agriculture, and carbon fixation, to name a few.

Intergovernmental policy processes, largely instigated by the UNFCCC, allow for collaboration and international capacity building. The Rio Conventions Joint Capacity-building Programme is a joint initiative by the secretariats of the UNFCCC, the CBD, and the United Nations Convention to Combat Desertification (UNCCD) working to enhance synergies and strengthen collaboration in sustainable land management, nature conservation, and climate action. The programme regularly publishes resources and guidance to build capacity across nature and climate-focused sectors, with a particular focus on finance, policy making, and implementation. The Paris Committee on Capacity-building (PCCB) network is a coalition of 413 members representing climate-focused stakeholders across the globe. With representation from NGOs, academia, intergovernmental organisations and the private sector, the PCCB network fosters collaboration and coordinates best practices in capacity building. For youth, the UNFCCC and the Italian Ministry of Environment and Energy Security support the Youth4Capacity programme, which contributes to youth capacity development around the world through mentorship, skill development, certification, and workshops.

In some cases, capacity building activities for local populations in rural and remote areas, who may be at higher risk of climate-related hazards, have win-win outcomes for risk reduction. Involving local populations in data collection, for example, has been shown to raise awareness of risk-prone areas, and contribute to increased assimilation of risk reduction practices. At the same time, on-the-ground populations fill in critical data gaps for EWS, climate services, and risk assessment.

Specialised training and education programs should be coordinated across different levels of government, by the private sector, and among civil society in order to develop a long-term and robust workforce that is equipped to implement adaptation over the coming years. This is particularly important for emerging solutions that will need to be scaled up to meet adaptation and sustainable development goals. One example of this is the implementation of green-grey NbS, which will require significant development of specialised technical and vocational education and training (TVET) in engineering, conservation, and finance. The ILO has developed the 'Greening TVET and skills development: A practical guidance tool' in order to provide guidance on adjusting curricula, training, and education to be more climate-focused. Notably, this tool is intended to develop green skills across all sectors, including traditionally underrepresented workforces such as the informal economy.

Best Practice

Capacity development, training, and education of local populations can support adaptation efforts by fostering relevant skills and knowledge among the workforce. Involving people who are informally employed and/or have limited economic opportunities can contribute to improved economic stability and development.

Finance

There are many financial tools available that address climate risk and capacity building actions related to the natural environment. From the largest global tools such as the Green Climate Fund to country-, region- and topic-specific ones. Debt restructuring, market-based investment, insurance & risk transfer instruments and concessional finance are some of the main typologies.

Especially relevant for most countries in need of financial aid for climate action are grants or non-reimbursable finance, concessional finance and similar instruments with characteristics that differ from the typical loans found in the market. Platforms, programmes and funds like the Climate Finance Lab (CFL), the Green Climate Fund (GCF), the Global Environmental Facility (GEF) and instruments at UNDP and UNEP. The GCF alone has provided USD 16.7 billion in financing for 297 projects in 133 developing countries to date.

Debt-for-Climate swaps (DfCS) are a particularly relevant typology for the natural environment. In such schemes, creditor and debtor countries agree on implementing specific climate change-related projects either in mitigation or adaptation in exchange for sovereign debt relief. Once implementation has successfully occurred, the debt is considered paid (Bundesministerium für wissenschaftliche Zusammenarbeit und Entwicklung, 2023). In many cases, conditions of DfCS include the use of certain areas which provide global climate services, only under strict environmental standards or even the prevention of certain activities like fossil fuels extraction at all. Similar mechanisms, focused on the protection of the local environment or whose underlying rationale do not include climate action, are called Debt-for-Nature swaps (DfNS) such as the Ecuador Galapagos Islands debt swap.

Climate events impact the overall sovereign risk of countries by affecting both the real economy and financial markets. Loss of income, costs of adaptation, rebuilding and other effects are to be expected. Therefore, it is important to understand how climate risks, both physical and transitional affect sovereign risk. Figure 9 contains a scheme to illustrate the relations between these elements.

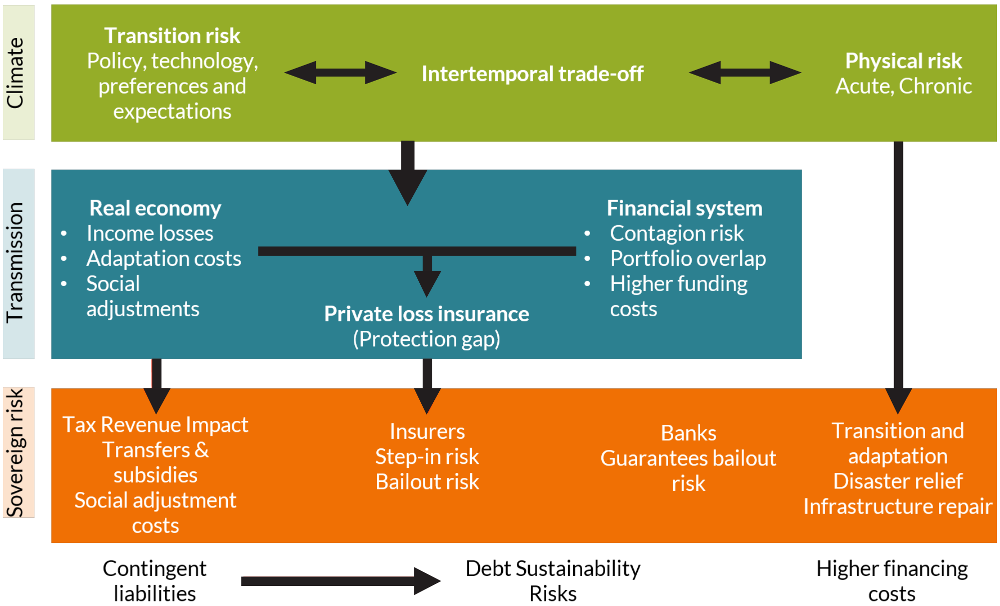


Fig. 9. Climate impacts and sovereign risk

Source: Authors of the report, modified from European Central Bank (2025)

In terms of risk management focused on the natural environment, insurance instruments play an important role. Parametric or index-based insurances are activated when a certain threshold of a parameter is reached (earthquake's magnitude, wind speed during a hurricane, water level during a river flood, etc.). If applied at a national or regional level, it may be found under the term of sovereign risk insurance. Trust funds such as the Global Index Insurance Facility (GIIF), managed by the International Finance Corporation (IFC) section of the World Bank, promote index-based insurance and provide risk transfer solutions in developing countries. It has facilitated about USD 2 billion insured in over 13 million contracts, benefiting 65 million people so far (Global Index Insurance Facility (GIIF). Overview, 2025).

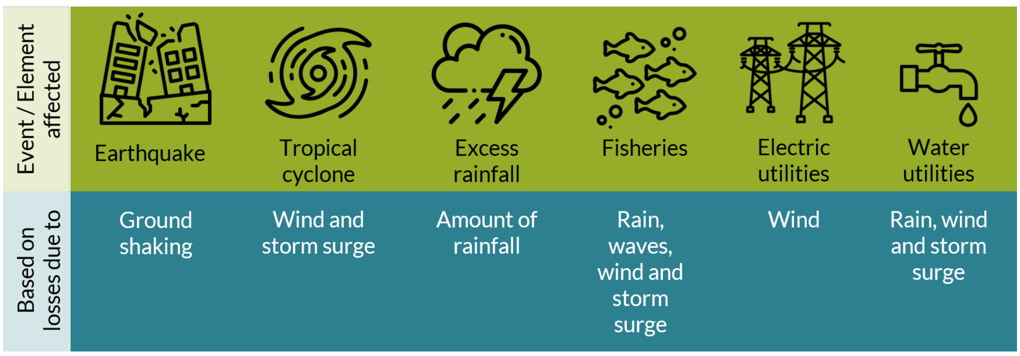


Fig. 10. Events, elements and parameters considered by CCRIF for parametric insurance products

Source: Authors of this report, modified from The Caribbean Catastrophe Risk Insurance Facility (2025)

Sources of graphic info (icons): Culmbio, Freepik, Iyikon, Konkapp, Rabit Jes, Smashicons; at Flaticon.

Countries like Peru offer public agricultural insurances that cover in part or whole damages to crops. It explicitly mentions climate and natural risks such as hailstorms, fires, floods, volcanic eruptions, strong winds and landslides (Seguro Agrícola Catastrófico (SAC)). Considering that the sector absorbs approximately 26% of climate-related disaster impacts in Low Development Countries (LDC) and Low-Middle Income Countries (LMIC) (Climate Risks in the Agricultural Sector) it is indispensable that institutions implement adaptation and mitigation measures to also guarantee the financial resilience of agricultural communities.

Private insurance plays an important role in regions like Europe. Weather insurance in European crop and horticulture production identified 107 insurance products by 48 different providers in Austria, France, Germany, Italy, Spain and Switzerland. European insurance markets, levels of political interventions like premium subsidies and product coverage tend to be highly heterogeneous. The authors highlight the level of market regulation, the coverage of systemic and non-systemic risks such as drought and heat; and frost and heavy precipitation, respectively. In regions particularly prone to extreme events such as California, insurance costs have increased dramatically forcing farmers to quit and providers to drop their clients (Climate Risks in the Agricultural Sector) increasing the vulnerability of the agricultural sector.

One example of institutions focused on financial risk management from climate events is the Caribbean Catastrophe Risk Insurance Facility (CCRIF). Developed with a grant from the Government of Japan and under the leadership of the World Bank, it consists of a multi-donor trust fund including contributions from the World Bank, the Caribbean Development Bank, the EU and the Governments of Canada, the UK, France, Ireland, Germany, Mexico and Bermuda. CCRIF aims to provide financing for Caribbean countries to make their national social protection systems shock responsive and offers parametric insurance products, services and tools tailored to the needs of its members (The Caribbean Catastrophe Risk Insurance Facility, 2025b).

Capacity Development and Finance at the Local Level

Since adaptation is inherently a context-specific process, local governance plays a key role in mediating top-down policies, funding, and strategies to local communities. On the other hand, national governments can support this process by providing much needed financing, capacity and technical assistance to local actors.

The UN Capital Development Fund (UNCDF) Local Climate Adaptive Living Facility (LoCAL) helps local governments in developing countries to access funding for adaptation. This is largely accomplished through performance-based climate resilience grants (PBCRGs), which provide funding that is channeled through national treasuries and overseen by national ministries. These grants are typically subject to audits and must meet key performance standards, such as capacity development and training for local governments, and integration of adaptation into local development plans.

In Lesotho, LoCAL initiatives have delivered a total of 7 water supply systems, servicing 4,900 local residents. Workshops targeting local government officials have helped build on-the-ground capacity, inform stakeholders about sustainable water management, and train participants to access grant funding. Today, LoCAL works in 38 countries, helping to establish locally led adaptation practices and bridging the gap between international climate finance and local capacity.

Source: UNCDF 2024

Toolbox for Practitioners

Adaptive Capacity

Benefits:	Considerations:	Policy Opportunities:
Often underutilised, enables the success of other solutions	Important to avoid unidirectional and ineffective knowledge transfer	Education, training, & skills Debt repayment local financing

Guiding Frameworks:

Action for Climate Empowerment

Greening TVET and skills development: A practical guidance tool

Supporting Tools and Data:

UNCC: e-learn – Access open online courses on climate change

SDG Academy – Access open online courses on SDGs

Communities of Practice:

Global green-gray community of practice

Green-gray infrastructure accelerator (Sub-Saharan Africa)

4 Recommendations and Best Practices

4 Recommendations and Best Practices

There is an urgent need to increase capacity for climate adaptation across sectors, regions, and projects. Here we provide general best practices and guidance which can be used to develop a roadmap for risk reduction.

4.1 Risk Assessment

The foundation of effective adaptation planning depends on robust risk assessment, which provides a framework for intervention, explaining why and how solutions should be implemented. Risk assessment can be considered the first 'stepping stone' in risk management and adaptation planning.

4.1.1 Setting the Scene - Beginning a Risk Assessment

context and scope at hand. This includes considering the geographical area or natural system studied, the time frame, and the components of the system (i.e. are there impacts on local populations, economy, wildlife, etc.). In general, a holistic approach should be taken, considering ecosystems as a whole, as opposed to a single species, for example. After establishing the temporal, geographical, and sectoral boundaries, the current state of knowledge should be assessed, including the availability of relevant data sources, stakeholder mapping, uncertainties and knowledge gaps.

In order to produce relevant and timely analyses that inform public policy and decision making in climate issues, data quality is pivotal. In this sense, it is important to resort to the best available information from reputable sources. The following is a non-exhaustive list of resources of primary and secondary data from different fields of climate science.

Regarding comprehensive sources of information about multiple aspects of climate change, the Assessment Reports (AR) of the Intergovernmental Panel on Climate Change (IPCC) are the gold-standard reference. They constitute a compendium of the best science available and present exhaustive summaries for policymakers, glossaries and other appendixes aimed to facilitate their use and understanding. The upcoming IPCC AR7 will also include risk assessment in the Working Group II report as agreed in the outline by governments.

Specifically for climate and weather, the World Climate Research Programme (WCRP), an international climate research coordination programme sponsored by the WMO, the ICSU and UNESCO's IOC is a good source of publications and tools related to climate research. WCRP also has an online academy that offers open training in diverse areas such as climate risk, modelling, education and country-specific trends, among others.

It is important to highlight that regional and local assessments and decision making cannot solely rely on global data. Differences in spatial and temporal resolutions between scales entail added uncertainty since top-down sensors usually compromise between coverage and detail. This uncertainty may not be easily decreased, if at all. Therefore, in an ideal scenario, this information is always used along high-quality local data series to provide robustness and validity to the models and projections of interest.

Beginning a risk assessment

Checklist:

- Establish the intended context, setting, and scope of the assessment
- Evaluate local needs, capabilities, and expected outcomes
- Conduct background research on your context
- Establish a team
- Find and assess relevant data

Background Information Sources:	Collaboration Opportunities:	Data Sources:
Intergovernmental Panel on Climate Change IPBES UNFCCC Chinese Academy of Sciences	Universities and research institutions Government agencies NGOs and development agencies	IPCC Data Distribution Center – climate, socio-economic and environmental data and scenarios used in IPCC outputs Climate Change Knowledge Portal – historical and future climate, vulnerabilities, and impacts Aquastat – country statistics, focused on water resources, water uses and agricultural water management NOAA OneStop – Ocean and atmospheric datasets

Considerations:

- Is data spatial and temporal resolution sufficient for your scale?
- Has similar work already been completed?
- Which stakeholder groups will provide relevant contribution?

4.1.2 Methods

A formal risk assessment draws upon and synthesises different types of data in order to quantify risk, incorporating vulnerability, exposure, and hazard. A variety of methodologies can be used and integrated, enhancing the reliability and complexity of the assessment.

Qualitative Methods

There are cases in which the underlying systems considered are too complex and/or lacking in data, that quantitative and modelling approaches will not be realistic. In such cases, risk can still be assessed through qualitative and conceptual approaches, which incorporate diverse stakeholder and sectoral input, and consideration of theoretical implications and interactions.

Case studies provide examples of real-world impacts in specific contexts, sectors, and locations. Historical cases often highlight worst-case scenarios, setting a baseline that should be avoided in the future. Typically, these case studies highlight particular vulnerabilities and weaknesses that contribute to heightened risk. One example of a case study that is widely used as the basis for risk assessment was the 2003 French heatwave, which broke records and led to the deaths of thousands of people. The heatwave highlighted systemic vulnerabilities and exposure as well as opportunities for robust adaptation policy. By 2004, France had initiated a national heatwave plan with the aim of reducing future risk. One benefit of case studies is that instead of describing theoretical risk, they highlight tangible stories that are easily communicated to the public, potentially increasing general awareness and participation.

Focus groups involving a wide range of stakeholders, community leaders, and experts can help to provide insight into particular climate risks, highlighting vulnerabilities, observations, and human behavior patterns that are otherwise difficult to obtain. For example, farmers can help to explain direct weather observations that they have noticed over time as well as how they respond. This approach helps to ground risk in a local context, ensuring that solutions are appropriate and well-received by the population. Focus groups can also develop long-term relationships with various groups, opening up opportunities for further collaboration, data sharing, and dissemination of findings.

Self-assessments and risk classification encourage sectoral experts, decision makers, and researchers to reflect on worst-case scenarios, impacts, and outcomes. These approaches allow for climate risk researchers to standardise research through predetermined investigative questions while obtaining expert insight. In turn, experts are asked to reflect on their own vulnerabilities to risk, making them more receptive to risk-reduction solutions and interventions. The World Bank (WB) provides a free interactive Assessment Tool, which can be filled out by practitioners to create a custom risk report.

In general, any effort to assess risk should begin and end with a qualitative approach, which makes judgement calls on the risks that are of highest concern and relevance, often by developing a matrix such as the one in figure 11. This exercise should be completed in collaboration between climate researchers and stakeholder groups, ideally in a workshop setting where participants can freely interact, ask questions, and explain their insight. Participants should be encouraged to come to consensus on classification of risk to ensure that the assessment is fully-informed by stakeholder input. While quantitative methods are useful in elucidating the extent of impact and relationship between variables, they can often overlook context-specific risk, particularly in the social dimension. Qualitative approaches, which categorise, rank, contextualise, and translate risk are also often more useful in policy planning and advocacy. Ideally, a mixture of both types of methods should be used to better understand risk.

	Consequence				
Likelihood	Negligible	Minor	Moderate	Major	Extreme
Highly likely	moderate	high	extreme	extreme	extreme
Probable	moderate	high	high	extreme	extreme
Possible	low	moderate	high	high	extreme
Unlikely	low	moderate	moderate	high	high
Very rare	low	low	low	moderate	moderate

Fig. 11. A likelihood and consequence matrix to effectively translate and communicate theoretical risk.

Quantitative Methods

Geospatial analysis, highlighting variation of risk across space, plays an important role in identifying regions and assets that are of increased vulnerability. In natural environments and ecosystems, quantifying spatial risk may play a particularly important role, as wildlife resilience and adaptation is often dictated by spatial dependence and habitat connectivity. Spatial analysis can also highlight areas of high vulnerability or exposure of human populations and assets, leading to better decision making with local stakeholders. Remote sensing methods can extend beyond well-measured regions and provide satellite data for large areas of land, which may otherwise be difficult to access or too difficult to provide ground measurements for (such as mountainous regions and oceans). However, this broad coverage may lack high-resolution detail, and should be supplemented with ground measurements where possible, allowing for better downscaling.

Scenario analysis considers how different actions and decisions will manifest over time. This approach considers how risk may vary in the future based on different scenarios. While scenarios are not exact predictions of the future, they represent distinct possibilities that may alter key outcomes. The most widely used scenarios when modelling climate change come from the IPCC's 6th assessment report. These scenarios are based on Shared Socioeconomic Pathways (SSPs) combined with Representative Concentration Pathways (RCPs). SSPs propose potential socioeconomic, geopolitical, and technological paths, which underpin RCPs projections of greenhouse gas concentrations in the atmosphere. The IPCC puts forward 5 illustrative scenarios, which are associated with a range of climate ambitions, resulting in various global mean temperatures. The IPCC's working group I (WGI) Interactive atlas is a useful tool to become familiarized with the impacts of different scenarios. Previous work has highlighted the potential to reverse the impact chain, allowing to 'work backwards' from certain impacts and determine which scenarios are in line to prevent these impacts. The Climate Risk Dashboard demonstrates this capability in its 'avoiding future impacts' mode, with a variety of indicators and impact thresholds, allowing decisionmakers to better link emissions and impacts.

Vulnerability index assessments work by establishing a given system, geography, or sector and selecting a variety of relevant indicators as proxies for vulnerability level. Indicators selection is based on sufficient data availability and relevance for a risk framework (particularly for a given study area or context). For example, when considering vulnerability indicators for mangrove forests, which can naturally tolerate some degree of sea level rise, an appropriate indicator would be the specific threshold at which sea level rise begins to cause damage. A more in-depth discussion of indicator selection is available by the Stockholm Environment Institute. Once appropriate indicators are selected, they are then normalised based on values of measured data and aggregated to provide a score or average. Results can then be mapped across space or ranked according to vulnerability level. This approach is especially useful in identifying policy interventions for at-risk groups and regions.

Often, multiple methodologies go hand-in-hand. Geospatial data combined with scenario analysis can provide the basis for specialised methods in understanding biodiversity and wildlife patterns, which play an important role in habitat functioning. **Climate envelope models**, for example, can be used to understand how different climate conditions may affect distributions of key species in the future, by mapping geographic shifts based on species-specific conditions. Naturally, findings from species-specific models can be limited, as co-occurring species rely on each other for key life cycle processes. Therefore, combination of specialized models with more robust ecological principles can provide a better understanding of future patterns.

Multi-Hazard Analysis

Under climate change, multiple interacting and co-occurring hazards are becoming more common, resulting in more extreme impacts. Climate risk assessments are increasingly moving from single-hazard to multi-hazard analysis. However, interrelations between hazards are still poorly understood and difficult to model. Multiple hazards may interact, exacerbating impacts and leading to non-linear responses. To complicate this, multiple hazards may affect risk on different spatial and temporal scales, with impacts distributed across space and time.

To model multi-hazard risk, one should first consider the relationship between hazards (i.e. does one event trigger another, intensify its effects, or merely coincide?). In the case of simultaneous but independent events, there is no causality, but there may be increased risk. For example, a flood and a heat wave may occur simultaneously by chance, but will result in worsened impacts on local populations, biodiversity, and infrastructure compared to only a single of these hazards occurring. In such cases, more qualitative approaches could be helpful, looking to case studies in other regions.

Attribution Science

Climate change attribution is a growing scientific field crucial for policymaking and climate litigation. It helps address key challenges that hinder climate action:

- **Global dispersion** (emissions affect the planet beyond their origin)
- **Agency fragmentation** (dispersed stakeholders with coordination barriers)
- **Institutional inadequacy** (limited jurisdiction, enforcement, or resources), and
- **Temporal delay** (delayed impacts reduce urgency and psychological proximity)

Attribution science links human-induced climate change to extreme weather or long-term trends by comparing climate model simulations with and without anthropogenic greenhouse gas emissions. These comparisons help estimating changes in environmental conditions, including the likelihood and intensity of extreme events.

The findings support decision-making, enabling targeted mitigation policies, and play a key role in climate litigation by establishing causality, harm, and liability for damages. However, attribution studies carry model-based uncertainties, which must be transparently reported.

Attribution science can be combined with other analytical frameworks, such as ecosystem service valuation, to investigate environmental degradation. For example, S. Liu et al. (2024) estimated the contribution of climate change to changes in the value of ecological services (ESV) in China's Yunnan Province between 2000 and 2019. The study found an average annual ESV increase of 52.34 billion yuan, primarily driven by land use and cover change (LUCC), which accounted for 92.3% of the change, with climate change contributing just 7.7%. Notably, wetlands—despite occupying the smallest area—had the highest ESV per unit area but also showed the largest per-unit decrease in ESV (-359,000 yuan/km²), highlighting their vulnerability to climate change.

Organizations like World Weather Attribution regularly publish peer-reviewed analyses of extreme weather events and their links to climate change, helping quantify the estimated role of anthropogenic influence in such occurrences.

Uncertainty

Some level of uncertainty in climate risk assessment is inevitable, especially when considering future impacts of climate change. Whether it be uncertainty in observational data, or the inherent uncertainty associated with modelling complex processes, unknowns can be reduced but never eliminated.

The IPCC AR6 follows a framework of assessing available evidence, evaluating confidence based on agreement and evidence type, and translating quantitative results into likelihood thresholds. The full overview of this framework can be seen in figure 12. While this process may be overly-comprehensive and impractical for contexts with limited research or data, it provides the basis for a standardised approach to uncertainty assessment. The representation of uncertainty by categories, thresholds, and probabilities is a useful way to communicate findings in a consistent and easily understood manner.

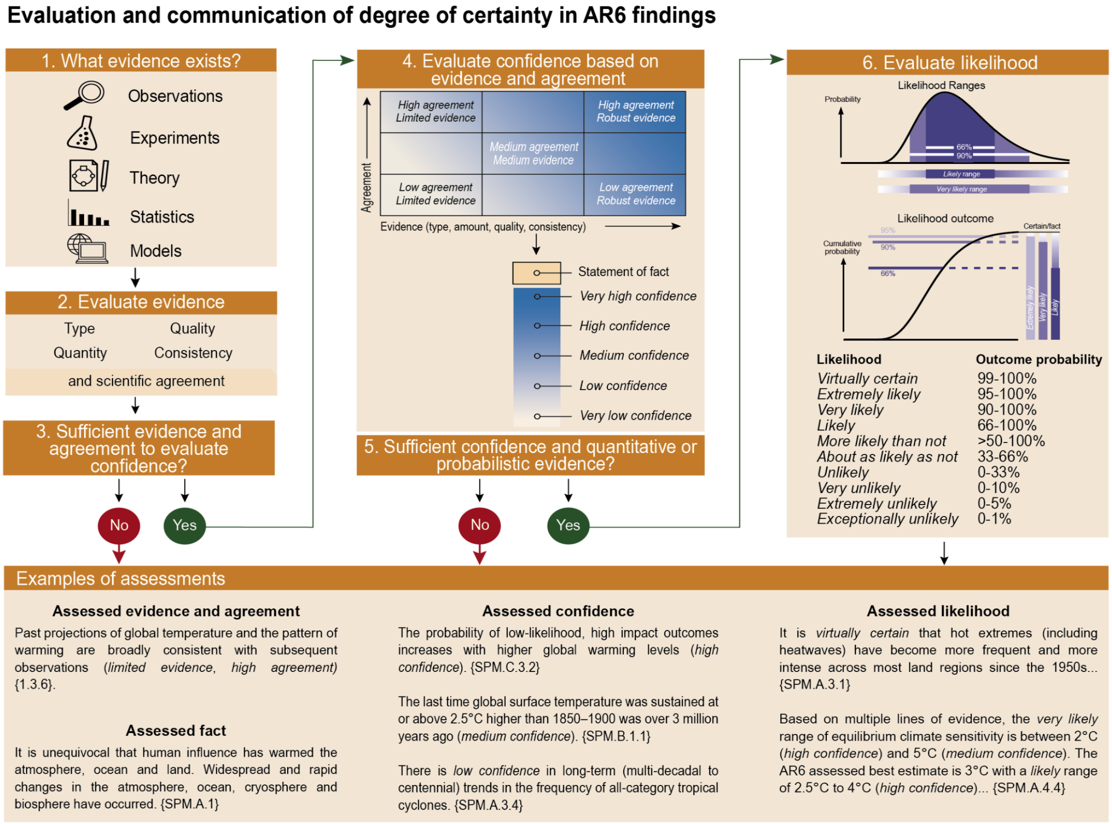


Fig. 12. Evaluation and communication of degree of certainty in AR6 findings

Source: IPCC (2023a)

When assessing future risks, it is important to not only communicate uncertainty along with results, but to highlight the significance of it for policy and adaptation. Often, results will be associated with moderate-to-high levels of uncertainty. Here it is useful to consider the role of science communication to those who are not climate scientists. Particularly when discussing high-impact future trends, the mention of uncertainty can sometimes cause stakeholders to minimise potential impacts, believing that it translates to limited impact. However, uncertainty may also confer the possibility that a given risk is more severe than expected, occurs earlier, or that an entirely new and unexpected risk could evolve. Therefore, high uncertainty may itself be a risk, creating the need for an even more precautionary approach to risk management. Furthermore, risk assessments should highlight that uncertainty is never a good reason for inaction.

Integrating Methods

Regardless of the methodology used, risk assessment is best done with a variety of data, tools, and methods to understand a fuller picture of the future. While the integration of multiple approaches can improve confidence in outcomes, even the best approach will have some degree of uncertainty. Before establishing a methodology, researchers should understand the benefits and drawbacks of different approaches, and thoroughly consider what outcomes they wish to obtain, which will dictate further decisions. Emerging technologies and advancements in computing and modelling capabilities will likely create a host of methodologies in the future, but even relatively simple approaches with strong justification can provide useful insights into risk management and adaptation.

Determining Methodology		
Considerations: • Is sufficient quantitative data available? • What is the end goal of the assessment (policy, litigation, communication)? • What technical infrastructure and expertise is available?		
Method	**Type**	**Use Benefit**
Case study	qualitative	Useful for public dissemination
Focus group	qualitative	Insight from various interest groups
Self assessment	qualitative	Encourages expert reflection
Geospatial analysis	quantitative	Considers risk variation across space
Scenario analysis	quantitative	Policy-relevant, mitigation focused
Vulnerability index	quantitative	Highlights at-risk groups
Multi-hazard	both	Highlights relationships between hazards
Attribution	quantitative	Establishes liability, relevant for litigation

4.1.3 Prioritising and Evaluating Solutions

The prioritization and evaluation of solutions to climate risks in the natural environment is critical to ensure not only the success of the intervention but also wise use of resources and optimal benefits among other factors. Numerous solutions have been outlined in this report but to be able to prioritize them, a number of factors have to be considered. This section focuses on some best practice guidance that can be used for prioritization and evaluation.

Feasibility is one such key aspect. It is important to consider the feasibility of solutions and also the impact of the solution. This can be done by undertaking a feasibility assessment that considers the effectiveness of the solution, aspects of equity and justice (especially within communities that rely on the natural environment), co-benefits and the ability to for scalability (Ruangpan et al, 2021; Roy et al, 2017; Cook-Patton et al, 2021).There are also methods such as multi-criteria decision making that can be used to prioritize possible solutions (Akbari et al, 2020).

Iterative Risk Assessment including adaptation is another activity that should be undertaken to provide the necessary data and information to prioritize one action over another. Such assessments should incorporate input from multiple stakeholders, and most importantly, the communities inhabiting the areas. This is also important to be able to manage associated risk such as the introduction of alien species in an ecosystem (Roy et al, 2017; Cook-Patton et al, 2021).

Linkages with policy at local, national to global levels are also important. This ensures that solutions are prioritized based on how they are linked with local, national and global policies such as local and national adaptation and biodiversity plans, sustainable development goals etc (Ruangpan et al, 2021).

Inclusivity is also critical to ensure that local communities are engaged in prioritization and especially the incorporation of local and indigenous knowledge which can be important in safeguarding the natural environment (Ruangpan et al, 2021; Cárcamo et al, 2014). Initiatives must also promote equity and the inclusion of vulnerable groups such as women, youth and persons with disability.

Evidence-based prioritization also has to be considered. Prioritization must be based on the best available data and information, especially scientific knowledge as well as local and indigenous knowledge. Some methods highlighted above such as multi-criteria decisionmaking, GIS applications, modeling etc. are important in helping support the choice of a particular solution (Akbari et al, 2020; Ruangpan et al, 2021).

Funds are a key determining factor as well, thus it is important to secure resources that will support the prioritization and implementation of solutions. Resource mobilization has to be undertaken across sectors, levels and with partners including non-state actors such as the private sector. Cost-benefit analyses are helpful to ensure that the resources available and the solution prioritized offer value for money and contribute to ecosystem resilience and human wellbeing (Roy et al, 2017; Cook-Patton et al, 2021; Ruangpan et al, 2021).

Resilience is therefore critical as well. The solutions have to be able to enhance the resilience of the natural environment, as well as that of communities that may be at risk. Awareness and capacity building are another important aspect. During evaluation and prioritization, it is important to also raise awareness about the solutions and ensure that there is understanding amongst the stakeholders about the options and their impacts (Key et al, 2022). Progress monitoring is also important to continuously monitor solutions to ensure that they are on track. If evaluation requires prioritization of other options, these should be done to ensure desirable outcomes for communities and the environment (Ruangpan et al, 2021).

Gann et al have set out some best practices for ecological restoration based on eight underlying principles. Adherence to this framework may aid in prioritization and evaluation of solutions. These principles which are summarized in the figure below can be applied by various stakeholders in the prioritization and evaluation of initiatives that address risks in the natural environment.

Fig 13: Principles of ecological restoration.

Source: Author generated figure from Gann et al, 2019

4.2 Customizable Approaches for Different Ecosystems

There are various approaches that can be customized at different scales for the protection and resilience of ecosystems from climate risks. Some approaches are cross-cutting and can be applied in different ecosystems. These include monitoring and continued research and observational data generation that can help support measures to address risks. Complementing this is the development of policies, laws and strategies that are necessary to support the interventions to address risks, for example a law or policy that designates a protected area or prioritizes certain land-use types. Establishing early warning systems and disaster risk management is also a cross-cutting approach as is the use of emerging technologies and the application of artificial intelligence. Finally, there is communication and dissemination including awareness creation that is an important approach in addressing climate risks and reducing exposure and vulnerability.

These are summarized in table 2, below:

Table 2. Key climate risk elements in different ecosystems and some customizable adaptation approaches

	Coastal and marine ecosystems	Mountainous ecosystems	Forests and grasslands	Agriculture
Key risks	Sea-level rise acidification Pollution Storm surges Coastal erosion	Landslides Loss of biodiversity Loss of glaciers Erosion Landslides Drought	Drought Floods Wildfires Deforestation Biodiversity and habitat loss	Drought Floods Pests Heat extremes
Adaptation measures	Mangrove planting integrated management sustainable utilization	Reforestation Monitoring of biodiversity and glaciers Adoption of use of local and indigenous knowledge and practices for management and conservation Integrated water management	Reforestation and afforestation Early warning systems Monitoring and management of invasive species	Climate-smart agriculture Provision of climate information services Early warning systems Planting drought-resistant crop varieties Sustainable management of livestock Insurance provision Biological pest control
Policy support	Designation of protected areas such as parks and nature reserves Designation of buffer zones	Designation of protected areas such as parks and nature reserves Regulations on water abstraction	Designation of protected areas such as parks and nature reserves Designation of buffer zones Establishment of wildlife corridors	Incentives for small-scale farmers and livestock keepers Socio-economic safety-nets
Additional support	Address non-climate anthropogenic drivers such as pollution Partnership with local communities	Partnership with local communities	Partnership with local communities	Partnership with local communities

4.3 Integrating Adaptation into Development Planning

Healthy ecosystem functioning provides a variety of services that underpin sustainable development. Many, if not all SDGs have a direct connection to ecosystem services. Some of these services include provision of food and fuel, water and air filtration, direct livelihood support, and protection from hazards. These services are particularly relied on by those in poverty, and are protective factors against falling further into poverty.

Currently threatened by climate change, land use change, pollution, and resource extraction, the degradation and collapse of ecosystems results not only in losses of biodiversity and carbon-storage, but significant economic, health, and employment consequences. As a result, development strategies should consider the 'Ecosystem Approach' which is the main framework put forward by the Convention on Biological Diversity (CBD) and promotes conservation and sustainable use of nature in an equitable way. This approach considers the full and diverse ways that nature provides benefits to humans, which are often overlooked in traditional economic approaches. The Ecosystem Approach allows for equitable decision making with full consideration of tradeoffs associated with conservation and use of natural resources. As a result, development should be pursued with the understanding that existing ecosystems should be left in-tact as much as possible to conserve ecosystem services.

Furthermore, the conservation and restoration of the natural environment can play an important role in promoting both climate mitigation and adaptation, as well as a variety of sustainable development goals. A joint report from the International Labour Organization (ILO), the UN Environment Programme (UNEP), and the International Union for Conservation of Nature (IUCN) found that NbS can create 32 million high-quality jobs by the year 2030. In particular, there is great potential in low and middle income countries for job creation in green-grey infrastructure. Traditional NbS can provide a variety of services that support adaptation, and agricultural NbS may alleviate climate risks to farmers, who are particularly vulnerable to impacts, while potentially improving and diversifying their incomes. The use of agricultural NbS may also reconcile other anthropogenic drivers of risk to ecosystems, such as pollution and land-use change, in regions with high-demand for agricultural land.

Socially-focused development, such as improvements in education, livelihoods and rights of local populations, also goes hand in hand with risk reduction, providing multiple co-benefits. For example, connecting rural populations to electricity and improving literacy can enhance the use and uptake of MHEWS. Education and capacity development in conservation and NbS can provide alternative employment opportunities to populations that may otherwise rely on harmful practices such as deforestation for farming and poaching. Involving those who rely on and live nearby natural ecosystems in decision making processes will increase local leadership while providing key stakeholder input. Highly vulnerable populations such as indigenous, women, and rural people allow for more robust adaptation that improves outcomes for all.

All in all, natural ecosystems can support adaptation efforts and contribute to development, particularly through NbS and the ecosystem services they provide. The natural environment is a key sector in adaptation, with the AR6 highlighting 'Land, Oceans and Ecosystems' as one of the 5 key systems needed to enable mitigation pathways for a 1.5°C world. Regional and national actors should therefore consider the climate risks that they face, and how they contribute to adaptation and mitigation goals.

Integrating Adaptation into Development

Key Concepts:

- All parties of the Paris Agreement are asked to formulate a long-term low greenhouse gas emission development strategy (LT-LEDS)
- The NDC Partnership works to align the missions of the 2030 Sustainable Development Goals and the Paris Agreement
- Low-Emission Climate Resilient Development (LECRD) relies on protection of natural ecosystems and management of climate risk

Resources	Communities of Practice
Guidance on how to develop a LT-LEDS	NDC Partnership
Long-term strategies portal	Climate & Development Knowledge Network

5 Conclusions

5 Conclusions

As the world confronts intensifying climate risks, it is clear that adaptation alone cannot substitute for urgent mitigation. Exceeding the 1.5°C limit, however temporarily, risks triggering irreversible impacts that no amount of adaptation can fully address. While NbS and healthy natural environments offer critical co-benefits and resilience gains, they are not a silver bullet. To protect lives, livelihoods, and ecosystems, particularly in the most vulnerable regions, adaptation efforts must be grounded in the science of physical limits and reinforced by ambitious, equitable mitigation pathways to remain below 1.5°C. Avoiding overshoot is not only a climate imperative, but a prerequisite for adaptation solutions to remain feasible, effective and just.

In this report, we explain the rationale, process, and applications of risk assessment and management in natural environments, highlighting best practices and common frameworks utilised in international processes.

The process of identifying, assessing, and adapting to climate risk allows for better preparation to the impacts of climate change. Throughout this report, we have touched on a variety of cross-cutting themes that are important to risk assessment and adaptation in the context of the natural environment. The main conclusions of this report are presented below.

Generalisable Best Practices

The box below provides a summary of generalisable best practices that can be adopted in addressing climate risks in the natural environment.

Identifying risk in the natural environment	Assessing risk (data and methodologies)	Nature-based solutions	Technological solutions
• Consider the multiscalar nature of risk and the respective differences in risk management approaches. • Integrate non-climatic drivers (pollution, land-use change, etc.) into risk assessments. • Account for interactions and feedback effects among climate and non-climate risks. • Incorporate sector-specific vulnerabilities.	• Prioritise widely recognized and reputable data sources and use platforms offering accessible and diverse datasets • Complement global data with high-resolution local sources. • Remain aware of scale limitations, scaling needs and resolution mismatches in your interpretations of the results and clearly state the corresponding uncertainties. • A variety of methodologies can be used to assess risk based on the availability of data and desired application of findings. • Attribution science is an emerging technique that can be used to support climate litigation and policy making.	• NbS can contribute to both climate change mitigation and adaptation, in addition to a variety of socio-economic benefits. • Prioritise the conservation of existing habitats to maximise benefits. • Follow frameworks such as the Global Standard for Nature-based Solutions to ensure that NbS are properly planned and managed. • The effectiveness of NbS may reduce under climate change. • NbS are important for mitigation, but are not a replacement for emissions reductions.	• MHEWS can significantly reduce loss of life and assets • Emerging technologies such as IoT, digital twins, and AI can improve understanding, management and adaptation to climate change. • Technological solutions should be developed and implemented with careful consideration for data privacy, environmental impact, and relevance.

Governance

- Policies and governance frameworks can help support effective implementation and enable mainstreaming and cross-sectoral collaboration for NbS
- Different countries have already integrated NbS in their NDCs and other national and local policies and strategies and this can be used as best practice when thinking about how to formulate NbS policies and strategies
- Policies and governance frameworks can ensure the inclusion of local and indigenous communities as well as the incorporation of indigenous knowledge which is critical for the successful implementation of NbS.

MEL

- MEL can support successful implementation of strategies as it enables continuous monitoring review and update to ensure the best possible outcomes.
- Key Performance indicators (KPI's) can be a useful tool in MEL as they help track and monitor progress, support the effectiveness of strategies and decision making.
- Different approaches have been adopted by different countries for MEL at national and subnational level and these can be useful resources when designing MEL frameworks.

Development

- Understand how climate risk threatens development progress.
- Take an ecosystem services approach to development, considering the economic, adaptation, and mitigation benefits that ecosystems offer.
- Conservation and implementation of NbS can support economic development

Fig. 14. Generalisable Best Practices applicable to risks and solutions in the natural environment.

Ecological Principles

Natural environments, ecosystems and biodiversity provide value to humans and the planet as a whole. While many of these benefits are directly tangible as ecosystem services and products, many others remain unseen and unaccounted for in traditional economic approaches. Diverse, natural, and healthy ecosystems tend to provide the most co-benefits when it comes to climate change mitigation, risk reduction, and development. Increased mitigation ambition and climate action in line with the Paris Agreement long-term temperature goal can retain the most co-benefits while boosting adaptation effectiveness, particularly for Nature-based Solutions. Long time-scales have provided these systems with unique adaptation and resilience to bounce back from stressors, store carbon, and function effectively. Human disruption (both climatic and non-climatic) however, is degrading these systems at an overwhelming pace.

Adaptation and mitigation efforts should acknowledge the importance of nature for societal functioning and continued development, and should also protect these natural systems from further harm. Human systems, which exist as part of nature and depend on its outputs, should work with, rather than against, natural systems.

Context Dependence

Climate change manifests differently in different regions and time scales depending on local conditions. On top of this, socioeconomic, governmental, and cultural factors vary across space, contributing to multiple levels of vulnerability. As a result, there is no one-size-fits-all approach to either risk assessment or management. Instead, research, knowledge, and solutions must be based on local and relevant context, and on the understanding that what works in one situation may not work in another. Naturally, this requires specialised research approaches as well as robust expertise, highlighting the importance of stakeholder engagement and interests of local populations.

Stakeholder Engagement

Involving stakeholders with unique perspectives and backgrounds can elucidate and uncover insights to enhance risk assessment and management. Furthermore, the involvement of stakeholders in decision making and knowledge sharing can facilitate greater buy-in from the community as a whole, and align interests to promote better adaptation strategies and solutions. The involvement of different stakeholders should be representative of local actors as well as traditionally overlooked groups, such as women, indigenous communities, and impoverished people, who can provide valuable perspectives.

Local and Indigenous Empowerment

Work done to reduce risk of a region, sector, or population should not infringe upon the rights or well being of local communities or indigenous peoples. Instead, an approach that respects their rights, involves them in decision making, and empowers them should be employed. Oftentimes, local and indigenous people provide unique insight into problems based on first-hand local experience. Additionally, their close proximity and dependence on nature allows them to assist in adaptation efforts and nature conservation.

Co-benefits Approach

Techniques and solutions that can deliver a variety of benefits in parallel to their primary function can enhance buy in and promote uptake. Where possible, co-benefits that satisfy a variety of stakeholder interests should be considered. In cases of tradeoffs, thoughtful consideration should be given with an understanding that compromise and balance are inevitable.

Next Steps

This report is a resource that stakeholders can utilize to address climate risks in the natural environment. It provides information for policymakers to formulate adaptation policies such as nature-based solutions and climate-resilient development. Best practices highlighted can be adopted and modified to fit different contexts such as mangrove forests in Guangxi province and the high plateau areas in Sichuan province. Nevertheless, this report provides a variety of approaches and examples of them, that are broadly accessible and useful for multiple contexts, regions, and sectors. Community members can engage by actively participating in finding solutions and also amplifying their own practices, experiences and local and indigenous knowledge that enables them to adapt to climate change over the years.

Private sector stakeholders also have a responsibility to actively participate in ensuring that their processes and practices do not lead to increased risks to the natural environment and rather, that they contribute to resilience and mitigation through sustainable use of the natural environment including water, forests, marine environment, land etc. The private sector can also provide resources which are critical in addressing climate risks and also deploy NbS and other solutions such as emerging technologies in their activities to reduce any adverse impacts on the natural environment. Although climate action may be perceived as a cost in the short term, avoiding climate-related impacts ultimately may pay off in the medium and long term by avoiding costly disturbances to business.

Academia and research also have a role to play in terms of adding to the body of knowledge on these risks, it:

- Provides robust scientific evidence to support responses
- Increases the range of options available for addressing risk

- Enhances the understanding of risks and associated feedback loops
- Develops and advances the use of emerging technologies and AI in addressing risks etc.

Academic stakeholders often have critical methodological and research skills that can aid in risk assessment and management, leading to more effective partnerships and well-planned policy.

Media has a role in communicating information on risks and especially supporting the dissemination of early warning information to the public. Additionally, they should highlight challenges and solutions that have worked in different contexts to be able to connect communities with other stakeholders in the amplification of best practices. Civil society organisations, on the other hand, provide advocacy and keep governments and other stakeholders accountable by assessing the policies, commitments and strategies set in place to address risks and their implementation. e.g the designation and conservation of protected areas, and also in advocating for the scaling up of action to address new and emerging risks and challenges.

The public sector, and in particular, agencies that oversee the management of the natural environment (such as forestry and agricultural departments), should coordinate and initiate partnerships and activities that mitigate climate risk, facilitating and aligning goals across various levels of government and planning for the medium and long terms.

In summary, all stakeholders have roles and responsibilities in addressing climate risks to the natural environment. It is imperative that all actors, stakeholders, and decision-makers proactively engage and collaborate in climate risk assessment and management, especially as climate impacts continue to intensify and become more frequent.

References

Aihemaitijiang (Ahmatjan) Rouzi. (n.d.). Study: China's ag outlook 2023-2032. DCZ - Sino-German Agricultural Centre. Retrieved 17 October 2025, from https://www.dcz-china.org/2023/06/28/study-chinas-ag-outlook-2023-2032/

Akbari, M., Memarian, H., Neamatollahi, E., Jafari Shalamzari, M., Alizadeh Noughani, M., & Zakeri, D. (2021). Prioritizing policies and strategies for desertification risk management using MCDM–DPSIR approach in northeastern Iran. Environment, Development and Sustainability, 23(2), 2503–2523. https://doi.org/10.1007/s10668-020-00684-3

Beck, D., Pal, A., Zaveri, P., Zheng, A., Tiwari, A. K., & Majumdar, S. (2025). Ecosystem Resilience for Climate Resilience, Strategies and Innovations: A Case Study from Developing Countries. In M. Choudhury, G. Dixit, & S. Majumdar (Eds), Sustainable Synergy: Harnessing Ecosystems for Climate Resilience (pp. 49–64). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-77957-2_4

Bennun, L., Van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., & Carbone, G. (2021). Mitigating biodiversity impacts associated with solar and wind energy development: Guidelines for project developers. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2021.04.en

Bevacqua, E., Schleussner, C.-F., & Zscheischler, J. (n.d.). A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit | Nature Climate Change. Retrieved 17 October 2025, from https://www.nature.com/articles/s41558-025-02246-9

Boers, N., Marwan, N., Barbosa, H. M. J., & Kurths, J. (2017). A deforestation-induced tipping point for the South American monsoon system. Scientific Reports, 7(1), 41489. https://doi.org/10.1038/srep41489

Bressan, G., Đuranović, A., Monasterolo, I., & Battiston, S. (2024). Asset-level assessment of climate physical risk matters for adaptation finance. Nature Communications, 15(1), 5371. https://doi.org/10.1038/s41467-024-48820-1

Bucheli, J., Conrad, N., Wimmer, S., Dalhaus, T., & Finger, R. (2023). Weather insurance in European crop and horticulture production. Climate Risk Management, 41, 100525. https://doi.org/10.1016/j.crm.2023.100525

Bull, J. W., Strange, N., Smith, R. J., & Gordon, A. (2021). Reconciling multiple counterfactuals when evaluating biodiversity conservation impact in social-ecological systems. Conservation Biology, 35(2), 510–521. https://doi.org/10.1111/cobi.13570

Bundesministerium für wissenschaftliche Zusammenarbeit und Entwicklung. (2023, December 8). Debt-for-climate swaps. https://www.bmz.de/en/issues/climate-change-and-development/climate-financing/debt-for-climate-swaps-195550

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Cárcamo, P. F., Garay-Flühmann, R., Squeo, F. A., & Gaymer, C. F. (2014). Using stakeholders' perspective of ecosystem services and biodiversity features to plan a marine protected area. Environmental Science & Policy, 40, 116–131. https://doi.org/10.1016/j.envsci.2014.03.003

Carlson, R. R., Evans, L. J., Foo, S. A., Grady, B. W., Li, J., Seeley, M., Xu, Y., & Asner, G. P. (2021). Synergistic benefits of conserving land-sea ecosystems. Global Ecology and Conservation, 28, e01684. https://doi.org/10.1016/j.gecco.2021.e01684

Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science, 333(6045), 1024–1026. https://doi.org/10.1126/science.1206432

Chinese Academy of Forestry. (2025). Key Technologies for Comprehensive Control of Wood-boring Beetles (Buprestids). https://www.caf.ac.cn/en/info/1020/1095.htm

Cook-Patton, S. C., Drever, C. R., Griscom, B. W., Hamrick, K., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Stevenson, M., Webb, C., Yeo, S., & Ellis, P. W. (2021). Protect, manage and then restore lands for climate mitigation. Nature Climate Change, 11(12), 1027–1034. https://doi.org/10.1038/s41558-021-01198-0

CRI Group. (2025). Risk Assessment Breakdown: Identification, Analysis, and Evaluation. Risk Assessment Breakdown: Identification, Analysis, and Evaluation. https://crigroup.com/risk-assessment-breakdown/

Crouzeilles, R., Beyer, H. L., Monteiro, L. M., Feltran-Barbieri, R., Pessôa, A. C. M., Barros, F. S. M., Lindenmayer, D. B., Lino, E. D. S. M., Grelle, C. E. V., Chazdon, R. L., Matsumoto, M., Rosa, M., Latawiec, A. E., & Strassburg, B. B. N. (2020). Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. Conservation Letters, 13(3), e12709. https://doi.org/10.1111/conl.12709

Deltares. (n.d.). Guyana Green-Gray Infrastructure Engineering Guidelines. https://publications.deltares.nl/11207078.pdf

DeSantis, R. D., Moser, W. K., Gormanson, D. D., Bartlett, M. G., & Vermunt, B. (2013). Effects of climate on emerald ash borer mortality and the potential for ash survival in North America. Agricultural and Forest Meteorology, 178–179, 120–128. https://doi.org/10.1016/j.agrformet.2013.04.015

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience, 4(5), 293–297. https://doi.org/10.1038/ngeo1123

Enenkel, M., Dall, K., Huyck, C. K., McClain, S. N., & Bell, V. (2022). Monitoring, evaluation, accountability, and learning (MEAL) in anticipatory action—Earth observation as a game changer. Frontiers in Climate, 4. https://doi.org/10.3389/fclim.2022.923852

Environment, U. N. (2021, December 10). Infrastructure for Climate Action | UNEP - UN Environment Programme. https://www.unep.org/resources/report/infrastructure-climate-action

Environment, U. N. (2023, March 11). Climate Information and Early Warning Systems | UNEP - UN Environment Programme. https://www.unep.org/topics/climate-action/climate-transparency/climate-information-and-early-warning-systems

Environment, U. N. (2024, October 30). Adaptation Gap Report 2024 | UNEP - UN Environment Programme. https://www.unep.org/resources/adaptation-gap-report-2024

European Central Bank. (2025). Climate change and sovereign risk. Climate Change and Sovereign Risk. https://www.ecb.europa.eu/press/financial-stability-publications/fsr/special/html/ecb.fsrart202305_03~f51dd11fd7.en.html

FAO. (2025). FAO Agricultural Stress Index System (ASIS). https://openknowledge.fao.org/items/1dd9a882-08d2-4658-bb74-895c5f054fff

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014a). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nature Communications, 5(1), 3794. https://doi.org/10.1038/ncomms4794

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014b). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nature Communications, 5(1), 3794. https://doi.org/10.1038/ncomms4794

Food and Agriculture Organization of the United Nations. (2021). Nature-based solutions in agriculture: Project design for securing investment. FAO and TNC. https://doi.org/10.4060/cb3144en

Forstliche Versuchs- und Forschungsanstalt Baden-Württenberg. (2025). Klimakarten 2.1. https://www.fva-bw.de/daten-tools/geodaten/klimakarten/klimakarten-21

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallett, J. G., Eisenberg, C., Guariguata, M. R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K., & Dixon, K. W. (2019). International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology, 27(S1), S1–S46. https://doi.org/10.1111/rec.13035

Geyman, E. C., Douglas, M. M., Avouac, J.-P., & Lamb, M. P. (2024). Permafrost slows Arctic riverbank erosion. Nature, 634(8033), 359–365. https://doi.org/10.1038/s41586-024-07978-w

GIZ. (2021). Assessment of climate-related risks. A 6-step methodology (Integrated CRM and Transfer). GIZ. https://www.giz.de/en/downloads/giz2021-en-climate-related-risk.pdf

GIZ. (2023). Managing Climate Risks in Wetlands. A Practitioner's Guide. German Corporation for International Cooperation. https://indianwetlands.in/wp-content/uploads/library/1675673478.pdf

Grafakos, S., Pacteau, C., Delgado, M., Landauer, M., Lucon, O., Paulo, S., Driscoll, P., & Wilk, D. (n.d.). Opportunities and Challenges. Climate Change and Cities.

Gray, E., Ozment, S., Altamirano, J.-C., Feltran-Barbieri, R., & Morales, A. G. (2019). Green-Gray Assessment: How to Assess the Costs and Benefits of Green Infrastructure for Water Supply Systems. https://www.wri.org/research/green-gray-assessment-how-assess-costs-and-benefits-green-infrastructure-water-supply

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change, 23(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E. van, & Deursen, W. P. A. van. (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. Climatic Change, 115(3), 795–819. https://doi.org/10.1007/s10584-012-0444-2

Helmer, E. H., Gerson, E. A., Baggett, L. S., Bird, B. J., Ruzycki, T. S., & Voggesser, S. M. (2019). Neotropical cloud forests and páramo to contract and dry from declines in cloud immersion and frost. PLOS ONE, 14(4), e0213155. https://doi.org/10.1371/journal.pone.0213155

Intergovernmental Panel On Climate Change (Ipcc). (2022). The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change (1st edn). Cambridge University Press. https://doi.org/10.1017/9781009157964

Intergovernmental Panel On Climate Change (Ipcc). (2023). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st edn). Cambridge University Press. https://doi.org/10.1017/9781009157896

International Institute for Sustainable Development. (2024). How to Strengthen Monitoring, Evaluation, and Learning Systems for Adaptation | International Institute for Sustainable Development. https://www.iisd.org/articles/explainer/strengthen-mel-systems-for-adaptation

International Labour Organization. (2024, July 12). Nature-based Solutions can generate up to 32 million new jobs by 2030, but investments in skills needed. https://www.unep.org/news-and-stories/press-release/nature-based-solutions-can-generate-32-million-new-jobs-2030

International Telecommunications Union. (n.d.). Multi-hazard Early Warning System. Retrieved 20 May 2025, from https://www.itu.int/en/ITU-D/Emergency-Telecommunications/Pages/Multi-hazard-early-warning-systems.aspx

IPCC. (2019). Special Report on Climate Change and Land—IPCC site. https://www.ipcc.ch/srccl/

IPCC. (2020). The concept of risk in the IPCC Sixth Assessment Report: A summary of cross Working Group discussions.

Guidance for IPCC authors (Guidance for IPCC Authors). IPCC. https://www.ipcc.ch/event/guidance-note-concept-of-risk-in-the-6ar-cross-wg-discussions/

IUCN. (2020). IUCN Global Standard for Nature-based Solutions: First edition. IUCN. https://portals.iucn.org/library/node/49070

Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. Environmental Science & Policy, 55, 135–140. https://doi.org/10.1016/j.envsci.2015.09.014

Key, I. B., Smith, A. C., Turner, B., Chausson, A., Girardin, C. A. J., Macgillivray, M., & Seddon, N. (2022). Biodiversity outcomes of nature-based solutions for climate change adaptation: Characterising the evidence base. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.905767

Kumar, V., Sharma, K. V., Kedam, N., Patel, A., Kate, T. R., & Rathnayake, U. (2024). A comprehensive review on smart and sustainable agriculture using IoT technologies. Smart Agricultural Technology, 8, 100487. https://doi.org/10.1016/j.atech.2024.100487

Lee, R., White, C. J., Adnan, M. S. G., Douglas, J., Mahecha, M. D., O'Loughlin, F. E., Patelli, E., Ramos, A. M., Roberts, M. J., Martius, O., Tubaldi, E., van den Hurk, B., Ward, P. J., & Zscheischler, J. (2024). Reclassifying historical disasters: From single to multi-hazards. Science of The Total Environment, 912, 169120. https://doi.org/10.1016/j.scitotenv.2023.169120

Liu, T., Chen, D., Yang, L., Meng, J., Wang, Z., Ludescher, J., Fan, J., Yang, S., Chen, D., Kurths, J., Chen, X., Havlin, S., & Schellnhuber, H. J. (2023). Teleconnections among tipping elements in the Earth system. Nature Climate Change, 13(1), 67–74. https://doi.org/10.1038/s41558-022-01558-4

Liu, Z., & Alexander, M. (2007). Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. Reviews of Geophysics, 45(2). https://doi.org/10.1029/2005RG000172

McKuin, B., Zumkehr, A., Ta, J., Bales, R., Viers, J. H., Pathak, T., & Campbell, J. E. (2021). Energy and water co-benefits from covering canals with solar panels. Nature Sustainability, 4(7), 609–617. https://doi.org/10.1038/s41893-021-00693-8

McNorton, J. R., Giuseppe, F. D., Pinnington, E. M., Chantry, M., & Barnard, C. (n.d.). A Global Probability-of-Fire (PoF) Forecast. Retrieved 20 May 2025, from https://www.authorea.com/users/713243/articles/697596-a-global-probability-of-fire-pof-forecast

Mengistu Asmamaw, Argaw Ambellu, Seid Tiku. Resilience of Ecosystems to Climate Change. American Journal of Environmental Protection. Vol. 4, No. 6, 2015, pp. 325-333. doi: 10.11648/j.ajep.20150406.19

Meybeck, A., Rose, S., & Gitz, V. (with FAO). (2019). Climate change vulnerability assessment of forests and forest-dependent people. Food and Agriculture Organization of the United Nations.

MIDAGRI. (2025, January 17). Seguro Agrícola Catastrófico (SAC). https://www.gob.pe/institucion/midagri/campa%C3%B1as/19256-seguro-agricola-catastrofico-sac

Moos, C., Fehlmann, M., Trappmann, D., Stoffel, M., & Dorren, L. (2018). Integrating the mitigating effect of forests into quantitative rockfall risk analysis – Two case studies in Switzerland. International Journal of Disaster Risk Reduction, 32, 55–74. https://doi.org/10.1016/j.ijdrr.2017.09.036

Mosebo Fernandes, A. C., Quintero Gonzalez, R., Lenihan-Clarke, M. A., Leslie Trotter, E. F., & Jokar Arsanjani, J. (2020). Machine Learning for Conservation Planning in a Changing Climate. Sustainability, 12(18), Article 18. https://doi.org/10.3390/su12187657

Muhammad, M. et al. (2025). A Comprehensive Insight on Ecosystem Services and Climate Resilience. In: Choudhury, M., Dixit, G., Majumdar, S. (eds) Sustainable Synergy: Harnessing Ecosystems for Climate Resilience. Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-031-77957-2_2

Mühlhofer, E., Bresch, D. N., & Koks, E. E. (2024). Infrastructure failure cascades quintuple risk of storm and flood-induced service disruptions across the globe. One Earth, 7(4), 714–729. https://doi.org/10.1016/j.oneear.2024.03.010

Munang, R., Thiaw, I., Alverson, K., Liu, J., & Han, Z. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. Current Opinion in Environmental Sustainability, 5(1), 47–52. https://doi.org/10.1016/j.cosust.2013.02.002

Mykleby, P. M., Snyder, P. K., & Twine, T. E. (2017). Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. Geophysical Research Letters, 44(5), 2493–2501. https://doi.org/10.1002/2016GL071459

Noltze, M., Köngeter, A., Römling, C., & Hoffmann, D. (2021). Monitoring, evaluation and learning for climate risk management (OECD Development Co-Operation Working Papers No. 92; OECD Development Co-Operation Working Papers, Vol. 92). https://doi.org/10.1787/58665de0-en

Numata, S., Yamaguchi, K., Shimizu, M., Sakurai, G., Morimoto, A., Alias, N., Noor Azman, N. Z., Hosaka, T., & Satake, A. (2022). Impacts of climate change on reproductive phenology in tropical rainforests of Southeast Asia. Communications Biology, 5(1), 311. https://doi.org/10.1038/s42003-022-03245-8

Nyathi, D., Ndlovu, J., & Ndlovu, C. N. (2025). Ecosystem-Based Adaptation to Climate Change and the Potential to Build Resilient Food Systems and Achieve Food Security in Africa. In The Palgrave Encyclopedia of Sustainable Resources and Ecosystem Resilience (pp. 1–12). Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-67776-3_62-1

OECD. (2021, June 30). Risk Management. Development Co-operation Fundamentals. https://www.oecd.org/en/publications/development-co-operation-tips-tools-insights-practices_be69e0cf-en/risk-management_2ee26df2-en.html

OECD. (2022). Strengthening capacity for climate action in developing countries: Overview and recommendations (OECD Development Co-Operation Working Papers No. 106; OECD Development Co-Operation Working Papers, Vol. 106). https://doi.org/10.1787/0481c16a-en

OECD. (2024). Framework on management of emerging critical risks (OECD Public Governance Policy Papers No. 49; Working Paper on Public Governance, Vol. 49). https://doi.org/10.1787/2f2eddd8-en

Pearce-Higgins, J. W., Antão, L. H., Bates, R. E., Bowgen, K. M., Bradshaw, C. D., Duffield, S. J., Ffoulkes, C., Franco, A. M. A., Geschke, J., Gregory, R. D., Harley, M. J., Hodgson, J. A., Jenkins, R. L. M., Kapos, V., Maltby, K. M., Watts, O., Willis, S. G., & Morecroft, M. D. (2022). A framework for climate change adaptation indicators for the natural environment. Ecological Indicators, 136, 108690. https://doi.org/10.1016/j.ecolind.2022.108690

Pfleiderer, P., Frölicher, T. L., Kropf, C. M., Lamboll, R. D., Lejeune, Q., Capela Lourenço, T., Maussion, F., McCaughey, J. W., Quilcaille, Y., Rogelj, J., Sanderson, B., Schuster, L., Sillmann, J., Smith, C., Theokritoff, E., & Schleussner, C.-F. (2025). Reversal of the impact chain for actionable climate information. Nature Geoscience, 18(1), 10–19. https://doi.org/10.1038/s41561-024-01597-w

Pillai, U. P. A., Pinardi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., Valentini, A., & Staneva, J. (2022). A Digital Twin modelling framework for the assessment of seagrass Nature Based Solutions against storm surges. Science of The Total Environment, 847, 157603. https://doi.org/10.1016/j.scitotenv.2022.157603

Polchar, J., & Alfonzo Santamaria, N. (2024). Mapping emerging critical risks (78th edn, OECD Working Papers on Public Governance) [OECD Working Papers on Public Governance]. https://doi.org/10.1787/eb642ada-en

Practical Action. (n.d.). Monitoring Rainfall for Early Warning: Peru's Ingenious Solutions. Retrieved 20 May 2025, from https://practicalaction.org/knowledge-centre/resources/monitoring-rainfall-for-early-warning-perus-ingenious-solutions/

Reise, Judith & Siemons, Anne & Böttcher, Hannes & Herold, Anke & Urrutia, Cristina & Schneider, Lambert & Iwaszuk, Ewa & McDonald, Hugh & Frelih-Larsen, Ana & Duin, Laurens & Davis, Mckenna. (2022). Nature-based solutions and global climate protection - Assessment of their global mitigation potential and recommendations for international climate policy.

Roy, H. E., Rabitsch, W., Scalera, R., Stewart, A., Gallardo, B., Genovesi, P., Essl, F., Adriaens, T., Bacher, S., Booy, O., Branquart, E., Brunel, S., Copp, G. H., Dean, H., D'hondt, B., Josefsson, M., Kenis, M., Kettunen, M., Linnamagi, M., … Zenetos, A. (2018). Developing a framework of minimum standards for the risk assessment of alien species. Journal of Applied Ecology, 55(2), 526–538. https://doi.org/10.1111/1365-2664.13025

Ruangpan, L., Vojinovic, Z., Plavšić, J., Doong, D.-J., Bahlmann, T., Alves, A., Tseng, L.-H., Randelović, A., Todorović, A., Kocic, Z., Beljinac, V., Wu, M.-H., Lo, W.-C., Perez-Lapeña, B., & Franca, M. J. (2021). Incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale Nature-Based Solutions. Ambio, 50(8), 1514–1531. https://doi.org/10.1007/s13280-020-01419-4

Salzman, J. (2025, April 1). Field Notes from India: Climate Adaptation from the Ground Up. Legal Planet. https://legal-planet.org/2025/04/01/field-notes-from-india-climate-adaptation-from-the-ground-up/

Schaefli, B., Manso, P., Fischer, M., Huss, M., & Farinotti, D. (2019). The role of glacier retreat for Swiss hydropower production. Renewable Energy, 132, 615–627. https://doi.org/10.1016/j.renene.2018.07.104

Schipper, E.L.F., A. Revi, B.L. Preston, E.R. Carr, S.H. Eriksen, L.R. Fernandez-Carril, B.C. Glavovic, N.J.M. Hilmi, D. Ley, R. Mukerji, M.S. Muylaert de Araujo, R. Perez, S.K. Rose, and P.K. Singh, 2022: Climate Resilient Development Pathways. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2655–2807, doi:10.1017/9781009325844.027.

Secretariat of the Convention on Biological Diversity. (2020). Global Biodiversity Outlook 5. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Secretariat of the Convention on Wetlands. (2021). Global Wetland Outlook. Special Edition 2021. Secretariat of the Convention on Wetlands. https://www.ramsar.org/sites/default/files/documents/library/gwo_2021_e.pdf

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B: Biological Sciences, 375(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Sturchio, M. A., & Knapp, A. K. (2023). Ecovoltaic principles for a more sustainable, ecologically informed solar energy future. Nature Ecology & Evolution, 7(11), 1746–1749. https://doi.org/10.1038/s41559-023-02174-x

Subbiah, A., Maniam, V. T., & Akma Katim, N. I. (2024). Project BlueForest: IoT Sensor Applications in Mangrove Ecosystem Management – an In-Depth Pilot Study Analysis. 2024 IEEE 15th Control and System Graduate Research Colloquium (ICSGRC), 216–221. https://doi.org/10.1109/ICSGRC62081.2024.10691055

Suich, H., Howe, C., & Mace, G. (2015). Ecosystem services and poverty alleviation: A review of the empirical links. Ecosystem Services, 12, 137–147. https://doi.org/10.1016/j.ecoser.2015.02.005

The Caribbean Catastrophe Risk Insurance Facility. (2025a). CCRIF SPC Parametric Insurance Products. CCRIF Home. https://www.ccrif.org/

The Caribbean Catastrophe Risk Insurance Facility. (2025b). Company overview. https://www.ccrif.org/about-us

Tölgyesi, C., Bátori, Z., Pascarella, J., Erdős, L., Török, P., Batáry, P., Birkhofer, K., Scherer, L., Michalko, R., Košulič, O., Zaller, J. G., & Gallé, R. (2023). Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation. Biological Conservation, 285, 110242. https://doi.org/10.1016/j.biocon.2023.110242

Umweltbundesamt. (2021). Climate Impact and Risk Assessment 2021 for Germany (Climate Change). https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_27-2021_climate_impact_and_risk_assessment_2021_for_germany_english_summary_bf.pdf

UN Environment Programme. (2023, March 11). Climate Information and Early Warning Systems | UNEP - UN Environment Programme. https://www.unep.org/topics/climate-action/climate-transparency/climate-information-and-early-warning-systems

UNEP FI. (2023). Climate Risks in the Agricultural Sector. UNEP FI. https://www.unepfi.org/wordpress/wp-content/uploads/2023/03/Agriculture-Sector-Risks-Briefing.pdf

UNFCCC. (2025a). Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) models. Modelling Tools to Assess the Impact of the Implementation of Response Measures. https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models

UNFCCC. (2025b). What is ACE? | UNFCCC. https://unfccc.int/news/what-is-ace

US Department of Agriculture - Forest Service. (2022, March 21). Mitigation of Invasive and High-Risk Wood-Boring Insects in China. https://research.fs.usda.gov/nrs/news/highlights/mitigation-invasive-and-high-risk-wood-boring-insects-china

Valiela, I., Lloret, J., Bowyer, T., Miner, S., Remsen, D., Elmstrom, E., Cogswell, C., & Robert Thieler, E. (2018). Transient coastal landscapes: Rising sea level threatens salt marshes. Science of The Total Environment, 640–641, 1148–1156. https://doi.org/10.1016/j.scitotenv.2018.05.235

Wang, X., Wu, B., Zhou, G., Wang, T., Meng, F., Zhou, L., Cao, H., & Tang, Z. (2025). How a vast digital twin of the Yangtze River could prevent flooding in China. Nature, 639(8054), 303–305. https://doi.org/10.1038/d41586-025-00720-0

Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M., & Karki, P. (n.d.). Climate change and the hydropower sector: A global review—Wasti—2022—WIREs Climate Change—Wiley Online Library. Retrieved 20 May 2025, from https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wcc.757?casa_token=uYjimzgAVv8AAAAA%3AueFS2TtNTXrhjV-V_LU446wakgba06S3JgbAXVCrook1br48IxKUsoZafhB_dHEvSQ78OmHCQp9g3PbF

Watson, J. E. M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J. C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J. G., Painter, M., Wilkie, D., Filardi, C., Laurance, W. F., Houghton, R. A., … Lindenmayer, D. (2018). The exceptional value of intact forest ecosystems. Nature Ecology & Evolution, 2(4), 599–610. https://doi.org/10.1038/s41559-018-0490-x

Wetlands International. (2014, March 1). The Role of Mangroves in Fisheries Enhancement. https://www.wetlands.org/publication/the-role-of-mangroves-in-fisheries-enhancement/

World Bank. 2022. The Greening of China's Agriculture: A Compendium of Thematic Papers. © World Bank.

World Meteorological Organization (WMO), & Reduction (UNDRR), U. N. O. for D. R. (n.d.). Global Status of Multi-Hazard Early Warning Systems: 2024.

Xu, C., Liu, Z., Chen, Z., Zhu, Y., Yin, D., Leng, L., Jia, H., Zhang, X., Xia, J., & Fu, G. (2021). Environmental and economic benefit comparison between coupled grey-green infrastructure system and traditional grey one through a life cycle perspective. Resources, Conservation and Recycling, 174, 105804. https://doi.org/10.1016/j.resconrec.2021.105804

Xu, C., Tang, T., Jia, H., Xu, M., Xu, T., Liu, Z., Long, Y., & Zhang, R. (2019). Benefits of coupled green and grey infrastructure systems: Evidence based on analytic hierarchy process and life cycle costing. Resources, Conservation and Recycling, 151, 104478. https://doi.org/10.1016/j.resconrec.2019.104478

Xu, Z., & Peng, J. (2024). Recognizing ecosystem service's contribution to SDGs: Ecological foundation of sustainable development. Geography and Sustainability, 5(4), 511–525. https://doi.org/10.1016/j.geosus.2024.05.001

Zeppetello, L. R. V., Cook-Patton, S. C., Parsons, L. A., Wolff, N. H., Kroeger, T., Battisti, D. S., Bettles, J., Spector, J. T., Balakumar, A., & Masuda, Y. J. (2022). Consistent cooling benefits of silvopasture in the tropics. Nature Communications, 13(1), 708. https://doi.org/10.1038/s41467-022-28388-4

Ziervogel, G., Enqvist ,Johan, Metelerkamp ,Luke, & and van Breda, J. (2022). Supporting transformative climate adaptation: Community-level capacity building and knowledge co-creation in South Africa. Climate Policy, 22(5), 607–622. https://doi.org/10.1080/14693062.2020.1863180

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered Offices
Bonn and Eschborn
Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66
E info@giz.de
I www.giz.de

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15