



Challenges and Recommendations for Equitable Use of Aerial Tools for Mangrove Research

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As the use of aerial tools such as unmanned aerial vehicles (UAVs) for mangrove monitoring gains in popularity, understanding who leads this research and where is critical for expanding efficient monitoring methods and achieving international commitments to sustainable development, technology transfer and reduced inequality. Between 2000 and 2019, mangrove research using aerial tools was largely conducted in and led by institutions in higher income countries, despite High-income countries accounting for only 9% of global mangrove coverage. Of studies where the country of the lead institution differed from that of the study site, only 38% of the studies included local co-authors. These results echo historical patterns of research conducted by researchers from higher income countries on biodiversity concentrated in lower income countries, frequently with limited involvement of local scientists—known as “helicopter research.” The disconnect between where mangroves are located and where aerial research is conducted may result from barriers such as government restrictions, limited financial and technical resources, language barriers hindering UAV deployment, or hampered findability of local research. Our findings suggest that expertise for aerial surveys currently lies in “High-income, Annex II” and “Upper-middle-income, Non-Annex” countries, and both groups could invest time and resources in building local, long-term technological capacity in Upper-middle, Lower-middle and Low-income countries. We identify strategic partnerships to expand aerial tools for mangrove research that also address commitments under the United Nations Framework Convention on Climate Change and potential international collaborations under the framework proposed by the UN Decade of Ocean Science for Sustainable Development.

Keywords: UAVs, ocean observing, capacity development, technology transfer, country income

INTRODUCTION

As the global climate rapidly changes, mangroves have emerged as critical players for adaptation and mitigation, protecting coastlines against storms, and erosion and sequestering atmospheric carbon (Alongi, 2008; Donato et al., 2011). Yet, mangroves have historically high rates of deforestation, and land-use changes continue to threaten the habitat's future (Friess et al., 2019). Mangroves are considered an essential ocean variable to be monitored by the Global Ocean Observing System (GOOS) and are listed as an ecosystem indicator by the Sustainable Development Goals (SDGs) (Malone, 2003; CBD High-Level Panel, 2014; Friess et al., 2019). Long-term observations are necessary to support implementation of country-specific Nationally Determined Contributions (NDCs) of the Paris Agreement and fulfilment of other commitments that foster sustainable mangrove management (Bax et al., 2018). Monitoring mangroves provides baseline data foundational to guiding spatial planning decisions and financial investments that mitigate pressures from climate change, coastal development, pollution, agriculture and other land- and sea-use changes (Schmitt and Duke, 2015; Pham et al., 2019).

Least Developed Countries and Small Island Developing States often lack the resources and technology to carry out sustained observations, which tend to be financially costly and require long-term investment. This is especially true of *in situ* observations, which provide extremely detailed diversity and extent information crucial to local management. Establishing sustained monitoring requires building capacity and transferring technology (and associated technological skills) with these communities (Bax et al., 2018). Lower income countries are especially vulnerable to “helicopter research,” the process of researchers from high-income countries conducting field research in lower income countries without local researchers involved in the study or benefiting from the results; a trend spotted in soil science, biology, and genomics (Minasny et al., 2020). Thus, capacity development and technology transfer have been highlighted as priorities by the World Ocean Assessment, UN Convention on the Law of the Sea, Intergovernmental Oceanographic Commission, and the UN Decade of Ocean Science for Sustainable Development (UN Ocean Decade) (Inniss et al., 2016; Bax et al., 2018).

To better observe mangrove ecosystems, researchers have increasingly used remote sensing technologies (Wang et al., 2019). While satellite imagery has been leveraged to provide global estimates of mangrove extent (Bunting et al., 2018), the use of aerial tools is particularly well suited for *in situ* coverage. Aerial tools such as manned aircrafts and unmanned aerial vehicles (UAVs) have captured high-resolution data on many mangrove attributes, including forest extent, species biodiversity, vertical forest structure, and carbon flux (Zulueta et al., 2013; Feliciano et al., 2017; Ruwaimana et al., 2018). Due to their cost-effectiveness, UAVs are revolutionizing conservation management by providing high spatio-temporal observations, especially in small, inaccessible, or highly sensitive areas (Jiménez López and Mulero-Pázmány, 2019). Although the cost is variable,

employing UAVs is often cheaper and more efficient than using manned aircrafts or conducting on-the-ground mangrove surveys (Otero et al., 2018; Ruwaimana et al., 2018; Navarro et al., 2020).

This study explores the global distribution of studies using aerial imaging to monitor mangrove forests worldwide in relation to country income and United Nations Framework Convention on Climate Change (UNFCCC) designations. We investigate how equitable access to aerial tools can directly contribute to the societal outcomes of the: (1) UNFCCC, for sustainable partnerships between Developed Countries and Developing/Least Developed Countries (UNFCCC, 1992) and; (2) UN Ocean Decade, for the integration of remote and *in situ* observations to reduce observational costs (A Predicted Ocean) and increase data accessibility to stakeholders (A Transparent and Accessible Ocean) (Ryabinin et al., 2019). Under these frameworks, we detail challenges and recommendations to guide capacity building and technology transfer of aerial tools for mangrove conservation in lower income countries with greater mangrove coverage.

CURRENT GLOBAL DISTRIBUTION OF AERIAL RESEARCH

We investigated differences in the distribution between mangroves and aerial research alongside each country's socioeconomic status and UNFCCC commitment. We referenced the 2016 Global Mangrove Watch extent layer to map the mangrove distribution across countries, cross-referencing these countries with: (i) 2019 income group classifications from the World Bank; and (ii) Annex I, Annex II and Non-Annex designations from the UNFCCC (Bunting et al., 2018; UNFCCC, 2018; World Bank Data, 2019; UNEP-WCMC, 2020). The term “countries” is used interchangeably with economies as defined by the World Bank, and “does not imply political independence but refers to any territory for which authorities report separate social or economic statistics.”

To describe where aerial research is occurring and who leads the effort, we performed a manual literature search in English for each country with mangrove coverage on Google Scholar and Web of Science using a formula of key terms: “(country name) + mangroves + (aerial tool).” In place of “aerial tool,” the search was repeated for “aerial photography,” “drone,” “UAV,” “unmanned aerial system (UAS),” and “remotely piloted aircraft (RPA).” Search results were reviewed for relevant scientific publications, conference documents, and theses. After three search pages of no additional relevant literature, the search was determined to be exhausted. From each article, we collected where the study was conducted, who led the study, and the country of the lead author's institution. We examined the institutions of all co-authors and noted authors with institutions local to the study site. From our literature review, we analyzed a total of 72 aerial *in situ* studies conducted in 24 countries led by researchers from 19 countries. The majority of the studies used small UAVs to capture imagery (60%), followed by small airplanes (42%) and kites (1%).

We identified three main discrepancies:

1. Gap between mangrove coverage and study site based on income

Based on World Bank income levels, **Figure 1A** shows that global mangrove coverage differs from the countries of study sites. High-income countries published at four times the rate of the amount of coverage they have (mangrove coverage of 11%, but comprise 43% of studies) and Upper-middle-income countries published at 1.5 times their coverage (32 and 44%). Lower-middle-income countries published at 0.25 their coverage (46 and 10%) and Low-income countries published at 0.1 times their coverage (10 and 1%). Thus, mangrove occurrence was greater in lower socioeconomic countries, while mangrove aerial research was conducted in higher income countries.

2. Gap between mangrove coverage and lead country based on Annex designations

Annex II countries led 61% of the studies but accounted for just 9% of mangrove coverage, while Non-Annex countries led just 35% of the studies but represented 88% of mangrove coverage. Study sites were split between Annex II (40% of studies) and Non-Annex countries (56% of studies) (**Figure 1B**). Thus, mangrove occurrence was greater in Non-Annex countries, but research was largely led by Annex II countries.

3. Gap in capacity building

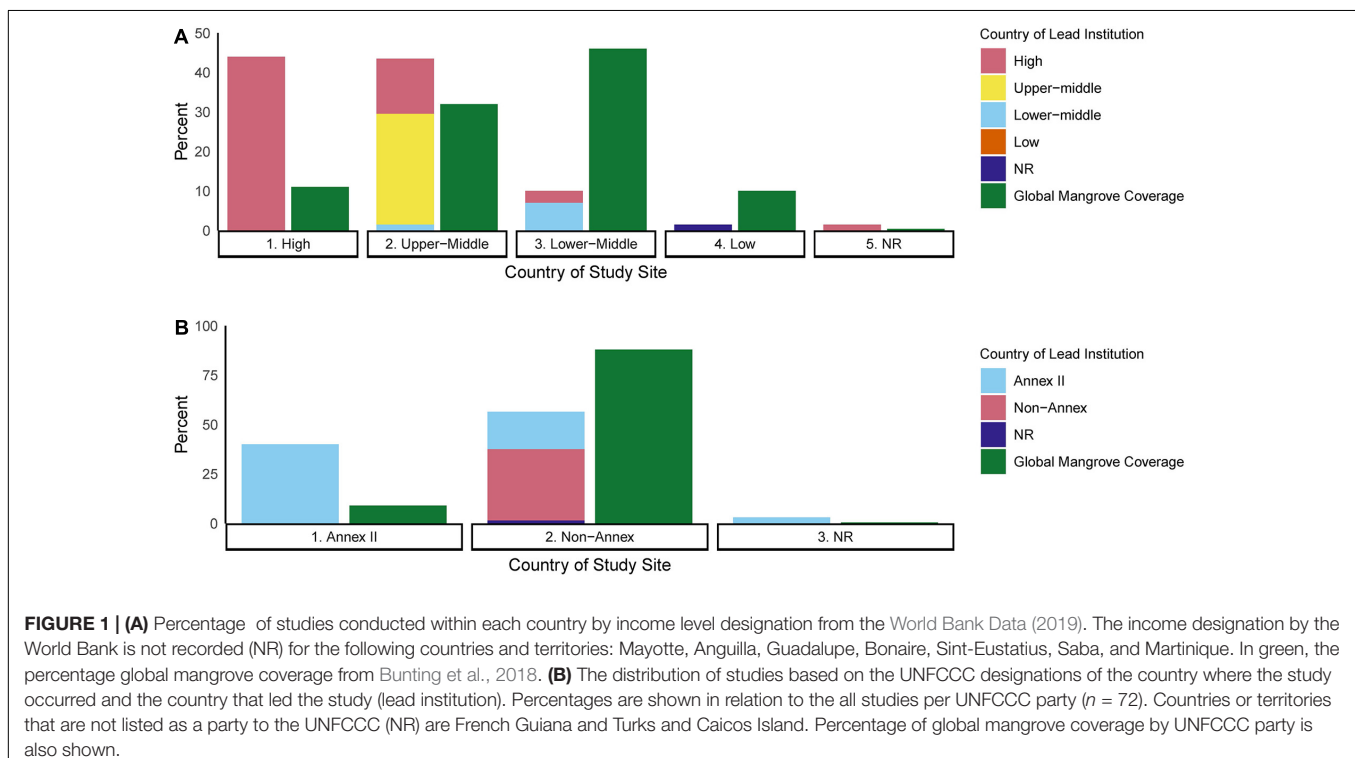
In 21 of the 72 studies (29%), the research site was in a different country than that of the lead institution (**Figure 2A**), and eight of these 21 studies (38%) included a co-author

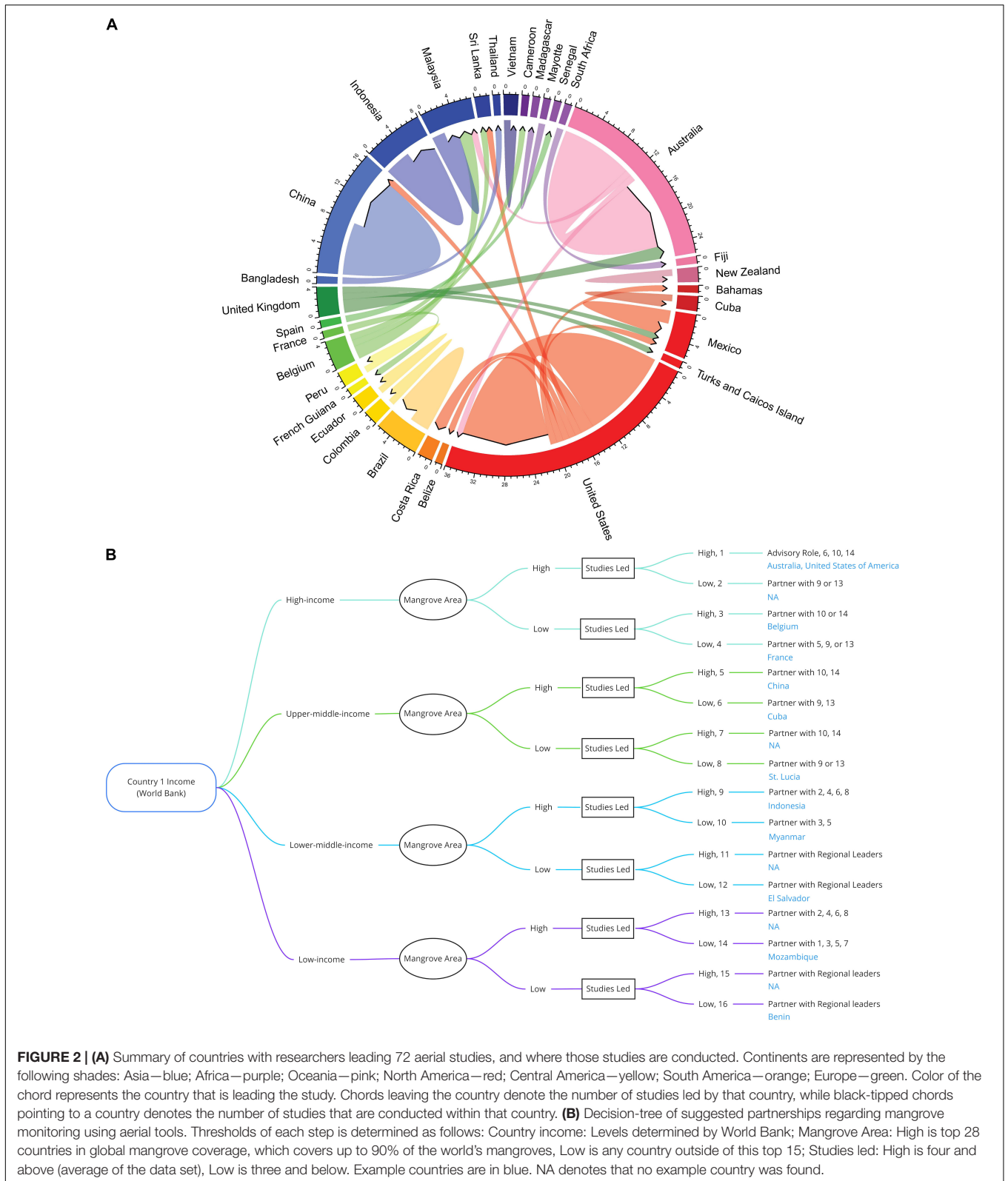
from a local institution. Of these eight studies, seven had lead institutions in High-income/Annex II countries and study sites in two other High-income/Annex II countries, four Upper-middle/Non-Annex countries, and one Lower-middle/Non-Annex country. The last study of the eight had an Upper-middle/Non-Annex country leading a study in a country without a World Bank income.

The gaps presented mirror the broader trend of a mismatch among biodiversity research and areas of high biodiversity. Higher biodiversity tends to be in countries with developing economies, yet biological research tends to be conducted in or by higher income countries (Fazey et al., 2005). The gaps also suggest trends of “helicopter research, and highlight a need to broaden aerial research endeavors and engage local communities in scientific leadership through capacity building and technology transfer.

CURRENT CHALLENGES AND RECOMMENDATIONS FOR UAVS

As UAVs are still an emerging technology, trends of helicopter research could be avoided. The 72 studies identified in this paper are just a sliver of the entirety of mangrove research; however, this problem has been identified across many disciplines and tools (Parsons et al., 2017; Minasny et al., 2020). By focusing on technology transfer, scientific equity, and collaborative processes across regions, the benefits of aerial tools could be harnessed globally and lead to greater collective knowledge generation.





Scaling UAV use for mangroves aligns with the UN Ocean Decade and could be achieved by filling gaps in data generation and resource availability early in the process and following

FAIR – findable, accessible, interoperable and reusable – data principles (Wilkinson et al., 2016). This study’s results suggest a disparity between countries where mangroves occur and

countries currently conducting aerial surveys. This can be explained by two reasons: the data have not been generated and/or were not found in this review. Both are likely true and are addressed below.

Data Generation

Government Restrictions

A lack of aerial data generation in some countries may be associated with restrictive government regulations of the scientific use of UAVs. For example, countries such as Cuba and India have bans against the commercial and scientific use of UAVs while others, including Chile and Colombia, place “effective bans” that technically allow UAV use but with strict requirements and licenses (Jones, 2017; Stöcker et al., 2017). Comparatively, several European organizations (i.e., European Union Aviation Safety Agency) focused on integrating regulated UAV use, allowing greater accessibility for commercial or scientific use (Stöcker et al., 2017). Countries like China, France, and the United States have experimental—and thus more flexible—UAV regulations as well as corporations (DJI, Parrot, Skydio) that manufacture UAVs. To enable emerging technologies to be used and established in low-income countries, regulations should be flexible to permit scientific UAV use while considering the sensitivity of local habitats.

Limited Financial and Technical Resources

Where government restrictions do not inadvertently restrict data generation, limited resources for mangrove research can be another common reason. As shown by several meta-analyses, biodiversity research tends to happen more in higher-income as opposed to lower-income countries, often due to lower research capacities in lower-income countries (Fazey et al., 2005).

To overcome financial difficulties, international collaboration for science and accessible funding sources for low-income country-led studies are key. The UNFCCC provides a framework to facilitate international capacity building and technology transfer in relation to climate change, since Annex II countries have committed financial support and knowledge transfer to developing countries (UNFCCC, 1992). Studying mangroves through aerial research is covered by this, as UAVs are well-suited to estimate local mangrove extent and carbon stocks relevant to NDCs (Ruwaimana et al., 2018). Thus, this study’s results can serve as one metric for Annex II countries’ mandatory reports on climate finance and technology support, and guide developing countries in their requests for technology and capacity building needs (Ellis and Moarif, 2015).

Outside of Annex II obligations, certain countries may find themselves in the position to lead. Upper-middle-income, Non-Annex countries such as China, Brazil, and Mexico comprised 28% of the studies and 32% of mangrove coverage. These Upper-Income Non-Annex countries may find themselves well-equipped to not only study their local mangroves, but to also act as regional leaders and extend their knowledge to neighboring countries. As such, the expertise for aerial surveys currently lies in High-income, Annex II countries and in Upper-middle-income, Non-Annex countries. These categories of countries can invest time and resources in the transfer of technology and skills to other

countries, especially Low-income countries (10% of mangrove coverage) which have only 1% of mangrove studies (**Figure 1**).

Furthermore, international journals could allow researchers and students in low-income countries access to articles free of charge, to promote the development of research capacity. This approach has already been implemented by organizations such as The Royal Society through their Research4Life initiative (Hamilton and Hurst, 2018). Other journals could consider implementing similar initiatives.

Software Language

Language barriers exist during the data acquisition process. With UAVs developed by Western and Chinese companies, languages are often limited to English, Chinese, and a handful of other languages. For example, DJI Ground Station Pro, a mission-planning companion app to DJI UAVs, is currently available in only Chinese, Japanese, and English (DJI, 2020). Likewise, Pix4Dcapture is available in English, German, Japanese, Spanish, Chinese, and Portuguese (Pix4D, 2020). The incompatibility in languages between the software and the end-users can be a challenge for capacity building of aerial technology. Private-public relationships and increasing demand for Unmanned aerial vehicle products could encourage broadening of available languages for associated software.

Data Findability and Accessibility

Our findings may also indicate that existing aerial mangrove observations and research conducted in Non-Annex and lower income countries are often not readily available online or are published in national journals or documented in other languages that hinder their integration into global baseline datasets, which are predominantly curated using the English language.

An additional challenge relates to making data accessible, which is a multi-faceted problem in itself. Often, data are not under a clearly defined data license, and “open access” itself is often insufficiently defined and communicated. Creative Commons licenses can help clarify different levels of access, and more organizations are promoting and implementing open data policies. Specific data contributor agreements often need to be put in place to use small, individual datasets together, which can be time-consuming and costly to implement.

DISCUSSION

To address these barriers, we recommend leveraging current frameworks for best practices and establishing new partnerships to facilitate knowledge sharing and technology transfer.

Leveraging Current Frameworks for Best Practices and Shared Methodologies

To support building capacity and the technology transfer of aerial tools for mangrove conservation, sharing the methodologies, metadata, and current data is crucial. Knowledge sharing can be done through the Global Mangrove Alliance (GMA), an alliance of global mangrove actors and stakeholders. The GMA’s extensive network encompasses a wide range of users, and their

Mangrove Knowledge Hub acts as a clearinghouse for accessible mangrove-related information. Adding resources for UAVs to the Mangrove Knowledge Hub can help increase the findability and accessibility of methodologies, and standardize methodologies. Further, through the GMA, encouraging members and non-members to deposit gray literature into the resources library can help elevate these studies, which can further increase the findability of gray literature—especially non-English literature. Findability of gray literature is further supported by platforms such as ePrints in Library and Information Science (E-LIS) which focuses on open science in multiple countries and over 27 languages (De Robbio et al., 2020). Effort on behalf of government and academic institutions to promote FAIR principles would also greatly reduce the “grayness” of literature and promote findability without the need to build new facilities or infrastructure (Schöpfel and Rasuli, 2018).

Partnerships

The low percentage of studies including local co-authors when lead institutions are foreign suggests that aerial research of mangroves may fall prey to helicopter research, and that robust partnerships and capacity building efforts are needed. To further support capacity building and technology transfer under the UNFCCC and UN Ocean Decade, developing effective partnerships to shepherd UAV training is needed. Some countries, such as Indonesia, maintain a legal mandate in which foreign researchers must involve local Indonesian scientists as equal collaborators (Rochmyaningsih, 2019). We identified the following potential partnerships to transfer use of aerial tools for mangrove conservation (**Figure 2B**):

- Upper-middle-income or High-income, Annex II countries could partner with Lower-middle or Low-income countries with high mangrove coverage to support training.
- Higher income countries that lead a low number of studies and have low mangrove coverage could offer investments for automated image analysis, such as improving internet access and supporting remote cloud processing (Miloslavich et al., 2018).
- Lower income countries that lead a low number of studies and have low mangrove coverage could train with respective regional leaders.

Even with these partnerships, effective capacity building and training workshops must be carefully conducted. As mentioned, limited language availability of associated software remains an obstacle, and demonstrates the important role of private institutions in expanding their multilingual support (Beekhuizen et al., 2005). Further, key considerations include determining the appropriate criteria for trainee candidates, the local stakeholders and scientists involved, teaching styles, local infrastructure limitations, and financial considerations (Miloslavich et al., 2018). A high degree of in-person support is often vital to successful capacity development, especially to avoid ‘brain drain’ of young locals to high-income countries and to foster technical resilience of local researchers. These partnerships can further promote data repatriation and findability, ensuring that these

data are held by in-country institutions or hosted on national data platforms to encourage accessibility and use for local decision-making (e.g., Dias et al., 2017; Asase and Schwinger, 2018). The GOOS and UNFCCC provide international guidance to facilitate capacity development and technology transfer (Bax et al., 2018).

Implications

Between 1996–2010, the world lost 12% of its mangroves, with 50% of this loss occurring in Southeast Asia (Thomas et al., 2017). This region not only maintains 34% of the world’s mangroves, but the income designations of these countries are largely Low, Lower-middle and Upper-middle-income. There is often an economic impetus to deforest mangroves: in Southeast Asia, mangroves have mostly been replaced by aquaculture, rice fields, and oil palm plantations, which are exportable commodities often held by large corporations (Richards and Friess, 2016), whereas the ecosystem services provided by healthy mangroves are more equitably accessible (Armitage, 2002). Equipping these countries with the tools needed to effectively monitor their mangroves can therefore be a double-edged sword. Changing the political and economic narrative to include the benefits and alternative livelihoods that local communities and the rural poor gain from mangroves is essential (Armitage, 2002).

Implementing and monitoring sustainable mangrove management is crucial to achieving international and regional commitments related to climate and sustainability. With just 45 NDCs including mangroves and global efforts failing to achieve the Aichi Biodiversity Targets, transferring UAVs and associated technology can boost countries’ capacity to integrate mangrove-specific targets in their NDCs and contribute to tracking relevant indicators within the post-2020 global biodiversity framework (Gallo et al., 2017; Secretariat of the Convention on Biological Diversity, 2020).

Mangrove ecosystem services, particularly coastal protection, are especially beneficial to developing countries (Barbier, 2016). Thus, capacity building of aerial tools for effective mangrove management can enhance resilience in the most vulnerable communities. *In situ* aerial studies further provide greater local context for on-the-ground issues while strengthening global datasets, but integration of aerial tools such as UAVs into community-based monitoring efforts requires external assistance and financing to build local capacity (Worthington et al., 2020). By sharing methods and data, promoting effective partnerships and FAIR data standards, and implementing mindful training, equitable access to aerial tools for mangroves can be achieved.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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