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Evaluating a Decade of Mangrove Restorations in Mumbai: Success or Failure?

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Abstract

From 2012-2022, more than US $5 million was invested in the restoration of Mumbai's mangrove forests. The present study is the first published evaluation of these restorations. Mangrove restoration is critical for coastal communities, rehabilitating forests that guard against floods and absorb eight times the CO2 of any other ecosystem. Mumbai has 150 km of shoreline and 65 km^2 of mangroves. Heavy pollution, industrialization, and major infrastructure development have led to the clearance of thousands of mangrove trees over the last two decades. A sample of 25 mangrove restoration sites were assessed through a remote sensing, time-series analysis. Sentinel-2 and Landsat-8 data were collated in Google Earth Engine and mangrove extent was determined through a random forest, machine learning model. Restoration failed at 13 of the 25 sites (52%) which saw no mangrove growth from their restoration start year until 2022. Across the 25 sites, there was an increase of 30.44 hectares (ha) of mangrove coverage, from 67.19 ha of cover prior to restoration, to 97.63 ha by 2022. Despite strong conservation laws and compensatory afforestation mechanisms, Mumbai's mangroves remain vulnerable to urbanization and land-use land-cover changes. Policy recommendations, including public transparency around mangrove restoration locations, long-term forest monitoring, and improved enforcement of the existing coastal regulation zone, are outlined at the local, national, and international levels to improve mangrove restoration outcomes in Mumbai.

Keywords: Mangrove restoration; Remote sensing; Time series analysis; Ecological restoration monitoring; Coastal management

1. Introduction

The motivation for a remote sensing analysis of Mumbai's mangrove restorations is presented below. First, general background information about mangrove ecosystems, their environmental benefits, and global trends in mangrove deforestation are reviewed. This is followed by a summary of mangrove restoration programs in Mumbai and the challenges they have faced worldwide. In addition, the characteristics of common rehabilitation methods, including sapling plantation and ecological mangrove restoration, are discussed. Finally, the importance of monitoring restoration outcomes and the gap in a public outcomes evaluation for Mumbai's coastal restoration projects is examined.

1.1 Background

Mangrove ecosystems grow in low coastal elevations and provide essential ecosystem benefits to coastal communities across the world. Mumbai's 150 km of coastline is banked with 65 km^2 of mangroves (Maharashtra Mangrove Cell, 2017). Southeast Asia is home to ⅓ of the world's mangroves and 75% of all mangrove restorations since 1990 (Gatt et. al., 2017). In Mumbai, the outcomes of more than a decade of mangrove restoration have yet to be assessed.

Mangrove trees provide essential benefits to the residents of Mumbai. Mangrove trees guard against sea-level rise through wave attenuation and shore stabilization (S.V. et. al., 2019). They are widely credited with protecting Mumbai neighborhoods from inundation during the devastating 2005 floods (Gupta, 2007). The trees' dense pneumatophoric root systems filter organic marine pollutants as well as sewage and anthropogenic effluents (heavy metals like chromium, lead, etc.) regularly discharged in the city's municipal waterways (Bayen et. al., 2005; Tam and Wong, 1995). Mangrove forests foster nutrient-rich environments that act as incubators for endemic fish, prawn, and crab species that are vital to local economies (Ellison et. al., 2020). Indeed, Mumbai's migrant workers and indigenous Koli community have long used mangroves for economic and subsidence activities. These include fishing, grass cutting, sand dredging, housing, medicinal treatments, shell collection, wood harvesting, and basket weaving (Parthasarathy, 2011; Kandasamy, 2017).

Moreover, mangroves' capacity for carbon sequestration is critical in the global fight against climate change and a major impetus behind their mass restoration. Mangrove forests are carbon sinks that can absorb up to 8 times the CO_2 of any other ecosystem (Donato et. al., 2011). Though mangroves represent less than 1% of tropical forest cover, they account for 10% of all carbon emissions due to deforestation (Simard, 2019). Therefore, the clearance of mangrove trees has a disproportionate impact on carbon emissions. This has created an urgent push for mangrove restoration among international organizations, states, and NGOs.

1.2 Global vs. Mumbai Mangrove Cover Losses

Mumbai proves an important global city case study for understanding the limitations of restoration initiatives in mitigating mangrove loss and the importance of rehabilitation monitoring. The number of people living in low coastal elevation cities (areas less than 10 m above sea level), ballooned from 360 million in 1990 to 900 million in 2020 (IPCC, 2023; MacManus et al., 2021). Mumbai's population grew by 65% in the same period (1990-2020), from 12.2 to 20.4 million people (UN DESA, 2018). Urban population growth in coastal cities is linked to mangrove loss as demand for housing, commercial development, and aquaculture create pressures for mangrove clearance

(Goldberg et al., 2020). As a site of rapid population growth, mass infrastructure investment, and international environmental aid, Mumbai is emblematic of the challenges that face growing global coastal cities and vulnerable mangrove forests in the developing world.

Global trends in mangrove deforestation and reforestation efforts track closely with Mumbai's own mangrove cover changes. Anthropogenic activities caused a 1% annual reduction in worldwide mangrove coverage during the 20th century and 1.04 million ha in loss from 1990-2020 (FAO, 2007; Shono, 2023). A meta-analysis of 200 studies indicated that the majority of global mangrove clearance (3870 km^2) was concentrated in South and Southeast Asia during this period (Bhowmik et al., 2022).

Mumbai's mangrove losses parallel global trends. Remote sensing analyses indicate a dramatic decrease in the greater Mumbai area's total mangrove extent from 1972-2001, from 200 to 118 km^2 (S. et al., 2022). From 1991-2001 alone, Mumbai lost 40% of its mangrove cover (Vijay et al., 2005). A 2017 analysis indicated 119 km^2 of mangrove cover remains in the area (Indian Institute of Space and Technology, 2019).

In light of significant losses, an increased awareness of mangroves' environmental benefits has led to thousands of mangrove restoration programs globally over the past decade, including dozens in Mumbai. From 1990-2020, the number of mangrove restorations across the world more than tripled (Duarte et al., 2020). As Mumbai's population and urban development continue to increase exponentially, so do the pace of its mangrove clearance and restoration schemes. The Maharashtra Mangrove Cell reported restoring more than 1500 hectares of mangroves in Mumbai from 2015-2022 (Table 1).

Table 1: Mumbai Mangrove Restorations 2015-2022 (Maharashtra Mangrove Cell, 2020; 2021; 2022)

Location	Area (ha)	Restoration Start Year	Saplings Planted
Not Listed	110	2015-2016	-
Not Listed	80	2016-2017	-
Not Listed	155	2017-2018	-
Not Listed	490	2018-2019	-
Not Listed	655	2019-2020	-
Alimgar Bharodi	13	2020-2021	57,772
Surai	5	2020-2021	22,220
Eksar	16	2020-2021	71,104
Vikhroli	4	2020-2021	22,000
Sarsole	3	2020-2021	13,332
Ghansoli (Survey)	3	2020-2021	13332
Koparkhairane	2	2020-2021	8888
Manori (Survey)	1	2020-2021	4,444
Gorai (Survey)	1	2020-2021	4,444
Vikhroli	5	2021-2022	22,220
Alimghar	5	2021-2022	22,220
Kharbav	13	2021-2022	57,772
TOTALS	**1561**		**319,748**

Yet the lack of publicly-available outcomes assessments of Mumbai's existing decade of mangrove restorations limits understanding of the soundness of mangrove restoration as municipal and conservation policy. Newly restored forests can struggle to reach mature growth in the absence of long-term monitoring, community buy-in, and consistent financial support (Brown et al., 2014; Ellison et al., 2020). Therefore, evaluating the methods and outcomes of Mumbai's decade-old mangrove restoration program is critical to its future success.

1.3 Mumbai's Mangroves: Tree Clearance and Restoration

Mumbai's mangrove loss, and corresponding restoration program, is primarily driven by land-cover land-use (LCLU) changes for national infrastructure projects, industrial pollution, and informal housing construction. Hundreds of hectares of Mumbai's mangroves were cleared from 2007-2022 with the promise of reciprocal mangrove afforestation in other parts of the city (S. et al., 2022).

Large-scale infrastructure projects have been a major driver of mangrove clearance in the city. Major schemes that involved clearance include the Mumbai Coastal Road, Bandra-Worli Sea-Link, Mumbai Trans-Harbour Bridge, Navi Mumbai International Airport, the Mumbai Metro, Ahmedabad-Mumbai Bullet Train, the Jawaharlal Nehru Port, and the Western Dedicated Freight Corridor, among many others (Bureau, 2022; Deshpande, 2019). The city will lose 1% of its total mangrove cover to the Coastal Road alone (Chatterjee, 2017).

Amid widespread reductions in mangrove cover, restoration has gained support from local civil society groups, businesses, municipal and state authorities, and international organizations. Yet despite widespread investment in restorations, scholars have long noted the lack of a global monitoring repository of restored areas and varying outcomes (Duarte et al., 2020). For instance, the UN Development Programme (UNDP) and the Global Climate Fund (GCF) allocated $9.32 million in 2019 for the Maharashtra Mangrove Cell to carry out coastal resilience projects across the state, including ten mangrove restorations in Mumbai (2021). Yet to date, the Maharashtra Mangrove Cell has not published a monitoring assessment of any of its extensive mangrove restoration programs in the Mumbai region, including the UNDP sites.

An independent, mid-term grant evaluation of the ten UNDP-funded restorations in Mumbai found that despite the significant resources invested, local communities are uninvolved in mangrove restorations and that the restoration was unlikely to meet its targets by 2025 (Paltsyn et al. 2022). The report is indicative of a broader need for monitoring assessments to flag errors and provide technical guidance for restoration efforts in the region.

1.4 History of Protective Regulations and Restoration Regime

The history of Mumbai's mangrove restoration program confirms the importance of public and scientific scrutiny in sustainable ecosystem management. Mumbai's mangrove restoration program can be traced to active civil society advocacy for coastal protections and legal mandates for restoration. As a result of local environmental NGO campaigns, mangroves were notified as "protected forests" in 1991 under India's federal Coastal Regulation Zone, also known as the CRZ (Krishnamurthy, 2014). The CRZ is India's overarching coastal conservation law that regulates development on India's shorelines and has been critiqued extensively. Scholars have widely noted the gaps in enforcement, the deficiencies in a national, one-size-fits-all coastal conservation policy, and the lack of viable space for successful restoration programs after coastlines have been cleared (Chouhan, 2017; Dhiman, 2019).

After long-promised government mangrove restorations in Mumbai failed to materialize despite CRZ mandates, a lawsuit brought by Bombay Environmental Action Group in 2005 led the Bombay High Court to issue a landmark conservation ruling (Bavadam, 2005). The Court forbid construction within 50 m of mangrove trees irrespective of the landowner, and mandated the creation of a new government body, the Maharashtra Mangrove Cell, to take charge of restorations (Bombay High Court, 2005).

As a result of these lawsuits, the Mangrove Cell began operations in 2012. Its mission is to carry out mangrove restoration, forest monitoring, and fund administration for marine science research. Between 2015-2022, the Cell's annual reports indicate that 430,197,000 INR (~ US $5.2 million) were allocated toward 1561 hectares of mangrove restoration and 319,748 saplings were planted (Table 1) (Maharashtra Mangrove Cell 2020; 2021; 2022).

De jure, Mumbai's mangroves are legally protected from clearance through the CRZ. De facto, regular exceptions for infrastructure projects deemed critical to the national interest often authorize mangrove tree clearance by the thousands. As development grows exponentially in Mumbai, so does the task of the Mangrove Cell and state ministries to restore lost forests.

Yet global trends in mangrove rehabilitation suggest persistent challenges in restoration outcomes. A lack of long-term monitoring can hamper mangrove recovery efforts. Without robust monitoring, good governance, and local involvement, well-intentioned mangrove restorations can quickly succumb to deforestation and negligence (Lewis et al., 2016).

1.5 Mangrove Restoration Overview and Challenges

Despite widespread efforts to revive mangrove forests, the majority of mangrove restoration projects globally have failed (Ellison et al., 2020; Lovelock et al., 2022). This is primarily due to a preference for sapling plantation over ecological mangrove restoration and a lack of quality monitoring assessments.

Ecological restoration is defined by Gann et al. (2019) as, "any activity with the goal of achieving substantial ecosystem recovery relative to an appropriate reference model, regardless of the time required to achieve recovery." The two predominant techniques for mangrove restoration are sapling plantations and ecological mangrove restoration. In the plantation method, mangrove saplings and propagules are planted at discrete intervals in a coastal restoration site. The long-term survival rates of saplings in monoculture plantations are as low as 20% and scholars have critiqued the method for its inconsistent results (Primavera and Esteban, 2008; Wodehouse and Rayment, 2019). Notwithstanding its documented shortcomings, the ease and relative affordability of sapling plantations have kept them popular as a restoration method. From 1972-2021, 74% of mangrove restorations in Southeast Asia were direct sapling plantations (Gerona-Daga and Salmo, 2022). Alternatively, researchers have long established that ecological mangrove restoration (EMR) leads to successful mangrove rehabilitation given the proper depth, duration, and frequency of tidal flooding (Lewis, 2009; Lewis et al., 2019. EMR involves the resumption of a restoration site's normal hydrology and tidal flows by removing blockages and digging channels (Lewis, 2001; Pérez-Ceballos et al., 2020). EMR helps to spur secondary succession and natural mangrove regrowth (Figure 2).

The community-based ecological mangrove restoration method (CBMER), consciously involves local stakeholders in all aspects of EMR from design through monitoring (Brown et al., 2014).

Assessments of mangrove restoration failures in South and Southeast Asia point to an overreliance on monoculture plantation practices, improper site selection, and a lack of follow-through on restoration monitoring. An evaluation of Sri Lanka's 23 mangrove restoration sites found that in five years, only 200 out of 1200 hectares of attempted restorations showed any growth, 54% of plantings failed, and nine sites showed no growth (Kodikara et al., 2017). Similar issues and high rates of failure hampered mass mangrove restoration projects across hundreds of thousands of hectares in the Philippines, Vietnam, and Pakistan (Primavera and Esteban, 2008; Lee et al., 2019; Powell et al., 2011. The low success rate of sapling plantations in more than 30,000 hectares of attempted restoration in the Gulf of Kachchh in the bordering state of Gujarat, further calls into question the viability of plantation as a compensatory afforestation method for Maharashtra's mangroves (Thivakaran, 2017).

1.6 The Restoration Monitoring Gap

To date, there is no publicly available monitoring of Mumbai's mangrove restorations. Despite consistent reporting on Mumbai's *total* mangrove coverage through remote sensing, there is no published long-term monitoring of mangrove restoration efforts in the greater Mumbai region. GIS satellite monitoring has enabled government bodies and scholars alike to regularly assess the total mangrove extent in Mumbai (Prasad et al, 2010; Mallick et al., 2015; Vijay et al., 2020; Forest Survey of India, 2020). Yet this has not translated into public monitoring of Mumbai's 1500 ha of restored mangrove areas. Available data from both academic and government sources do not disaggregate to differentiate between natural growth and mangrove areas nurtured through restoration.

Restoration monitoring is critical to successful outcomes. Given the variable record of mangrove restorations globally, monitoring has been deemed an essential component of successful mangrove rehabilitation. Early detection of mangrove degradation through remote sensing monitoring embedded in coastal management plans can help officials pre-empt mangrove loss and improve afforestation practices [37]. The design of appropriate restoration monitoring timelines with ecologically informed checkpoints is crucial to full ecosystem rehabilitation.

Though mangroves need 20-25 years to reach maturity, the vast majority of monitoring studies take place within three years of restoration (Lewis, 2007; Wodehouse et al., 2019). As Bayraktarov et. al. notes, "The outcome of [marine coastal] restoration success or failure is directly related to the period of observation" (2016, p. 1068). Reported success rates in the literature are biased towards published successes over failures (ibid). Consequentially failed restorations rarely undergo published scrutiny, limiting lessons learned and alternative paths forward.

The present study addresses this gap in the literature through a remote sensing analysis of Mumbai's mangrove restorations in the period from 2012-2022. The study indicates that most restorations in the city failed. Through this investigation, the author identifies the locations of restoration and clearance sites in Mumbai and measures how many hectares have been successfully restored.

2. Materials and Methods

A remote sensing assessment of Mumbai's mangrove restorations was conducted utilizing GIS, Google Earth Engine, a random-forest machine learning algorithm, and satellite data from LANDSAT and Sentinel systems. The following section details how a sample of 25 restoration sites was identified and selected for analysis from Government of India databases including Parivesh and E-Green Watch. The optimization of Landsat and Sentinel satellite data for time-series analysis and cloud correction is discussed. Subsequently, the parameters for a random-forest machine-learning algorithm and subsequent accuracy assessment are also reviewed.

2.1 Remote Sensing

Remote sensing has proven an efficient and accessible way for practitioners to monitor both mangrove extent and restoration outcomes. Researchers have utilized a bevy of satellite systems, including LANDSAT, Sentinel, SPOT, ALOS, Aster, and IKONOS, among others, to track mangrove extent (Heumann, 2011; Valderrama-Landeros, 2018). Mangroves have spectral signatures that can be tracked in six hyperspectral channels: visible range, red edge, near-infrared, infrared slope, mid-infrared absorption pitch, and mid-infrared peak (Vaiphasa, 2007). The availability of free, high-resolution satellite data has enabled scholars to establish a baseline of global mangrove extent called the Global Mangrove Watch (Bunting et al., 2022). Platforms like Google Earth Engine have allowed researchers to efficiently and autonomously provide mangrove extent analyses all across the globe (Ghorbanian et al., 2021; Mondal et al., 2019).

2.2 Geographic Inclusion Criteria and Site Identification

For this remote sensing analysis, the geographic inclusion criteria were mangrove restoration sites from 2012 onwards in the greater Mumbai metropolitan area. These include the Maharashtra districts of Palghar, Thane, Raigarh, Mumbai City, and Mumbai Suburban (Figure 1).

Restoration sites were identified through a combination of federal and state government publications, environmental impact statements, and satellite imagery. These included the Indian Forest Service's E-Green Watch Database, the Ministry of Forest, Environment, and Climate Change (MoFECC) environmental clearance database (Parivesh), and available documents of the Maharashtra Mangrove Cell.

The E-Green Watch Database is a federal repository of India's Forest Service, National Information Center, and State Forest Departments that tracks compensatory afforestation and plantation projects across India (Forest Service of India, 2023). It includes geo-referenced information and metadata about afforestation projects (i.e. site area, rationale for diversion of protected environmental land, etc.). Similarly, Parivesh is a federal database hosted by MoFECC that tracks environmental clearances for construction projects, environmental impact assessments, budget justifications, and geo-referenced data for sites at the state, district, and local levels (MoFECC, 2023).

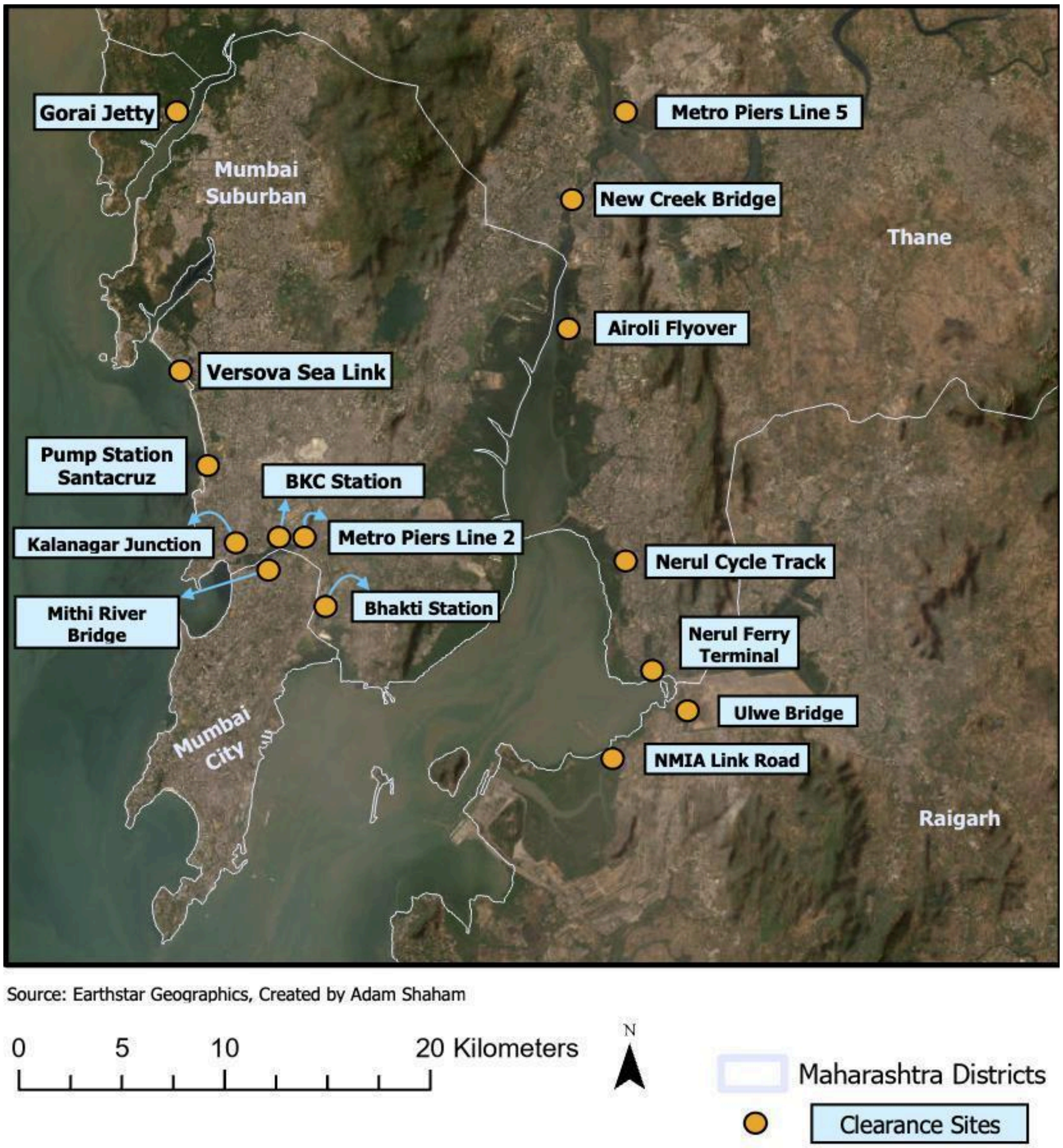

Figure 1: Locations of mangrove clearance projects in Mumbai corresponding to 25 restoration projects identified in the study analysis.

Utilizing the keyword search function in both databases, restoration sites that had "mangrove" in their title or project details were identified in the greater Mumbai region. 71 files were identified in E-Green Watch as meeting the inclusion criteria from initial query results. Using the same search criteria, another 13 restoration sites were identified on Parivesh for a total of 84 candidate sites. The 84 restoration sites identified from E-Green Watch and Parivesh were cross-referenced with corresponding environmental clearances as well as project details from the Maharashtra Mangrove Cell's annual reports. Of these, 52 sites were deemed to have involved either mangrove clearance or restoration.

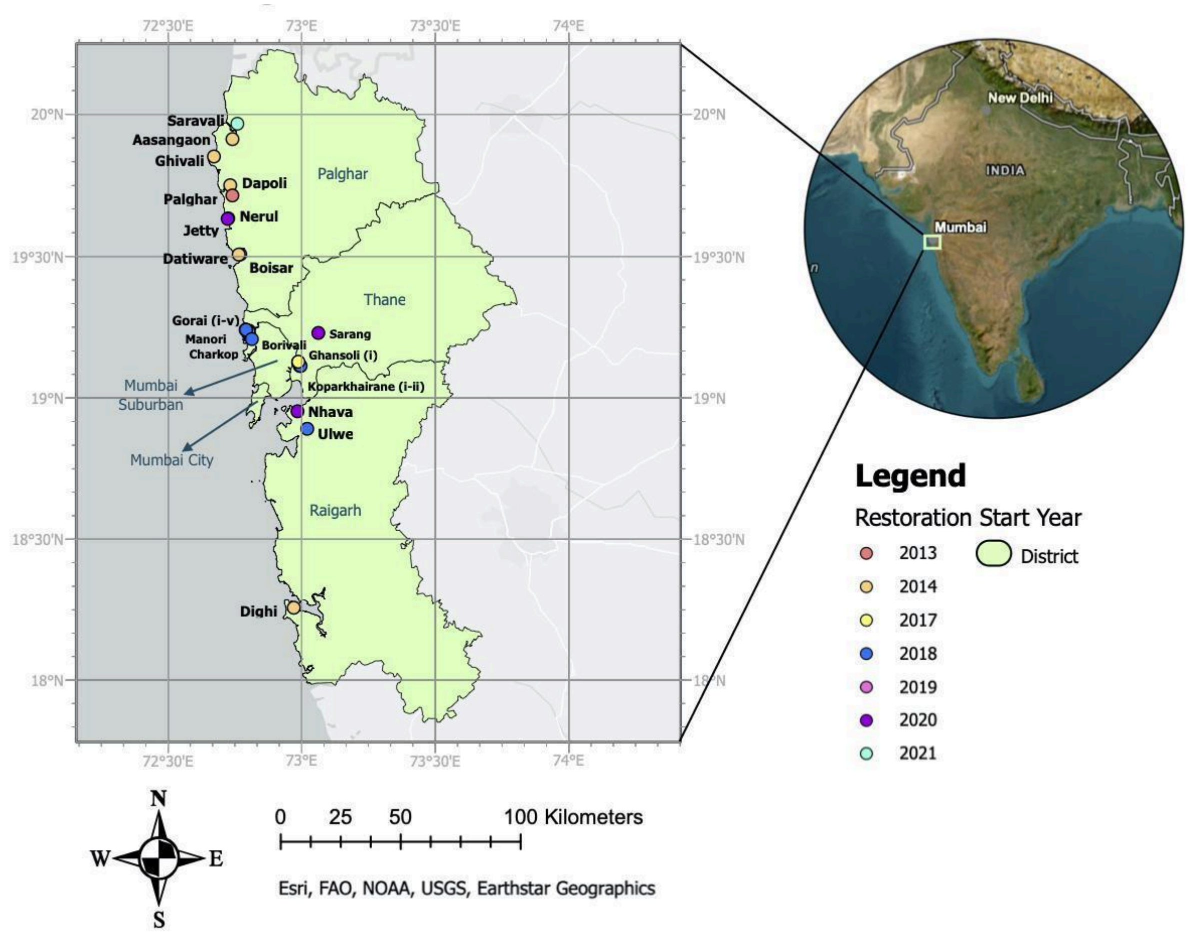

Figure 2: Locations of mangrove restoration projects (n=25) across the greater Mumbai region identified for remote sensing analysis. Sites are designated by their respective restoration start years. 14 duplicate entries were identified and removed. An additional 13 construction sites where mangroves were cleared in the Mumbai region but the corresponding compensatory afforestation projects did not involve mangrove restoration were also removed.

The remaining 25 sites were confirmed as mangrove restoration areas by project documentation and visual assessment utilizing high-resolution satellite imagery (Figure 2). For each of these 25 sites, the start date of restoration, restoration site area (ha), area of mangrove cleared for approved construction project (ha), restoration method (plantation, EMR, mixed), restoration project timelines, and justification for mangrove clearance were recorded where data was available (Table 2, Table 4).

Table 2: Mangrove restoration sites summary table. The table records the restoration start year, the amount of mangrove land cleared for each restoration site (ha), the number of mangrove trees cut, and the construction project justifications for mangrove clearance recorded from project documents (National Informatics Centre; Forest Service of India, 2023; National Informatics Centre & Ministry of Environment, Forest and Climate Change, 2023).

Site	Start Year	Site Name	Mangroves Cleared (ha)	Trees Cut	Reason for Mangrove Clearance
1	2013	Palghar	17.5356	-	Construction of railway line from Jawaharlal Nehru Port to Dadri UP.
2	2014	Boisar	10	-	
3	2014	Ghivali	5	-	
4	2014	Aasangaon	15	-	
5	2014	Datiware	25	-	
6	2014	Dapoli	15	-	
7	2014	Dighi	1	-	
8	2017	Ghansoli (i)	0.279	57	Construction of stormwater pumping station in Santacruz, Mumbai.
9	2018	Ghansoli (ii)	0.274	60	Construction of New Creek Bridge, Thane to Kalwa & Rabodi.
10	2018	Koparkhairane (i)	0.46	190	Passenger Water Terminal Project, Nerul, Alibag, and Ferry Warf.
11	2018	Charkop	2.997	1585	Versova-Bandra Sea Link at Versova, Juhu and Bandra, MSRDC.
12	2018	Gorai (i)	0.985	357	Metro Pier and Bhakti Park Station, Metro line 4 (MMRDA).
13	2018	Ulwe	0.4859	245	Bridge construction, Ulwe River for Navi Mumbai Airport CIDCO.
14	2019	Manori	0.983	63	Construction of flyover (bridge), Airoli to Thane - Belapur Road.
15	2019	Borivali	0.194	3	Widening and reconstruction of existing bridge across Mithi River.
16	2019	Gorai (ii)	0.048	14	Interchange at Kalanagar Junction, Bandra East (BKC), MMRDA
17	2019	Koparkhairane (ii)	0.91	-	Construction of BKC Metro Railway Station at Bandra.
18	2019	Gorai (iii)	0.226	-	Mangrove Conservation Center and Mangrove Park, Gorai MMCU.
19	2019	Gorai (iv)	0.226	-	Mangrove Conservation Center and Mangrove Park Gorai, MMCU.
20	2019	Gorai (v)	0.2	86	Metro Piers, Vakola Nalla, Mumbai Metro Line 2-B, MMRDA.

21	2020	Nhava	31.7869	3728	Coastal Road, Amra Marg-MTHL Airport Link at Navi Mumbai.
22	2020	Jetty	0.005	-	Construction of Jetty and at Gorai.
23	2020	Sarang	0.6983	62	Construction of the Metro Piers for Mumbai Metro line 5.
24	2021	Saravali	4.0122	1454	Construction of Ghansoli to Airoli Creek Bridge in Navi Mumbai.
25	2021	Neral	0.061	21	Construction of cycle track in Nerul at Sonkhar village, Taluka.
TOTALS			133.3669		

2.3 Google Earth Engine and Satellite Systems

Google Earth Engine (GEE) is a web-based platform for geospatial analysis (Gorelick et al., 2017). The platform provides access to continually updated datasets for satellites (i.e., LANDSAT, Sentinel, MODIS, etc.) and land cover (global forest cover, fire, water, mangrove, etc.). Users can efficiently leverage the petabytes of data that GEE hosts in its repository through Google's cloud computing service. This eliminates the need for independently downloading large batches of imagery, stand-alone data processors, or time-intensive preprocessing involved for traditional remote sensing studies.

GEE has been reliably used for mangrove extent analysis in country-wide assessments, like in The Gambia, and remote sensing analyses of restorations (Mondal, 2019). In China, Jia et. al., collated 42 years of mangrove extent data to track reforestation efforts in national mangrove reserves (Jia et. al., 2018). For the present study, Sentinel 2 and Landsat 8 images were utilized for extent analysis based on the methodology outlined by Barenblitt and Fatoyimbo (2021).
Sentinel 2 is a satellite system operated by the European Space Agency's Copernicus program. Launched in 2015, the satellite captures 13 spectral bands using a Multi Spectral Instrument (MSI) and has a 10 m per pixel resolution. The Sentinel 2 Level-1C dataset includes the derivation of TOA (top of atmosphere) reflectance values after geometric and radiometric corrections (European Space Agency, 2015). Landsat 8, launched in 2013 by the US Geological Survey, is a publicly available satellite data system that measures eight spectral bands at a 30 m per pixel resolution (USGS, 2023).

A spectral index is an equation that reflects the combination of multiple pixel values from spectral bands in a multispectral image (Lenhardt, 2023). Spectral indices are used to identify vegetative cover, wetlands, coastal zones, and other distinct land use properties. In the present study, spectral indices were derived from both the Sentinel-2 and Landsat-8 bands and included the Natural Differentiated Vegetative Index (NDVI) and Modified Normalized Difference Water Index (MNDWI) (Kriegler, 1969; Xu, 2006).

2.4 Image Cloud Correction

Cloud-free satellite images were generated for the restoration start year and 2022 at each restoration site. Images were composed of pixels using a year's worth of satellite data. A total of 774 Sentinel images and 147 Landsat images were used in the creation of the composites (Table 3).

Table 3: Number of satellite images used to generate composites for restoration sites. Sentinel 2 data were used for mangrove restoration sites with start years from 2016-2022. Landsat 8 data were used for start years 2013-2015.

Year	**Sentinel 2**	**Landsat 8**
	Number of Images	Number of Images
2013	-	37
2014	-	55
2015[1]	-	-
2016[1]	-	-
2017	58	-
2018	138	-
2019	140	-
2020	144	-
2021	150	-
2022	144	55
TOTAL	774	147

[1] Year without restorations in the sample of 25 sites.

Mangroves grow in the tropics and subtropics, areas characterized by high annual precipitation. Consequently, cloud cover frequently obscures remote sensing studies of mangrove extent (Wang et al., 2019). To minimize cloud cover in restoration analysis, images from Sentinel 2 were filtered with a cloud mask using the S2 Cloud Probability dataset where bands are upsampled through bilinear interpolation and missing values are eliminated (Google Earth Engine, 2023). The median reducer function was also applied to eliminate outlying pixel values and to produce seasonally balanced data (Zhang et al., 2021). With the Landsat data, the reduction of cloud interference was achieved by utilizing the pixel_qa band (USGS, 2023).

The resulting image was clipped to low coastal elevations (<40m). Images were also clipped to documented appropriate values for mangroves in spectral indices, above .25 for NDVI to ensure the presence of vegetation and below -.5 for MNDWI, to exclude water bodies from consideration in analysis (Fatyoinbo and Barenblitt, 2021)

2.5 Random Forest, Training Data, and Mangrove Extent Analysis

Landcover values were classified using random forest, a decision-tree-based, and a supervised machine learning method. Of various machine learning methods—random forest, CART, maximum likelihood classification (MLC), support vector machines (SVM), artificial neural networks, etc.—random forest has been shown to be a robust classifier in mangrove extent analysis (Toosi et al., 2019; Nagarajan et al., 2022).

The training data for the model was derived from intertidal regions along Mumbai's coast. Mumbai's mangrove community is largely dominated by single-species *Avicennia marina* (Kantharajan et al., 2018). The model was trained on 200 points to differentiate between mangrove cover (100) and non-mangrove cover (100 points) such as mudflats, coastal and intertidal water bodies, non-mangrove vegetative cover, and the built environment.

The training group was randomly split so that 80% of the samples were used to train the model, and the remaining 20% were used to test its accuracy. Random splitting reduces bias in the models' endpoint classifications (Diettrich and Kong, 1995). The model was programmed to utilize 100 trees with five randomly selected predictors per split.

Pixels classified as mangroves with less than four other "mangrove" pixels appended were removed from the random forest output to reduce model noise. The model was further refined through comparison with the biannual Global Mangrove Watch to exclude inaccurate mangrove identifications, and then retrained appropriately, resulting in an overall accuracy (OA) of 85.33% and kappa coefficient (KC) of 0.71.

To establish a baseline, cloud-free composites were generated in Google Earth Engine and analyzed for mangrove extent area (ha) for all sites in the restoration Start Year. This process was repeated for all sites in the year 2022. Time series analysis helps to mitigate issues of tidal interference and disparities in mangrove extent that result from changes in high and low-tide measurements and strengthen the accuracy of model classification results. Mangrove extent for restoration areas was calculated in hectares on GEE utilizing the 'image.CalculatePixelArea' function cover and recorded.

3. Results

In total, 25 mangrove restoration sites were identified in the Mumbai Metropolitan Region. Restoration start years ranged from 2013-2021 (Table 4). Of the selected sites, the year with the most restorations identified was 2019 (n=7). For the construction projects corresponding to these restorations, the total amount of mangrove forest cleared was 133.4 ha. Across the 25 restoration sites, the total land allotted by authorities for mangrove restoration projects was 157.3 ha (Table 4).

Table 4: Restoration analysis results by restoration site number. Each site records the start year of restoration, the restoration method used, project timeline, site area (ha), mangrove extent at start (ha), and mangrove extent in 2022 (ha), change in mangrove extent, percent extent at start and 2022, and change in percentage of extent.

Site #	Site Name	Year	Project Method	Time (yrs)	Site Area (ha)	Mangrove Extent at Start (ha)	Mangrove Extent in 2022 (ha)	Change in Mangrove Extent (ha)	% Extent Before	% Extent After	Change in % Extent
1	Palghar	2013	Plantation	-	8.5	0.0	0.00	0.00	0.0%	0.0%	0.0%
2	Boisar	2014	Mixed	-	11.4	3.0	9.08	6.12	26.0%	79.7%	53.7%
3	Ghivali	2014	Mixed	-	5.0	4.5	4.89	0.39	90.2%	97.9%	7.7%
4	Aasangaon	2014	Mixed	-	15.0	0.0	0.00	0.00	0.0%	0.0%	0.0%
5	Datiware	2014	Mixed	-	25.0	8.9	16.70	7.76	35.8%	66.8%	31.0%
6	Dapoli	2014	Mixed	-	15.0	8.1	14.85	6.72	54.2%	99.0%	44.8%
7	Dighi	2014	Mixed	7	23.4	3.6	11.46	7.82	15.6%	49.0%	33.4%
8	Ghansoli (i)	2017	Mixed	7	1.0	1.0	1.00	0.00	100.0%	100.0%	0.0%
9	Ghansoli (ii)	2018	Mixed	7	1.0	1.0	1.00	0.00	100.0%	100.0%	0.0%

10	Koparkhairane (i)	2018	Mixed	7	1.0	0.3	1.00	0.65	34.8%	100.0%	65.2%
11	Charkop	2018	Mixed	7	3.0	0.0	0.05	0.00	1.6%	1.6%	0.0%
12	Gorai (i)	2018	Plantation	7	1.0	0.5	0.82	0.30	51.6%	81.5%	29.9%
13	Ulwe	2018	Mixed	7	1.0	0.0	0.00	0.00	0.0%	0.0%	0.0%
14	Manori	2019	Mixed	7	1.0	0.0	0.01	0.01	1.5%	1.5%	0.0%
15	Borivali	2019	Mixed	7	1.0	0.7	0.90	0.24	66.3%	89.9%	23.6%
16	Gorai (ii)	2019	Mixed	-	1.0	0.8	0.80	0.00	80.3%	80.3%	0.0%
17	Koparkhairane (ii)	2019	Plantation	7	1.0	1.0	1.00	0.00	100.0%	100.0%	0.0%
18	Gorai (iii)	2019	Plantation	7	0.7	0.6	0.64	0.05	85.1%	91.8%	6.7%
19	Gorai (iv)	2019	Plantation	7	0.3	0.2	0.27	0.06	71.9%	90.4%	18.5%
20	Gorai (v)	2019	Mixed	7	1.0	0.4	0.39	0.00	38.6%	38.6%	0.0%
21	Nhava	2020	Plantation	10	34.0	32.4	32.41	0.00	95.3%	95.3%	0.0%
22	Jetty	2020	Plantation	10	1.0	0.0	0.09	0.09	0.0%	8.6%	8.6%
23	Sarang	2020	Mixed	10	1.0	0.0	0.27	0.27	0.0%	26.9%	26.9%
24	Saravali	2021	Plantation	10	4.0	0.0	0.00	0.00	0.0%	0.0%	0.0%
25	Neral	2021	Mixed	10	0.1	0.0	0.00	0.00	0.0%	0.0%	0.0%
TOTALS					157.3	67.2	97.63	30.44			
AVERAGE					6.3	2.7	3.91	1.22	41.9%	56.0%	14.0%

3.1 Restoration Timeseries Analysis

More than half of restoration sites, 13 of 25 (52%), saw no mangrove growth from the start year of their restoration until 2022. In the 12 restoration sites that showed mangrove growth, there was an average 29% increase in coverage from the time of restoration until 2022. The average coverage growth per restoration site was 2.5 hectares. The site that saw the greatest change in mangrove coverage is Site #10 in Koparkhairane, from 0.35 ha in 2018 to 1 ha of mangroves by 2022 (Table 4). Across all restoration sites, there was an average increase of 14% in mangrove coverage in sites from before restoration until 2022. Across the 25 sites (157.34 ha), there was an increase of 30.44 ha of mangrove coverage, from 67.19 ha of cover prior to restoration, to 97.63 hectares by 2022.

3.2 Prior Growth

Ten of the 25 sites designated for restoration showed more than 50% mangrove cover before restoration works began. Out of the total 157.3 hectares allocated by the Forest Service for restoration, 42.7% (67.2ha) of the land was already covered in mangroves prior to restoration. Of these, three sites (Sites 8, 9, and 17) were measured to have 100% mangrove coverage before being designated for mangrove restoration. These three sites saw no change in mangrove extent between their restoration start years and 2022 (Table 4, Figure 3).

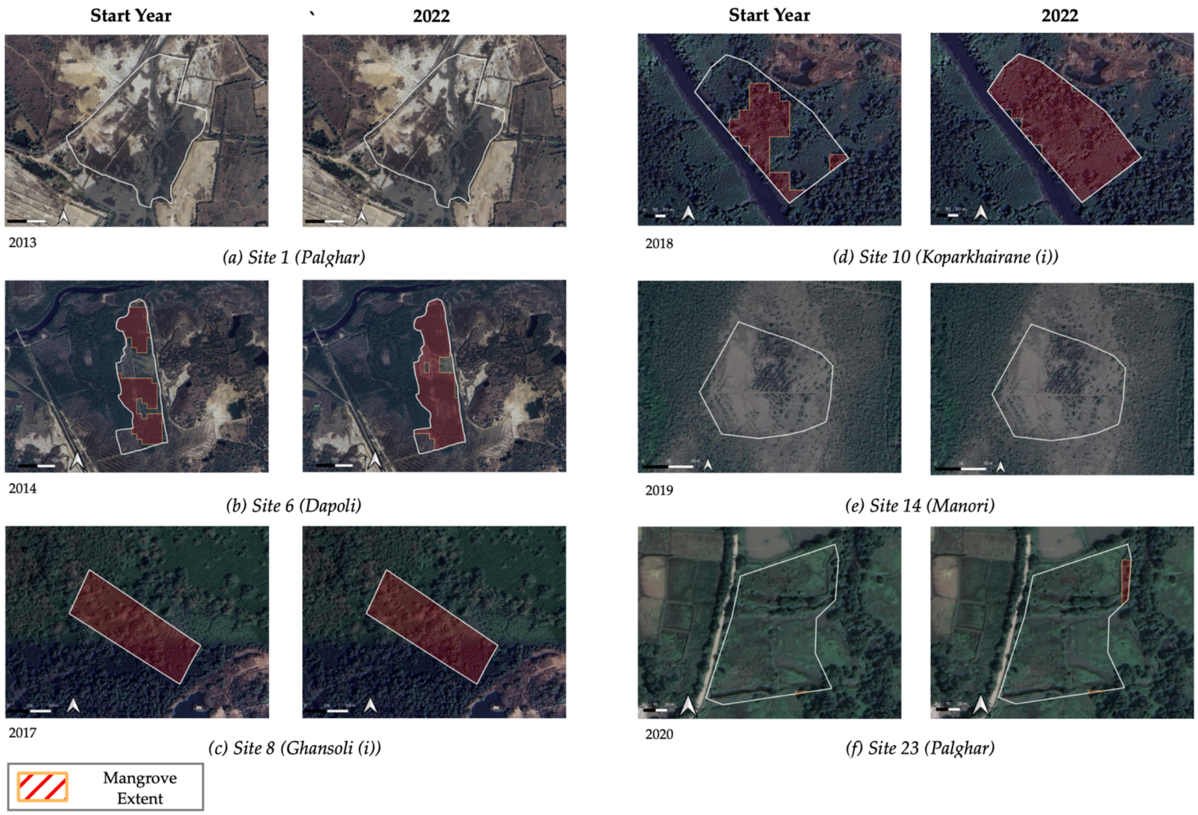

Figure 3: Mangrove extent at six coastal restoration sites in Mumbai. **(a, e)** More than half of all sites in the sample, as at Sites 1 and 14, showed no mangrove growth from the restoration start to 2022. **(c)** Some areas allocated for compensatory restoration, such as Site 8, already showed 100% cover prior to restoration activities. Other sites varied more widely in restoration outcomes. **(d)** Sited 10 achieved full restoration in mangrove extent. **(b, f)** In contrast, Sites 6 and 23 only achieved partial coverage recovery.

4. Discussion

The present study is the first evaluation of a decade of mangrove restoration in the greater Mumbai region. An analysis of 25 mangrove restoration sites across Mumbai indicates a low increase (14%) in mangrove extent cover (Table 4). Moreover, half of the restoration sites in Mumbai (52%) failed to show any mangrove growth. Out of 157 hectares set aside for mangrove restoration, only 30 hectares were successfully restored from 2013-2022. This places Mumbai in line with regional efforts at mass mangrove restoration in South Asia which show a similarly low rate of success (Kodikara et al., 2017; Thivakaran, 2017).

As a burgeoning megacity, Mumbai is representative of the tension between urbanization, rapid population growth, and coastal conservation. The mixed results of the Coastal Regulation Zone (CRZ) as a conservation law for mangrove trees in Mumbai tracks with the efficacy of similar environmental protection laws globally. Over 30 countries have designated more than 50% of their mangroves as protected areas (Worthington et al., 2020, p. 436). These regulations have not fully stopped anthropogenic clearance, but instead only slow degradation.

The present study revealed that while the majority of mangrove clearance projects in Mumbai take place in its urban core, restorations are often located in the outlying suburban and periurban regions. For instance, none of the mangrove clearance projects identified in the analysis took place in the northern district of Palghar. The area was host to nine different mangrove restoration projects over the last decade (Figures 1, 2). The externalization of mangrove restoration to the outer regions of the city deprives densely-populated urban coastal regions of the flood protection and fishery support that mangroves provide.

4.1 Study Limitations

Certain limitations should be considered when interpreting the results of the present analysis. Assessing mangrove extent with remote sensing for 1-year-old sapling plantations is prone to variability as satellites may not adequately capture spectral signatures for small trees with low canopy height and leaf coverage. Furthermore, the results of remote sensing must be taken with circumspection without ground truthing as there could be changes in canopy cover that can go undetected by remote sensing instruments.

This study represents only a partial sample of mangrove restoration sites across Mumbai that were able to be publicly verified through environmental impact reports, compensatory afforestation documents, and geospatial confirmation (i.e. presence of fishbone channels). The author identified more restoration sites but was unable to incorporate them for study inclusion because of a lack of available public documentation. Future studies should seek to evaluate all of the restoration efforts in the greater Mumbai region.

With these limitations in mind, the remote sensing methods utilized in this study have proven accurate in providing detailed assessments of mangrove coverage (Ghorbanian et al., 2021; Mondal et al., 2019). In the Mumbai Metropolitan Region, mangrove restoration is part of an established policy regime for mangrove clearance. The assurance of restoration provides legal cover for developers to seek exemptions from mangrove protection laws. In reality, restoration rarely, if ever, manages to compensate for the number of trees that are lost. Only one of the restoration sites (Site 10) showed mangrove growth commensurate to the number of trees cut in a corresponding construction project. In the following section, recommendations at the local, national, and international levels are outlined to improve mangrove restoration outcomes in the greater Mumbai region.

4.2 Local Recommendations

At the municipal level, geo-referenced location data for Mumbai's restoration sites should be published regularly. This will promote transparency with the public and allow for external accountability on mangrove restoration by academic, NGO, and community stakeholders. The lack of a monitoring assessment of Mumbai's mangrove restorations until now likely stems from the lack of transparency about the location of restorations in Mumbai. For the present study, the sample of 25 sites was identified through federal Indian databases and resources. The Maharashtra Mangrove Cell reported restoring more than 1500 hectares of mangroves from 2015-2021 (2020; 2021; 2022). Despite the legal mandate for the publication of compensatory afforestation sites, only 25 sites that covered 157 hectares of restorations were able to be verified through available public records. Municipal and Maharashtra state authorities should regularly disclose the location and geographic data of restoration areas to improve monitoring.

4.3 National Recommendations

At the national level, conservation officials should prioritize ecological mangrove restoration and better enforce existing legal protections for mangrove clearance. The present study revealed that the majority of restorations in Mumbai involved sapling plantations, with 319,748 saplings planted from 2012-2022 (Table 1). Plantations are a historically inconsistent rehabilitation method (Primavera and Esteban, 2008; Wodehouse et al., 2019). Policymakers should reform restoration programs to focus on proven ecological mangrove restoration methods for a higher chance of restoration success.

Furthermore, coastal oversight boards should not green-light mangrove clearance projects until restoration sites are selected and their locations and requisite public documentation publicly released. Mangrove clearance decisions are controlled by the National and State Coastal Zone Management Authorities (NCZMA and MCZMA respectively). An Auditor General of India evaluation of State and Federal CZMAs found that the boards are irregularly staffed, meet infrequently, and unqualified private contractors often conduct the environmental impact assessments necessary for coastal clearance (Jha, 2022). The report concluded that these chronic issues led to poor oversight in the coastal clearance process and inadequate enforcement of compensatory afforestation plans. The NCZMA and MCSZMA need to effectively enforce CRZ rules and staff in a full-time capacity, to effectively carry out their oversight mandate of mangrove clearance

4.4 International Recommendations

On the international front, Mumbai's struggles with restoration are symptomatic of gaps in global mangrove restoration standards (Duarte, 2020). The UN has declared 2021-2030 the decade of Ecosystem Restoration, with a particular focus on marine projects (Waltham et al., 2020). As the number of funded restorations increases, there is a strong need for reform and standardization of restoration methodologies, rigorous guidance on site selections, and success benchmarks that exceed the current average three-year follow-up timeline in the region. This author echoes the call of Gatt et. al. (2022), in the need for scholars, practitioners, and international organizations to consolidate a more unified monitoring assessment regime.

Many of Mumbai's largest infrastructure projects that involve mass mangrove clearance—the Coastal Road, Mumbai Metro, Ahmedabad-Mumbai Bullet Train, NMIA, JNPT, etc.—have largely been financed through private-public partnerships with international financial institutions. These include hundreds of billions ($USD) in combined infrastructure investment from the World Bank, Asian Development Bank (ADB), Japan International Cooperative Agency (JICA), and the European Bank for Reconstruction and Development (EBRD). As international financial institutions transform the physical landscape of global cities, they have a responsibility to rigorously weigh the environmental impacts of clearance and financially support restoration structures at the multi-decadal scale. Moving forward, international stakeholders and local officials should develop a targeted whole-of-city approach to conserving and monitoring Mumbai's mangrove restorations.

Supplementary Materials

The following supporting information on project clearances and restoration area shapefiles can be downloaded at: https://www.dropbox.com/scl/fo/rfk59n8pe8swkkqvw2qtl/h?rlkey=udr0ezkvw5ijaqk184of6pedu&dl=0 .

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Data Availability Statement

Publicly available datasets were analyzed in this study. This data can be found here: https://parivesh.nic.in/, https://egreenwatch.nic.in/.

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Conflicts of Interest

The author declares no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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