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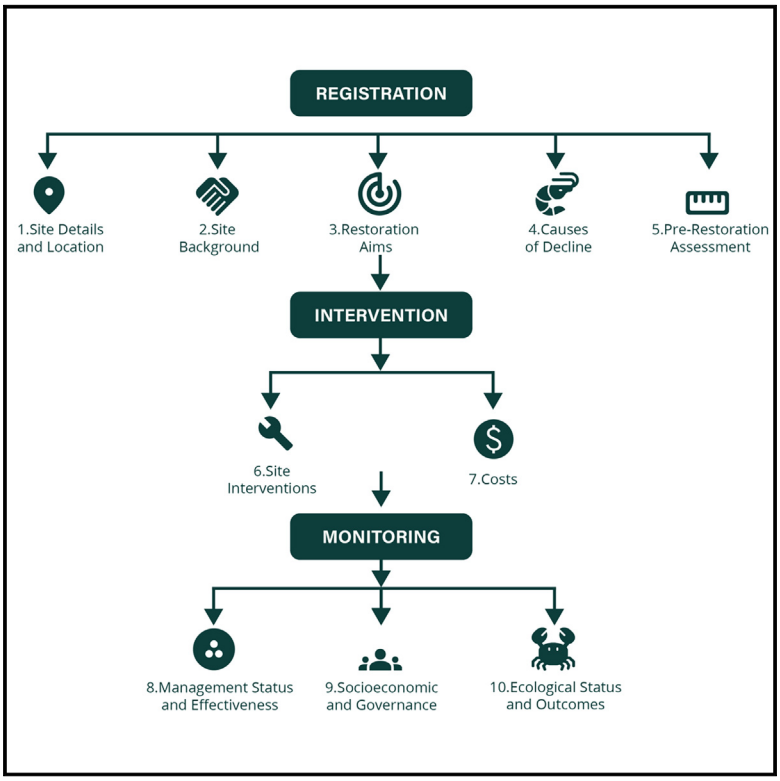
Resource

The Mangrove Restoration Tracker Tool: Meeting local practitioner needs and tracking progress toward global targets

Graphical abstract



Highlights

- We developed the MRTT to capture data on mangrove restoration projects
- The MRTT will improve data coverage and consistency between projects
- The MRTT aims to stimulate data-sharing, enabling future efforts to be more effective
- The MRTT is a global repository to track progress toward conservation targets

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In brief

There is significant impetus to restore mangroves as part of ambitious targets to combat ecosystem degradation, reduce biodiversity loss, and adapt to climate change. However, we currently have limited capacity to track progress toward such targets in a standardized and consistent manner. Here, we describe the development of the Mangrove Restoration Tracker Tool (MRTT), an open-access resource to capture information on the key variables from mangrove restoration projects and to improve data coverage and consistency.

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The Mangrove Restoration Tracker Tool: Meeting local practitioner needs and tracking progress toward global targets

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SUMMARY

Restoration is a key component of global and national efforts to combat ecosystem degradation, reduce biodiversity loss, and adapt to climate change, and there is currently an impetus to scale up restoration efforts. However, our ability to track progress toward restoration targets is limited by the lack of consistent and standardized data on objectives, interventions, and outcomes. To address this, a collaboration of conservation practitioners and scientists from around the world have developed the Mangrove Restoration Tracker Tool (MRTT), an application to record and track outcomes from mangrove restoration projects. The MRTT records information across the lifetime of a project, capturing data describing the site background and pre-restoration baseline and the restoration interventions and costs, as well as post-restoration monitoring that incorporates both socioeconomic and ecological factors. The MRTT allows decision makers, practitioners, and site managers to access information that is essential in making informed, evidence-based decisions on restoration interventions to maximize impact and success.

INTRODUCTION

The current decade, 2021–2030, has been declared the United Nations (UN) Decade on Ecosystem Restoration by the UN General Assembly, with restoration being a key component of countries' efforts to increase adaptive capacity to climate change[1] and meet the UN Sustainable Development Goals.[2] This declaration builds on past efforts such as the Bonn Challenge,

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which in 2011 set ambitious global forest restoration targets to recover 350 million ha of lost and degraded land.[3] The Kunming-Montreal Global Biodiversity Framework has further bolstered these efforts by including the target "that by 2030 at least 30 percent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration."[4] This has stimulated nations and organizations to set ambitious targets regarding the amount of the land or ocean that can be restored. These initiatives set aspirational targets about what society can and must achieve to combat ecosystem degradation, reduce biodiversity loss, and adapt to climate change, while protecting the rights of local and Indigenous peoples. However, our ability to track progress toward these targets is often limited.[5] Understanding the drivers of where and why restoration efforts are successful, partially successful, or not successful, and how these challenges can be addressed, is critical to achieving cost-effective restoration, given that current investment in nature-based solutions is less than half of what is needed to tackle the global climate change and biodiversity crises.[6]

Although relatively small in area globally, coastal vegetated ecosystems—seagrass meadows, tidal marshes and mangrove forests—sequester disproportionally large amounts of fixed carbon per unit area compared to many terrestrial ecosystems, and thus, there has been a growing interest in their conservation and restoration to mitigate climate change.[7] In addition, there has been increasing recognition of the other multiple ecosystem processes and services that mangrove forests provide[8–10]; this includes supporting both commercial and subsistence fisheries,[11] havens for wildlife (e.g., migratory and resident birds),[12] providing materials for fuel and construction,[13,14] and providing areas for tourism and recreation.[15] The restoration of coastal and marine ecosystems is less developed than for many terrestrial systems[16,17]; however, restoration efforts in coastal ecosystems have increased markedly over the last 40 years.[18] Mangrove forests in particular have been the focus of increased restoration efforts, driven partly by the potential for intact forests to reduce the impact of storm surges,[19,20] which attracted attention following the 2004 Indian Ocean tsunami.[21,22]

Given their importance, there is a compelling incentive for restoring mangroves alongside efforts to effectively govern and manage existing mangrove areas. However, many mangrove restoration efforts have been beset with low survivorship or no long-term positive change in mangrove cover.[22–25] Failures have been driven by a number of factors, such as species plantings in sites outside of their physiological tolerance,[22,24] attempts to plant mangroves in other ecosystems (e.g., mudflats below mean sea level, tidal marshes) where they do not naturally occur,[26] lack of community engagement and support,[27] or failure to tackle the underlying drivers of mangrove loss. While some of these factors are attributable to applying incorrect technical restoration methods,[22] they are often driven by a failure to address the underlying social, economic, or political enabling conditions, such as social equity or land tenure.[28,29] In addition, pressure to meet area-based or planting targets promotes the pursuit of short-term goals rather than long-term sustainability when designing, implementing, and monitoring a restoration project.[28] Despite these challenges, there are many examples of successful mangrove restoration efforts.[16,25,30] Understanding the enabling conditions and drivers of recovery along the continuum of success[31] and quantifying the most cost-effective approaches will be crucial to successfully scale up restoration globally.

To allow practitioners to learn from experience and deliver a higher return on investment,[5] restoration efforts need to consistently capture standardized data on objectives, interventions, and outcomes, but this is lacking. Reporting should include the outcomes of all efforts, including those that are partially

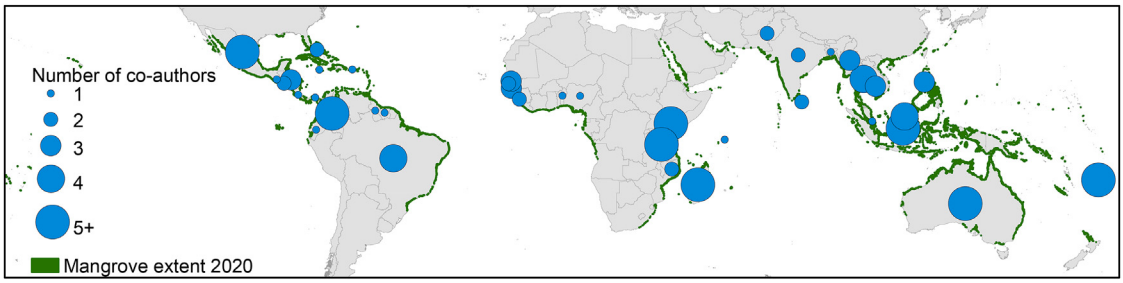

Figure 1. Countries in which the paper's co-authors have expertise in mangrove restoration projects

successful or even failed efforts.[32] Consistent and comprehensive project recording would allow more rapid assessment of diverse approaches and their outcomes, alongside enabling the tracking of progress toward restoration targets. Recent syntheses of mangrove restoration efforts[25,33–37] have each required significant inputs of time and resources to extract project metadata from highly diverse sources. A repository that is open access, well documented, and has funding for long-term maintenance and support, in which organizations and practitioners can submit and store data on their restoration projects, would help to ensure coverage and consistency in the data recorded, something that is currently lacking and hampers knowledge exchange.[37] Accurately recording the location of projects would also afford the potential to independently monitor the outcome of restoration efforts. Additionally, standardizing the measures of project success will be beneficial, because currently hundreds of different metrics are used across projects,[33,35] which makes systematic data-driven syntheses challenging.

Here, we describe the Mangrove Restoration Tracker Tool (MRTT), an open-access resource to capture information on the key variables from mangrove restoration projects and to improve data coverage and consistency. It can be used by any project aiming to assist in the recovery of degraded, damaged, or destroyed mangroves. The MRTT is designed both to aid in reporting on individual restoration actions and, through information sharing, to enable future efforts to be more effective financially, ecologically, and socially. The information reported in the tool provides a comprehensive, evidence-based baseline for evaluating restoration, and thus could be adapted to track restoration efforts in other ecosystems. Having a tool that captures and shares standardized information will aid decision makers, practitioners, and site managers in making inferences across restoration projects and understanding the nuances that drive the degree of success. The MRTT will act as a guide to practitioners who are designing restoration projects, ensuring that the data they collect cover the range of factors that are important for restoration efforts to succeed. The MRTT will also allow decision makers, practitioners, and site managers to access information on their organization's restoration sites quickly and easily. This will be essential in making informed, evidence-based decisions on restoration interventions to maximize impact and success. Finally, the MRTT is envisioned as a global repository, with the potential to conduct assessments using stored data at scale to calculate progress and impact toward national and international targets and initiatives and the representativeness of restoration efforts.

RESULTS

Method summary

The MRTT data entry application is underpinned by a set of questions designed to capture metadata that fully describe a mangrove restoration project throughout its life cycle, from planning through implementation to long-term monitoring. These questions form a standardized framework that is split into 3 main sections and 10 sub-sections. The aim was to create a framework that was comprehensive in terms of the topics covered and applicable to mangrove restoration projects across the world, yet simple and intuitive so as not to be too time-consuming for participants to complete. While several other data entry, storage, and analysis platforms have been developed to record and synthesize information on restoration projects, the MRTT differs in that it specifically focuses on mangrove ecosystems and as such, can provide greater depth on the topics covered.

The MRTT was co-designed with the Global Mangrove Alliance (GMA; www.mangrovealliance.org) and was developed through a broad collaboration of over 100 researchers and practitioners from academia, research agencies, and non-governmental organizations (NGOs). The long-term use of such a tool is dependent on it being established within the mangrove conservation community, easy to use, and the recipient of secure funding to support continued hosting and maintenance. As such, the MRTT is hosted on the GMA's Global Mangrove Watch geospatial data platform (http://www.globalmangrovewatch.org), which was launched in 2020 and has secured funding to 2027.

To develop the framework, we applied an iterative process of discussion, comment, and reflection based on the input of mangrove restoration experts, including practitioners and scientists, from around the world. Over 100 participants were convened to develop the framework for the MRTT. The aim was to acquire input from participants from different locations, with backgrounds across research, project management, or on-the-ground implementation, with expertise in aspects such as mangrove ecology and the socioeconomic, governance, financial, and biophysical aspects of restoration. All participants were invited to co-author this paper, and the final group of authors have expertise in mangrove restoration projects from 38 countries, covering the majority of the global mangrove regions (Figure 1).

The number, wording, and formatting of the questions that form the MRTT framework were developed over an approximately

2-year period through an interactive process including workshops and written drafts, until a consensus was reached (Figure 2; see experimental procedures for full details). An initial list of questions that covers the information needed to comprehensively describe a mangrove restoration project was based on research by Gatt et al.[37] These questions were modified during five virtual workshops that enabled researchers from academia, research agencies, and NGOs to review the framework question by question. To gather input from practitioners carrying out on-the-ground mangrove restoration, workshops were held in three locations: Fiji, Mexico, and east Africa (with participants from Kenya, Tanzania, Mozambique, and Madagascar). These workshops were used to assess whether the MRTT met the needs of the restoration practitioner community and provided a space for feedback to further tailor the tool to restoration implementors. To further test the MRTT using active restoration sites, the MRTT was trialed at sites in Mexico, with feedback from these field trials resulting in further revisions to the framework. The final framework was then used to develop the MRTT data entry application.

The MRTT data entry application was designed to provide a user-friendly interface to record information on mangrove restoration projects. The questions within the MRTT are generally closed ended, including multiple choice, tabular, or spatial data formats. The number of open-ended questions is limited to allow more rapid data entry and provide easier comparison across different restoration projects. Data are entered for "sites," which are defined as the area where the biophysical or community-based interventions took place, with the geographical boundary of the site captured in the tool to provide an accurate location. For larger projects where interventions are carried out at multiple sites, these can be grouped under a "landscape." Each landscape is linked to one or more "organization(s)" that are leading the project and entering the data. The tool has been designed to be intuitive and cohesive for the user, and therefore, there are linkages between different sections of the tool. For example, mangrove species lists in the later sections of this paper are automatically sorted based on the countries selected in the first section.

The MRTT data entry application and project database is hosted on the Global Mangrove Watch platform (https://mrtt.globalmangrovewatch.org/) and designed to complement other geospatial data such as mangrove extent and change and restoration potential. To support data entry, guidance documentation is provided that describes the background and rationale behind the questions and defines the key terms used. The aim is to provide online training on the MRTT for practitioners undertaking mangrove restoration. The MRTT will be housed alongside other guidance documentation, providing information on ecologically and socially focused restoration.

Resource description

Structure of the MRTT framework

The framework is split into 3 main sections and 10 sub-sections (Figure 3), which can be completed at different points during the lifetime of a mangrove restoration project or concurrently for historical projects. The registration (first) section comprises five sub-sections: (1) site details and location, (2) site background, (3) restoration aims, (4) causes of decline, and (5) pre-restoration assessment (Figure 3). This part of the tool describes the background to the site and project, capturing information on the site location, the stakeholders involved in developing the project, and the site's management and protected status and governance and land tenure arrangements (Table 1). This section also records the aims of the restoration project, which can be ecological or socioeconomic, and provides the context for restoration by describing the underlying drivers of mangrove loss and degradation at the site, as well as a pre-restoration baseline in terms of the species present at the site and site biophysical measurements. The registration section is envisaged as being completed prior to on-the-ground restoration activities commencing.

The intervention (second) section is composed of two subsections, (6) site interventions and (7) costs (Figure 3), which can be completed once restoration activities have been undertaken. In the site interventions sub-section, information is recorded on what biophysical interventions were used to restore/rehabilitate the site, whether best-practice restoration training was provided, and whether other activities, such as securing tenure arrangements or formal protection, were implemented at the site to address the causes of decline. For costs, questions included whether the support was monetary or voluntary (or both), what funders supported the project, and what was the total cost of the project (Table 1).

The final monitoring section comprises 3 sub-sections, (8) management status and effectiveness, (9) socioeconomic and governance status and outcomes, and (10) ecological status and outcomes (Figure 3), and was designed to capture data over single or multiple monitoring surveys through time at a site. There is no limit to the number or timing of monitoring surveys that can be entered into the MRTT, with each monitoring survey tagged with the survey date, allowing changes in management status, socioeconomic outcomes, and ecological indicators to be recorded pre- and, at multiple times, post-intervention, and relative to a reference site. Topics within management status and effectiveness include identifying the stakeholders managing the site post-restoration, whether stakeholders can influence management rules, and the sustainability of funding for the site (Table 1). There are also questions about whether the management status and protected status have changed relative to the information collected in the site background subsection. Similarly, in socioeconomic and governance status and outcomes, changes in governance and tenure arrangements relative to the site background subsection are recorded, as well as the socioeconomic outcomes of the project. The changes in socioeconomic outcomes can be observational or quantitative and can be reported relative to baselines such as a before-measurement or comparison site. The final subsection on ecological status and outcomes captures information on changes in mangrove area and condition, whether natural regeneration is apparent, and the survival of any planted material (Table 1). The subsection also records changes in ecological outcomes that can be reported relative to baseline measurements (for a full narrative on the different sections, see Note S1, and for the full framework, see Note S2).

Outputs of the MRTT

There are a number of outputs associated with the MRTT. A data entry application of the MRTT framework is hosted through the

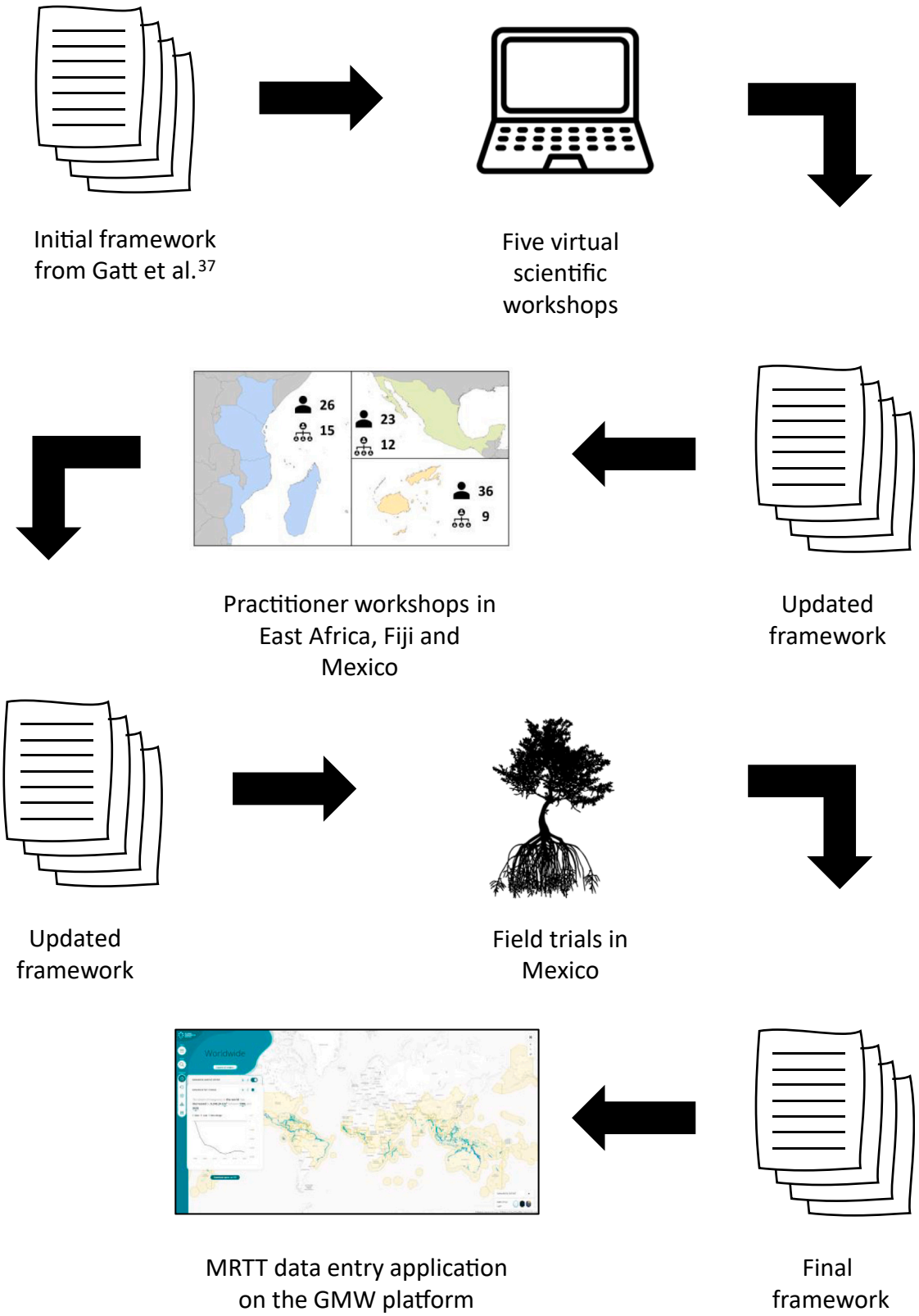

Figure 2. Schematic showing the iterative process used to refine the framework underpinning the MRTT data entry application

Numbers of participants (person icon) and organizations represented (organizational structure icon) for the practitioner workshops are shown for each region. Laptop icon made by Uniconlabs from www.flaticon.com.

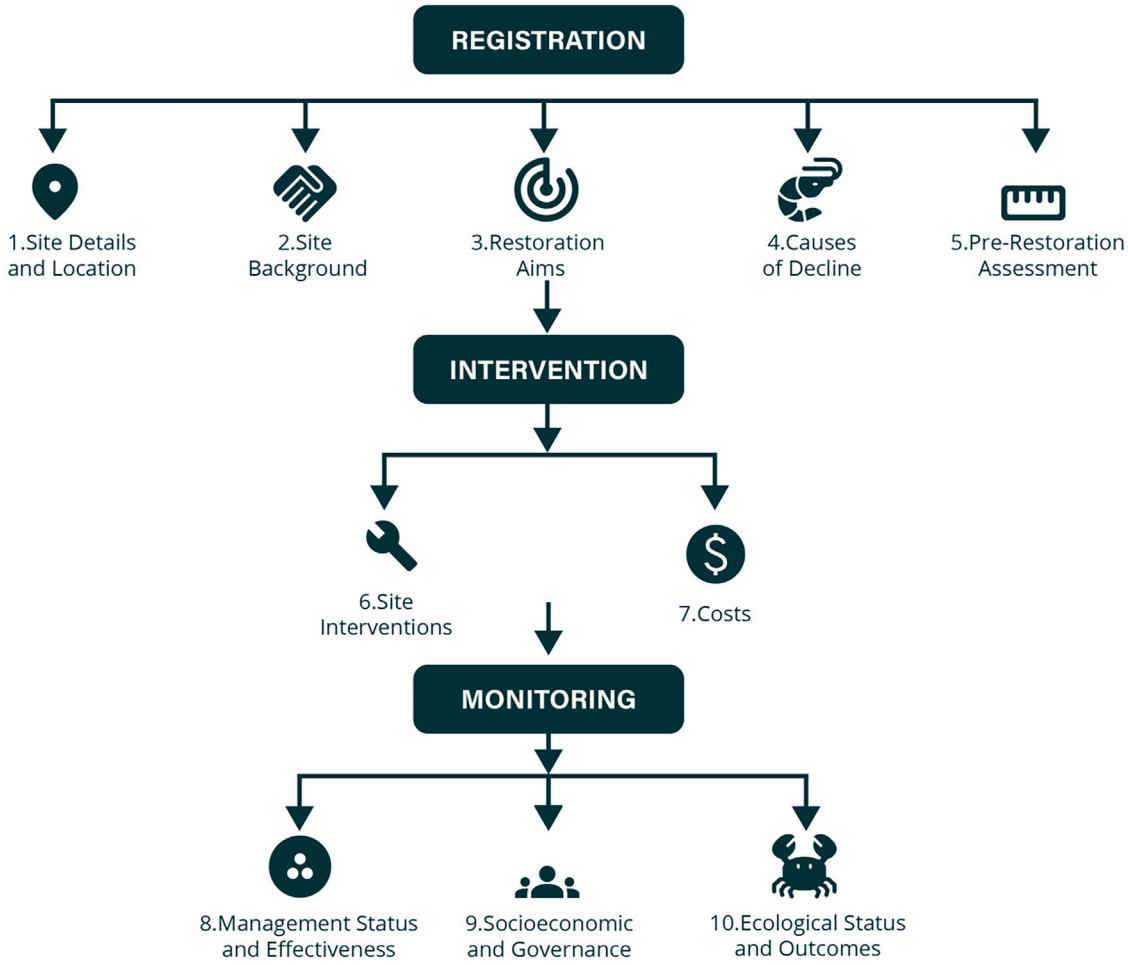

Figure 3. The structure of the MRTT framework with the 3 main sections and 10 sub-sections

Global Mangrove Watch website, with access through a secure user registration process. Users can enter their information into the data entry application (Figure 4) and use the MRTT as data storage for all their restoration projects. Data can then be downloaded as a project report for each site. This will aid users to quickly collate an easy-to-read summary of their project for use in communication and decision-making processes. The online platform and framework are available in English and Spanish, with French and Bahasa Indonesia to be added in the near future. A user guide that provides a step-by-step description of the portal and the data entry process is available in seven languages (English, French, Spanish, Bahasa Indonesia, Portuguese, Swahili, and Arabic). A map of all sites entered into the tool will be available on the Global Mangrove Watch website. This visualization of restoration efforts will help future projects to identify the restoration techniques used in areas with similar environmental and socioeconomic settings.

Data-sharing considerations

The global database containing projects submitted to the MRTT data entry application will be hosted on the Global Mangrove Watch website. In the interest of collaboration, the approximate site location, name, and contact details for a person responsible for a project for all sites will be made public. However, the tool will allow users to select from a range of data-sharing options for all other data input into the MRTT.

(1) All data treated as private and available only to other individuals with whom the project owner chooses to share them.
(2) Sections with sensitive information (e.g., project costs) kept private, while other data are made public.
(3) All data publicly accessible.

The GMA Science Working Group has access to all raw data, but these will only be used in an anonymized and aggregated way to conduct large-scale mangrove restoration analyses without project sites or organizations being individually identifiable.

Technical validation

To demonstrate the utility of the MRTT to capture the full breadth of information describing a mangrove restoration project, here, we transcribe the narrative from a published case study into the questions outlined in the MRTT framework. While such

Table 1. Sections of the MRTT, the topics covered in each section, and notes or justification for their inclusion

No.	Section	Notes
Registration		
1	Site details and location ● project start and end dates ● location	accurate location data provide an opportunity to independently monitor and validate restoration outcomes; when coupled with remotely sensed data, there is the potential to monitor key ecological indicators[38,39]
2	Site background ● stakeholders ● site management status, protected status, governance, and land tenure	the long-term viability of mangrove restoration efforts has been linked to factors that support the stability of the site, such as institutional strength, legal frameworks, and governance arrangements[40–42]
3	Restoration aims ● Ecological, socioeconomic, and other aims ● Ranking of the importance of the selected aims to different stakeholders	there are a diverse range of potential aims of a mangrove restoration project, and these aims should help determine the interventions used and the monitoring carried out
4	Causes of decline ● causes of mangrove loss or degradation, and the magnitude of their impact	understanding the underlying cause of mangrove loss and degradation can help indicate the most appropriate restoration interventions[43,44]
5	Pre-restoration assessment ● previous restoration efforts at the site ● pre-restoration site measurements (e.g., year of mangrove loss, evidence of natural regeneration, species present) ● baseline physical site measurements	biophysical setting such as salinity,[45,46] hydrology,[47] microtopography,[48,49] and sediment conditions[22] is important in determining the most appropriate restoration actions
Intervention		
6	Site interventions ● biophysical interventions, including duration and species used ● other activities to address causes of decline	information on the type of restoration activities implemented alongside the outcomes from the monitoring sections will provide quantitative data on the effectiveness of different approaches
7	Costs ● types of support monetary versus voluntary ● funders ● total costs and costs across broad categories	data on costs of restoration activities are underreported in the peer-reviewed literature but are crucial to understanding cost-effectiveness[50,51]
Monitoring		
8	Management status and effectiveness ● stakeholders managing the site ● changes in management status, protected status ● ongoing funding and resources	the monitoring sections, in combination with the preceding contextual information on the background of the site and project, provide an opportunity to assess the effectiveness of different restoration activities; post-restoration management and protected status, governance, and land tenure are compared to pre-restoration responses; information and data can be recorded on a range of outcomes, including socioeconomic indicators that are often not reported in the peer-reviewed literature[37]
9	Socioeconomic and governance status and outcomes ● changes in governance, land tenure ● socioeconomic outcomes	
10	Ecological status and outcomes ● changes in mangrove area and condition, evidence of natural regeneration ● survival of planted material ● ecological outcomes	

information could likely be supplemented by the knowledge of those involved in the project, this example is used simply to demonstrate the scope of information that the MRTT can record. This case study is an example of Community-Based Ecological Mangrove Rehabilitation from Indonesia.[52] The restoration took place at six villages and as such could be entered into the MRTT as six sites within an overall landscape; however, for the purposes of this example, the information was summarized for a single site. (For a list of the sections and questions, see Note S2).

The project took place on Tanakeke Island, South Sulawesi Province, Indonesia (section 1: question 2 [1.2]). Stakeholders from several groups were involved in developing the project, and its planning, management, and implementation such as international or national NGOs (Mangrove Action Project Indonesia) and local NGOs (Yayasan Konservasi Laut, Indonesia), local community representatives, and government representatives at local, sub-national, and national levels (2.1). The tenure of the site prior to restoration was a mixture of communal and national government (2.8). The project had multiple aims, both ecological (including increase mangrove area, increase native fauna/wildlife, and restore hydrological connectivity [3.1]) and socioeconomic (including secure management rights and land tenure, generate employment and income, promote women's equal representation

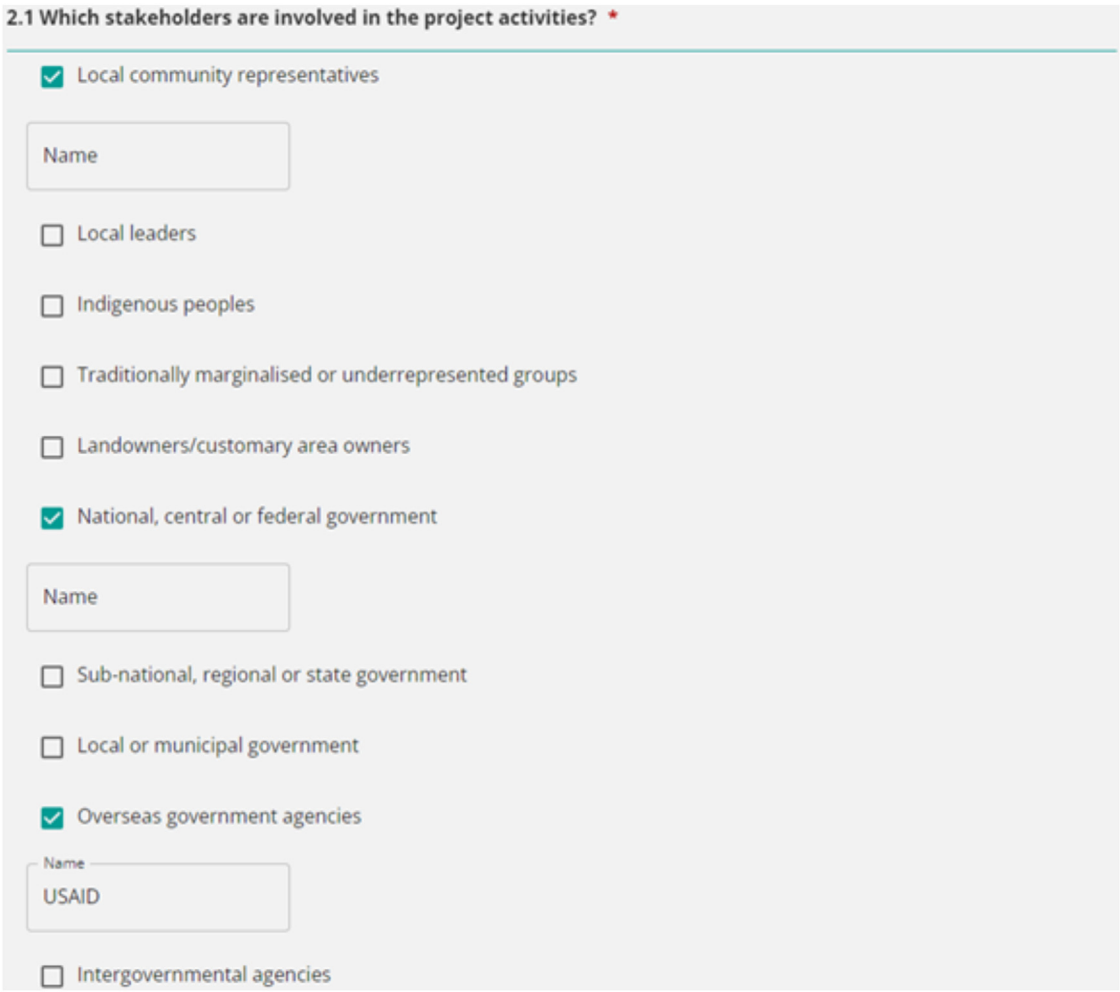

Figure 4. Example of data entry on a question from the site background section showing a hypothetical example

and participation in employment, and education/raise environmental awareness [3.2]).

The main drivers of mangrove loss and degradation in the area were known (4.1) and were fish and shrimp aquaculture, logging and wood harvesting for building materials and charcoal production, and fuel wood collection (4.2). Mangroves had previously naturally occurred at the site (5.1), and restoration through planting (5.2b) had been attempted (5.2). Prior to restoration activities the site was assessed (5.3) through a field assessment (5.3a), with natural regeneration apparent at the site (5.3d) and the species present identified (5.3e).

Interventions at each site were restoring hydrology through the breaching of aquaculture pond walls and excavating channels, reprofiling and changing the elevation of the site, planting, and the broadcasting of propagules (6.2). The local community helped undertake project activities (6.2), with local participants trained in ecological mangrove rehabilitation (6.3). Other activities implemented at the site to address the causes of mangrove decline were environmental education and the development of mangrove management groups (6.4). The project received monetary support (7.1), with funding from the Canadian International Development Agency (90%) and OXFAM-GB (10%) (7.3), at a total cost of $590,000 (7.4).

The creation of a multi-stakeholder mangrove management working group provided an opportunity to access funds for ongoing site management through fiscal financial mechanisms (8.6). Ecological monitoring was undertaken by a team consisting of members of an international or national NGO, community members, and an academic institute (10.2). Mangrove area had increased (10.3), by 43 ha (10.3a). Data were collected on tree density and species, relative to before measurements and literature value baselines (10.7a).

Limitations

The aim of the MRTT is to fully describe and document a mangrove restoration project, from planning through implementation to long-term monitoring, incorporating a variety of stakeholders, such as local communities, practitioners, managers, and scientists. Thus, the framework that underpins the data entry application was designed to be comprehensive in terms of the topics covered and applicable to mangrove restoration projects across the world. However, there is a

trade-off between comprehensiveness and practicality, where questions need to be simple and intuitive and not too time-consuming for participants to complete. Therefore, some topics were covered with less depth than would be needed to fully capture the nuances among projects. For instance, recording associated costs is complex and multifaceted[50]; however, within the MRTT, only total costs and those associated with broad categories are recorded. This reduces the time required to complete that section and allows easier synthesis of project data.

While the aim was to provide questions that were easy to complete, the number of possible responses for some individual questions with the MRTT is extensive. This is driven by factors such as the large number of stakeholders involved in mangrove restoration,[31,37] the number of potential restoration aims, and the range of different ecological and social metrics that have been used to monitor restoration efforts.[35] For example, Cadier et al.[35] identified 238 indicators that had been used to monitor coastal restoration projects, with up to 23 indicators used in a single project. As mangrove restoration science continues to develop, consensus on a set of key functional indicators would facilitate comparison across projects.[53] In the MRTT, we address this complexity in the number of potential responses by providing clear definitions of the key terms.

Data accuracy, as one of the main challenges with data-gathering applications, such as the MRTT, has been widely identified.[54,55] To address this, we used several approaches: we limited the number of open-ended questions within the framework; we designed an inherent logic within the tool for some of the numerical values, for example, percentages not being able to sum to greater than 100%; and we created connectivity such that previous answers affected the output of following questions. In addition, we applied a number of the methods that have been advocated for citizen science initiatives, such as producing the MRTT through iterative design, particularly engaging practitioners who will undertake data entry, providing training through online guidance documentation, and making data entry simple and intuitive.[56,57]

DISCUSSION

Comparison to existing platforms

Given the impetus behind restoration efforts, a number of data entry, storage, and analysis platforms have been developed such as Restor,[58] FERM (Framework for Ecosystem Restoration Monitoring),[59] and FL-WES (Forest and Landscape Water Ecosystem Services).[60] Similar to the MRTT, in general, these tools allow both field-level data capture and rapid synthesis of restoration efforts. Restor, FERM, and FL-WES capture some information similar to that gathered by the MRTT; however, owing to these platforms' broader focus, the breadth of information gathered is generally reduced to one or two metrics (Table 2). All the platforms, including the MRTT, are centered around accurately recording the location of the restoration sites via the delineation of the site boundary.

The focus and ecosystem scope of Restor, FERM, and FL-WES differ significantly from those of the MRTT, crossing ecosystem boundaries and capturing information on restoration projects in multiple habitats. Restor and FERM use the site location to provide data to the user on the site's biophysical and socioeconomic setting (e.g., temperature, precipitation landcover, human population), biodiversity, and carbon, based on global geospatial datasets. FL-WES uses data input to suggest key indicators for monitoring water ecosystem services. The MRTT differs from these platforms in that it is specifically tailored to mangrove restoration, allowing the nuances and specific techniques of interventions in the coastal zone to be more explicitly captured. It also captures far more information across the different sections to provide a detailed description of the restoration efforts. The challenge will be to integrate the data from the MRTT alongside these other data synthesis platforms to quantify restoration efforts generally, as part of the UN Decade on Restoration and the Kunming-Montreal Global Biodiversity Framework targets.

Application and usage

Here, we have developed a standardized mangrove restoration reporting tool, which has the potential to support a step change in how we record, communicate, and assess outcomes of mangrove restoration globally. The success of the tool will ultimately depend upon it being adopted by the mangrove restoration community. With this in mind, we elicited expertise from more than 100 experts globally through collaborative co-design and field testing and developed the tool in collaboration with the GMA, whose members support or are actively involved in restoration projects around the world.[61] This approach also ensured the robustness and applicability of the approach.

Adoption and use of the MRTT will support objectives such as the assessment of mangrove restoration outcomes, greater access to information on the factors contributing to mangrove restoration success, and comprehensive tracking of progress toward restoration targets. Past restoration efforts demonstrate a mixed record on reporting and monitoring, and improvements to this situation may be further hindered by a lack of common protocols or tools for undertaking such work. The MRTT provides such a framework, covering, in a single tool, preparatory processes, restoration, and monitoring. It enables a common approach applicable to the considerable range of restoration approaches already being undertaken and should encourage practitioners to record and report in a comprehensive manner. As data entered are made available to others, a considerable added value will come from enabling new practitioners or sites to benefit from past and ongoing work around the world, but potentially also enabling direct connections to be made between practitioners and new approaches to be transferred between places and continents.

These benefits will support a number of high-level initiatives, including the Bonn Challenge and New York Declaration on Forests, the UN Framework Convention on Climate Change, and the Kunming-Montreal Global Biodiversity Framework. Ultimately, better data on mangrove restoration outcomes will help local, regional, national, and international efforts toward the successful restoration of mangrove ecosystems, which in turn support the benefits that mangroves provide, including livelihoods, delivery of ecosystem services, and climate change mitigation and adaptation.

Table 2. Questions from MRTT that have equivalents in the Restor, FERM, and FL-WES platforms

MRTT section	No. of questions	MRTT questions
Registration		
Site details and location	5	project start date? (Restor, FERM) project end date? (FERM) what is the overall site area? (Restor, FERM, FL-WES)
Site background	9	which stakeholders are involved in the project activities? (FERM) what best describes the governance arrangement of the site immediately before the project started? (Restor) what was the land tenure of the site immediately before the project started? (Restor)
Restoration aims	3	what are the ecological aim(s) of the project activities at the site? (Restor, FERM, FL-WES) what are the socioeconomic aim(s) of project activities at the site? (Restor, FERM, FL-WES)
Cause of decline	3	is the cause(s) of mangrove loss or degradation at the site known? (Restor, FL-WES)
Pre-restoration assessment	15	what physical site measurements were taken? (FL-WES) was external expertise or guidance consulted on how to best restore the site? (FL-WES)
Interventions		
Site interventions	8	what biophysical interventions were used to restore/rehabilitate the site? (Restor, FERM, FL-WES) were there other activities implemented to address the causes of decline at the site? (FERM)
Costs	7	–
Monitoring		
Management status and effectiveness	14	–
Socioeconomic and governance status and outcomes	9	–
Ecological status and outcomes	11	–

EXPERIMENTAL PROCEDURES

Mangrove restoration assessment framework

The initial list of questions to describe a mangrove restoration project was compiled into a 10-section framework by Gatt et al.[37] This framework was used to evaluate the coverage and consistency of key indicators when reporting on mangrove restoration projects within the peer-reviewed scientific literature. Across 123 published case studies, many gaps in reporting were identified, particularly in relation to topics such as pre-restoration site baselines or socioeconomic outcomes.[37] Other areas such as the project aims or aspects of ecological monitoring were much more widely covered.[37]

Scientific workshops

The framework developed by Gatt et al.[37] was modified based on a series of five virtual thematic workshops held between January and June 2021. These workshops addressed different sections of the framework and enabled researchers from academia and NGOs to review and input into the framework structure on a question-by-question basis. They involved over 40 participants from across North and South America, Europe, Africa, Asia, and Australia. The participants self-selected into at least one of the workshops, which covered the following:

(1) Defining a mangrove restoration project, the project details to be recorded, site-enabling conditions for restoration, and the project aims
(2) Assessing the causes of mangrove decline, conducting site baseline surveys, and biophysical interventions
(3) Determining project costs
(4) Addressing management, regulations, and social and governance monitoring
(5) Monitoring ecological health

Following the workshops, participants were able to access a draft of each section where they could provide written comments and suggestions. These workshops resulted in continuous iterative changes to the structure and questions of the framework.

Review of framework

The development of the framework was an iterative process, and the draft document was reviewed multiple times by the participants. After feedback

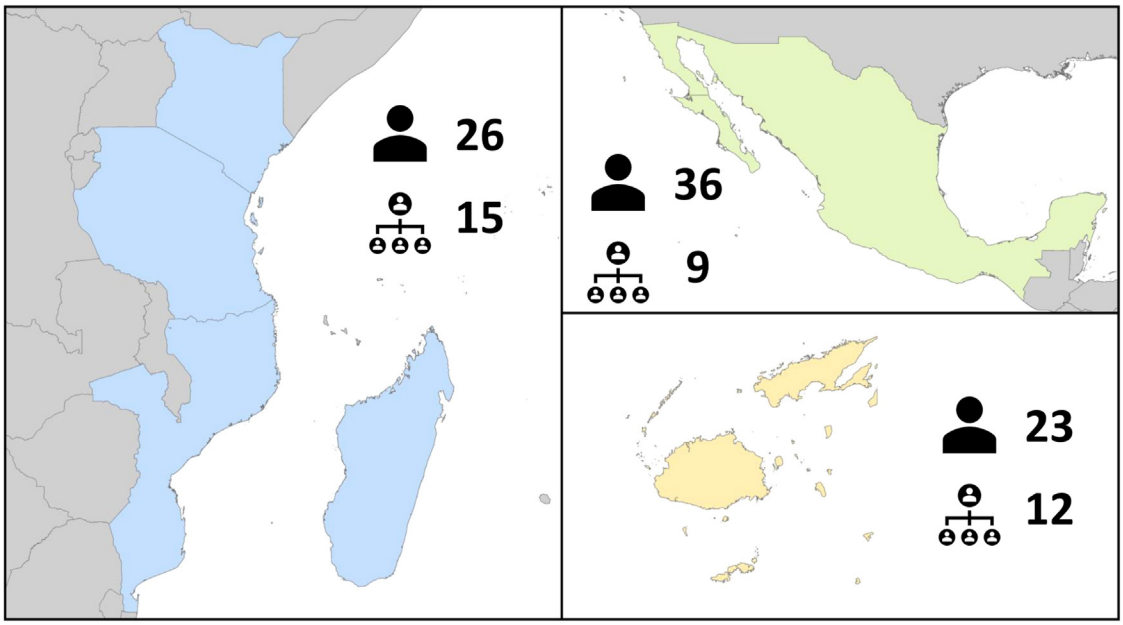

Figure 5. The number of participants (person icon) and organizations (organisational structure icon) represented at the MRTT practitioner workshops in Fiji, Mexico, and east Africa (Kenya, Tanzania, Mozambique, and Madagascar)

from the scientific workshops, the original 10 sections were merged into 3 overarching sections: registration, interventions, and monitoring, with sub-sections nested within them. The entire revised framework was sent to the workshop participants so that feedback could be provided on all sections, allowing a more holistic overview of how the framework was structured to capture data across a project's lifetime. Given that the focus of many participants was more centered on biophysical and ecological aspects of restoration, the framework was also reviewed by the Landscape and Livelihoods Group, whose experts use interdisciplinary approaches to support the development of nature-based solutions to ensure that socioeconomic, governance, and management effectiveness information was represented in the framework.

Practitioner workshops

To gather input on the framework from practitioners implementing mangrove restoration, three workshops were held between July and September 2021 in Fiji, Mexico, and east Africa (covering Kenya, Tanzania, Mozambique, and Madagascar; Figure 5). Participants in these workshops were from national and international NGOs, research organizations, and universities (Table S1). The workshops consisted of five 2-h virtual sessions and aimed to (1) share best practices guidance for mangrove restoration; (2) review the MRTT framework through a lens of best practices; (3) analyze the utility of the tool and assess whether it met the needs of the local restoration community; and (4) provide a space for feedback on changes to the tool to make it more applicable for local use. Feedback and suggestions on how to improve the framework were collated and integrated into the framework.

Field trials

To further test the MRTT using active restoration sites, field trials were carried out in Mexico's Marismas Nacionales Biosphere Reserve. Participants from the World Wildlife Fund/WWF, The Nature Conservancy, La Comisión Nacional de Áreas Naturales Protegidas, Comisión Nacional Forestal, and community restoration groups undertook a 2-day field trial of the framework at four restoration sites in December 2021. Official mangrove restoration activities have been undertaken in the reserve since 2010. The field trial evaluated the framework based on field data entry and partner interviews. The trial considered questions such as: do the framework questions provide options that capture the details required? Is anything missing in the framework that would capture desired information about restoration project sites? Are there changes to make that would make users more likely to employ the framework for restoration projects? The feedback from the field trial initiated further revisions to the framework, particularly in regard to the scale of the assessment, and the perimeters of restoration sites when they overlap (see Note S2 for the full framework).

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to the lead contact, Thomas Worthington (taw52@cam.ac.uk).

Materials availability

The MRTT is freely available at https://mrtt.globalmangrovewatch.org/, with training materials available at https://www.mangrovealliance.org/tools-and-resources/.

Data and code availability

No new data or code were generated in this study.

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AUTHOR CONTRIBUTIONS

Conceptualization, Y.A.G., T.A.W., M.D.S., and D.A.A.-B. Methodology, Y.A.G., T.A.W., and D.A.A.-B. Validation, all authors. Investigation, all authors. Resources, R.W.W., T.A.W., L.H., K.L.-W., and D.A.A.-B. Writing – original draft, Y.A.G., R.W.W., and T.A.W. Writing – review & editing, Y.A.G., R.W.W., and T.A.W., and significant input from all co-authors. Supervision, T.A.W., D.A.A.-B., and M.D.S. Project administration, T.A.W., D.A.A.-B., and L.V. Funding acquisition, T.A.W., D.A.A.-B., and M.D.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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