Mapping +30 Years of Mangrove Extent in Tanzania Using Historical Data and Remote Sensing: A Collaborative, Open-Source Approach

Mapping +30 Years of Mangrove Extent in Tanzania Using Historical Data and Remote Sensing: A Collaborative, Open-Source Approach

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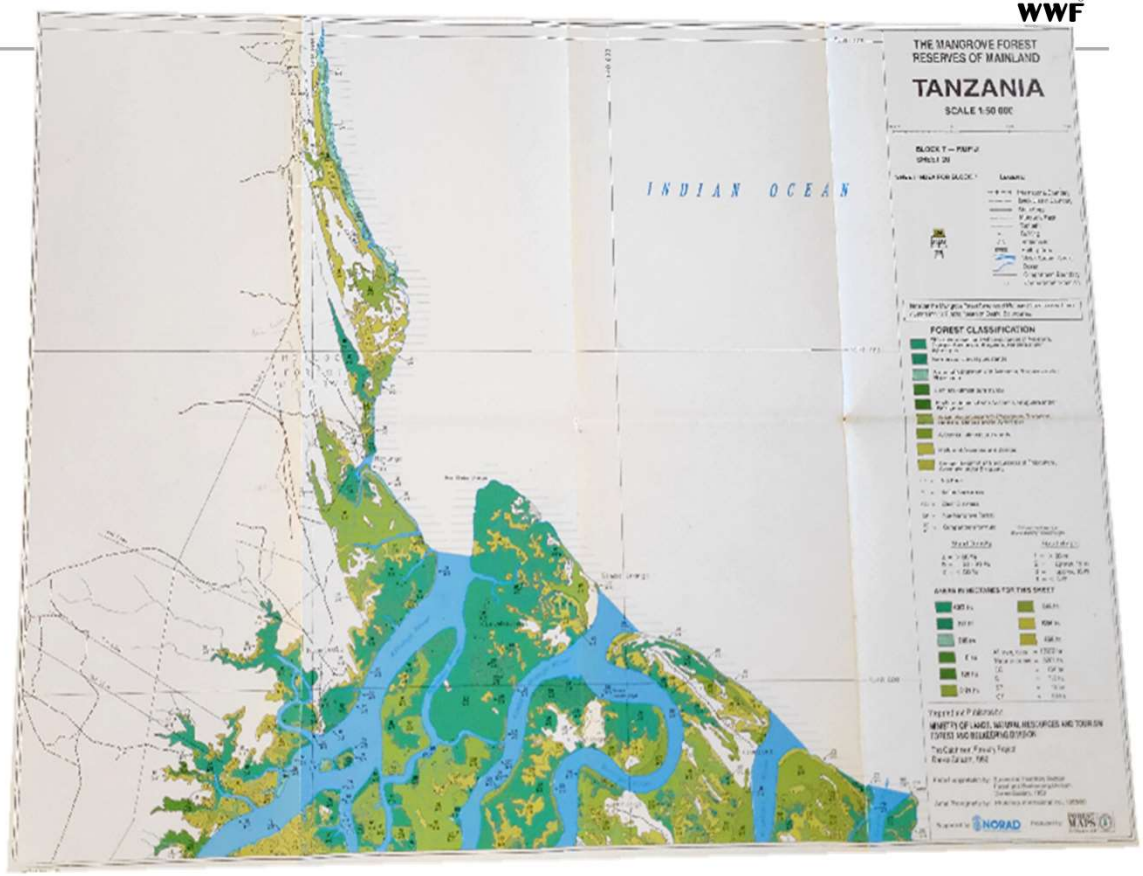
History of Mangrove Mapping in Tanzania

- Management of mangroves forests in Tanzania dates to the early 1900s
- 1991 first national management plan 1989/1990 national mangrove inventory – **first official dataset**
- No long-term monitoring – fragmented, inconsistent estimates



Semesi, A.K. Developing management plans for the mangrove forest reserves of mainland Tanzania. Hydrobiologia 247, 1–10 (1992). https://doi.org/10.1007/BF00008199

Conflicting Numbers

Example Mainland Tanzania

- Estimates from past studies range from 90,000 to 245,000 ha
- government recognized 2015 NAFORMA study, which is however still debated

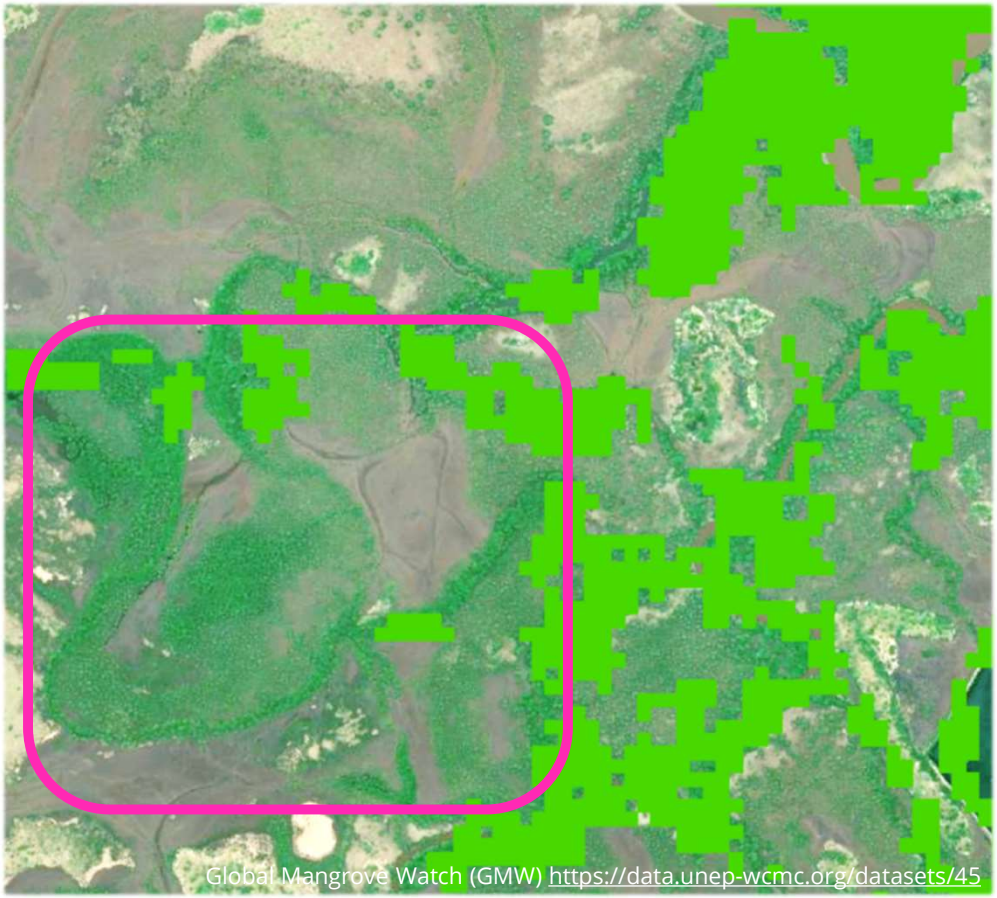
Year	Area (ha)	Methodology/Comment	Coverage	Source
1980	90,000	Analysis of the deforestation rate	Mainland Tanzania	**FAO & UNEP (1981)**
1989	245, 600	Analysis of aerial photography of 1988/1989 by Ministry of Lands	Mainland Tanzania	**Spalding et al. (1997)**
1989	115,467	Inventory and analysis of aerial photography of 1988/1989 (Ministry of Lands, 1990), Tanzania mainland	Mainland Tanzania	**Semesi (1992)**
1990	323,300	Unspecified	United Republic of Tanzania	**Earth Trends (2003)**[1]
2000	127,200	Map analysis for East African Coastal Database & Atlas Project: Tanzania, 2001	Unspecified	**Taylor et al. (2003)**
2003	108,138	Remote sensing	Mainland Tanzania	**Wang et al. (2003)**
2006	127,052	Digitization of topographic maps and aerial photographs 1980-1990 for mainland and aerial photos of 2006 for Zanzibar	United Republic of Tanzania	**TANSEA (2016)**[2]
2010	128,683	Expert reports and analysis of literature		**Spalding et al. (2010)**
2015	158,100	Remote sensing data analyzed for NAFORMA report	Mainland Tanzania	**MNRT 2015**
2015	114,419	Landsat 8, created through a supervised digital image classification technique at 30-m spatial resolution	United Republic of Tanzania	**RCMRD**[3]
2016	110,025	Remote sensing data from JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2.	United Republic of Tanzania	**GMW (2016)**[4]
2016	98,000	Remote sensing data from JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2.	Mainland Tanzania	**GMW (2016)**[4]

[1]Earth Trends www.earthtrends.wri.org
[2]Tanzania Sensitivity Atlas (TANSEA) www.ims.udsm.ac.tz/tansea/
[3]Regional Center for Mapping of Resources for Development (RCMRD) SERVIR project http://gis1.servirglobal.net:8080/geonetwork/srv/api/records/74e6c47b-a6c9-49fa-bddb-46f091257022
[4]Global Mangrove Watch (GMW) https://data.unep-wcmc.org/datasets/45

Conflicting Numbers

Example Mainland Tanzania

- Estimates from past studies range from 90,000 to 245,000 ha
- government recognized 2015 NAFORMA study, which is however still debated
- Global datasets (e.g., Global Mangrove Watch) miss inland areas



Global Mangrove Watch (GMW) https://data.unep-wcmc.org/datasets/45

Bridging 30+ Years of Data: Goals & Outputs of the Earth Observation Activities

Mangrove extent mapping along the complete mainland coast of Tanzania & Zanzibar 1990-2023

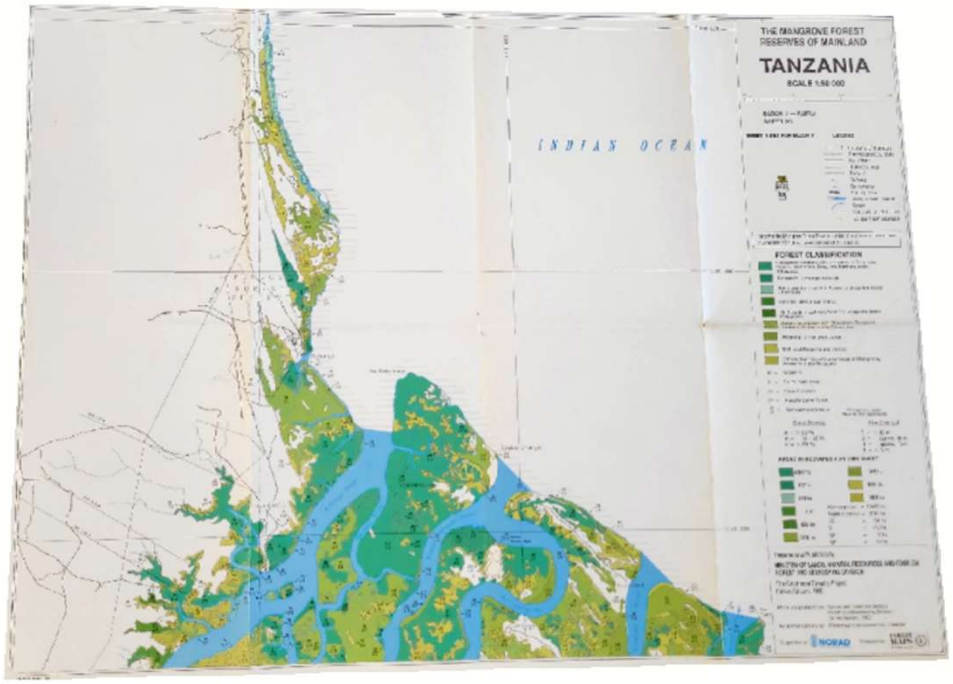
1. **Historical paper maps (1989/90) ➞ digitized & georeferenced**
   First ever **digitized & georeferenced product of the 1988/89 mangrove forest inventory (georeferenced map images and geodata)** (Semesi, 1992).

2. Extensive **ground samples (geodata)** & **expert knowledge**

3. **Satellite Image Classification** with Earth Observation **over a +30 years period**
   1. **Baseline Mangrove extent** for mainland coast of Tanzania & Zanzibar **1990** (Landsat)
   2. **Current Mangrove extent** for mainland coast of Tanzania & Zanzibar **2023** (Landsat, Sentinel 1&2)
   3. **Change analysis** of mangrove extent **1990-2023** (gain, loss and stable mangroves)
   4. Breakdown of mangrove area by designated **administrative management blocks**.

Incl. **open data sharing** online **apps** for ground sample collection, validation, monitoring & communications

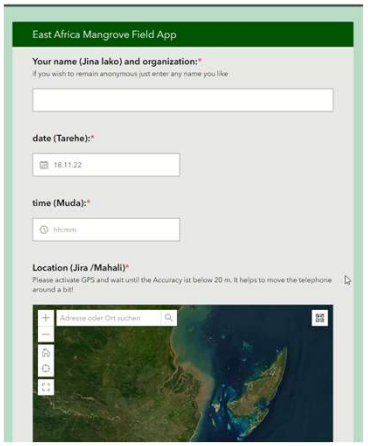
Preserved for the future: Mangrove Maps – digitized, georeferenced & vectorized

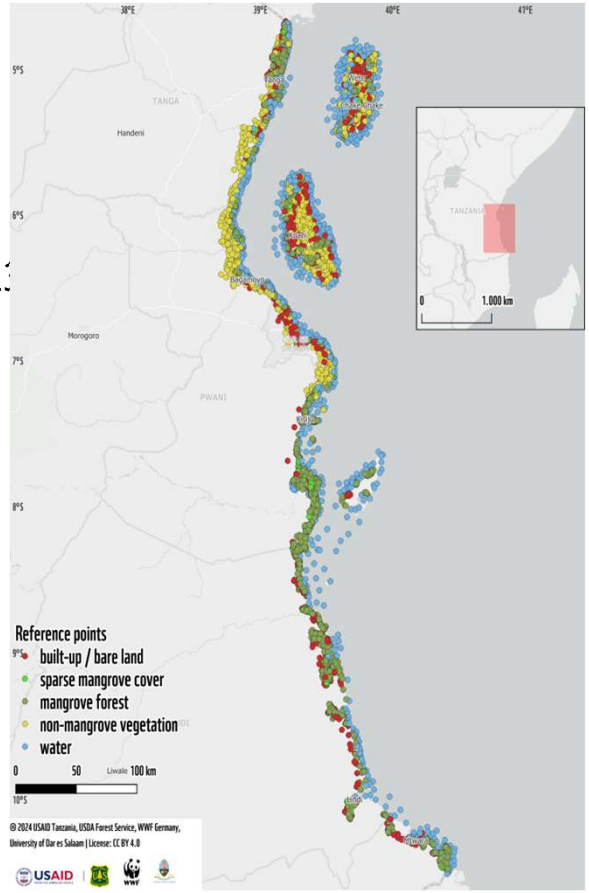


Semesi, A.K. Developing management plans for the mangrove forest reserves of mainland Tanzania. Hydrobiologia 247, 1–10 (1992). https://doi.org/10.1007/BF00008199

Training & Validation data - Multiple Sources

1. existing data collections (Rufiji delta 2018 and other missions)
2. new **field data collection** for 2022/23 with the field survey app (field work)
3. new **manually digitized** from **1988/89 mangrove forest inventory (georeferenced map images and geodata)** (Semesi, 1992).
4. new **manually digitized** from higher resolution satellite images for 2023/2
(desktop work)
5. new **training and validation data collection** with a feedback online map app (desktop work)





Survey Form (survey123): East Africa Mangrove Field Data Form v3 2023
Map: Map for East Africa Mangrove Field Data Form v3 2023

Preprocessing

- Cloud free composites (all available images)
  - Landsat (USGS) 1990 +/- 3 years (1988-1992)
  - Landsat (USGS) 2023 wet & dry season composite
  - Sentinel 2 (ESA) 2023 wet & dry season composite
  - Sentinel 1 (ESA) 2023 monthly mean composite

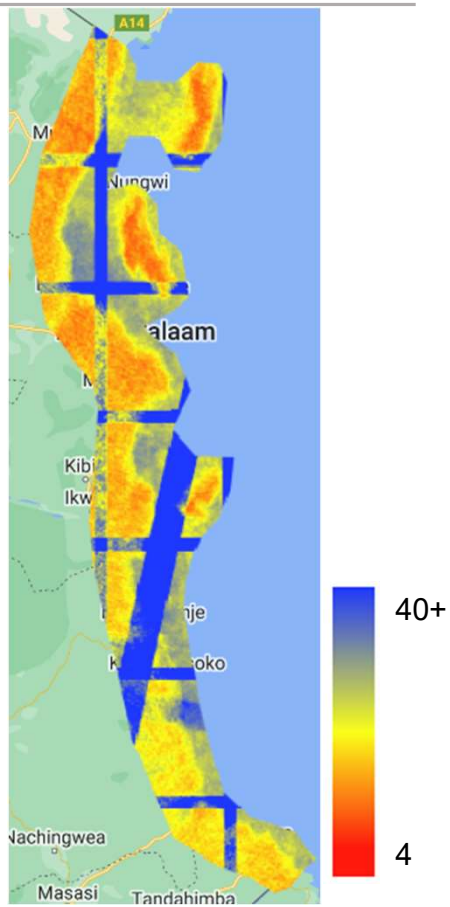
- Landsat/Sentinel 2:
  - **10 vegetation indices**
  - **Spectral Temporal Metrics** (proxy for phenology)
  - 10, 25, 50, 75, 90 percentiles, standard deviation, and 10-90 percentile range
- Sentinel 1:
  - Monthly S1 time series for VH, VV
  - **Radar Vegetation Index**

Total model features:

→ for 2023 Sentinel: 294 optical & 36 radar features

→ For 2023 Landsat: 224 optical

→ For 1990 Landsat 105 optical



Number of cloud free dry season S2 images available per pixel

Preprocessing

Indices used

Index Name	Initialism	Formula	Reference
Normalized Difference Vegetation Index	NDVI	(NIR - RED) / (NIR + RED)	Kriegler et al.,1969
Enhanced Vegetation Index	EVI	2.5 * ((NIR - RED) / (NIR + 6 * RED - 7.5 * BLUE + 1))	
Normalized Difference Water Index	NDWI	(Green - NIR) / (Green + NIR)	Gao, 1996
Normalized Difference Moisture Index	NDMI	(NIR - SWIR) / (NIR + SWIR)	Jin & Sader, 2005
Mangrove Index	MI	(NIR - SWIR/NIR * SWIR) * 10000	Winarso et al., 2014
Green Mangrove Vegetation Index	MVI	(NIR - Green)/(SWIR - Green)	Baloloy et al., 2020
Combined Mangrove Recognition Index	CMRI	NDVI - NDWI	Gupta et al., 2018
Tasselled Cap	TC	Greenness, Wetness, Brightness	Crist & Cicone, 1984
Radar Vegetation Index	RVI	4σ0VH/(σ0VV + σ0VH)	Mandal et al., 2020

1990 & 2023 Mangrove Extent & Change

- **5 Random Forest Models** built from training features (100 trees) GEE python API used to generate mangrove extent maps for 1990 and 2023
- post classification filtering
  - For 1990: water mask / 50m buffer around digitized 1990 maps
  - 3x3 majority filter
  - < 0.5ha minimum mapping unit removed
  - < 40m elevation (SRTM)
  - Expert knowledge
- Vector output

Google Earth Engine

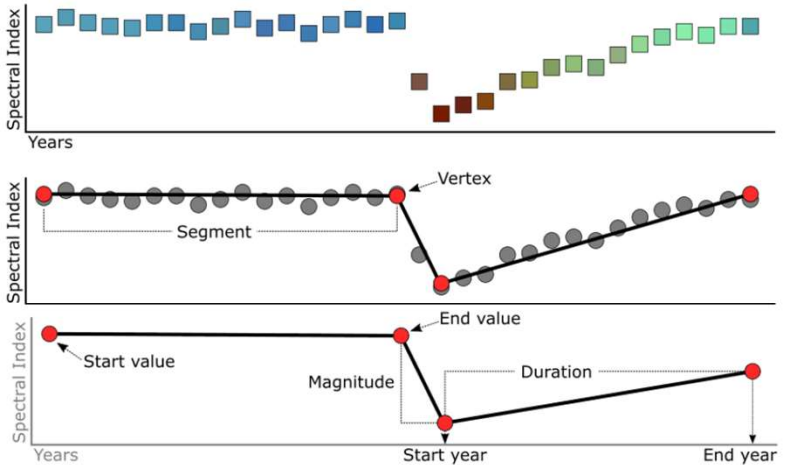
```
var training = data.select(bands)
.sampleRegions({
collection: trainingpts,
properties: ['class'],
scale: 30
});

var validation = data.select(bands)
.sampleRegions({
collection: validpts,
properties: ['class'],
scale: 30
});

// Make a Random Forest classifier and train it.
var classifier = ee.Classifier.randomForest({
    numberOfTrees: 10,
});

// Train the classifier.
var trained = classifier.train(training, 'class', bands);
```

1990 & 2023 Mangrove Extent & Change

- **5 Random Forest Models** built from training features (100 trees) GEE python API used to generate mangrove extent maps for 1990 and 2023
- post classification filtering
  - For 1990: water mask / 50m buffer around digitized 1990 maps
  - 3x3 majority filter
  - < 0.5ha minimum mapping unit removed
  - < 40m elevation (SRTM)
  - Expert knowledge
- Vector output

- **LandTrendr** GEE python API used to generate mangrove 1990-2023 change analysis
  - Landsat NDMI composites (1988-2023, median annual NDMI)
  - Masked to area of change of 1990 & 2023 extent maps

Google Earth Engine



https://emapr.github.io/LT-GEE/landtrendr.html

Model Accuracy

	Mangrove	Non-Mangrove	Water	Total	User's Accuracy
Mangrove	192	34	0	226	0.85
Non-Mangrove	23	275	0	298	0.92
Water	0	0	22	22	1.00
Total	215	309	22	546	
Producer's Accuracy	0.89	0.89	1.00		
Overall Accuracy	**0.90**				

1990

Mainland

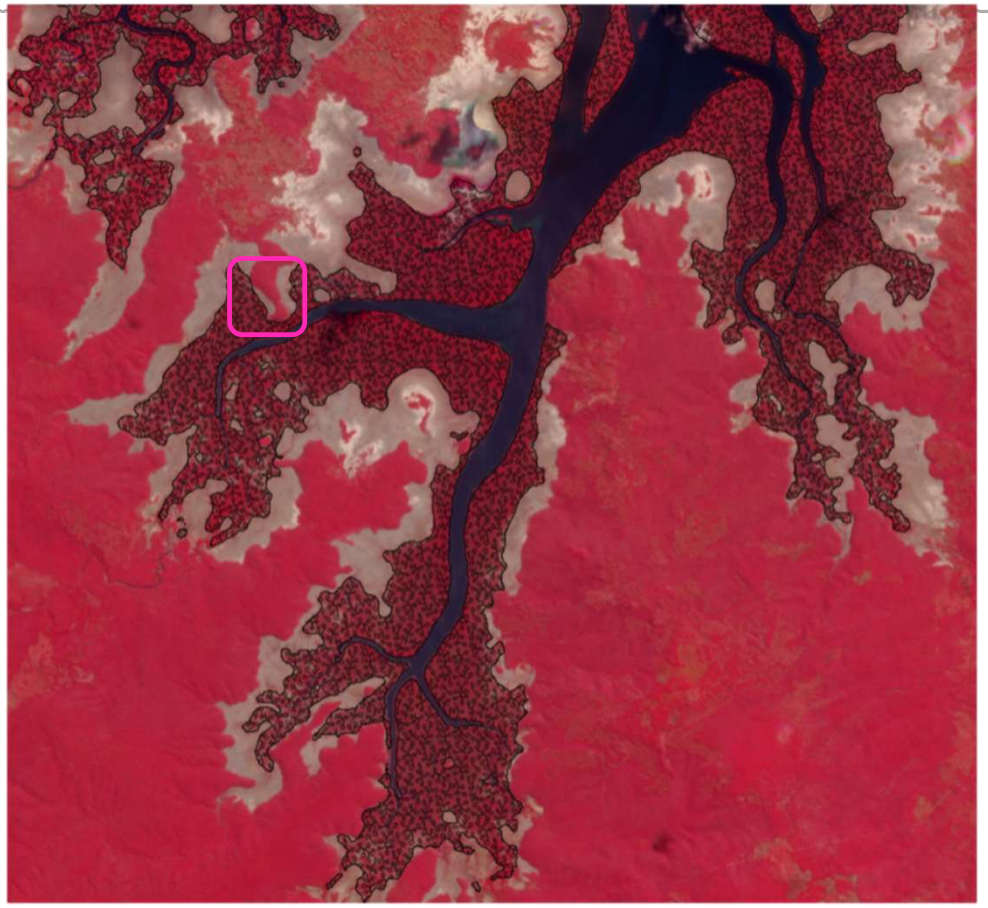
2023

Zanzibar

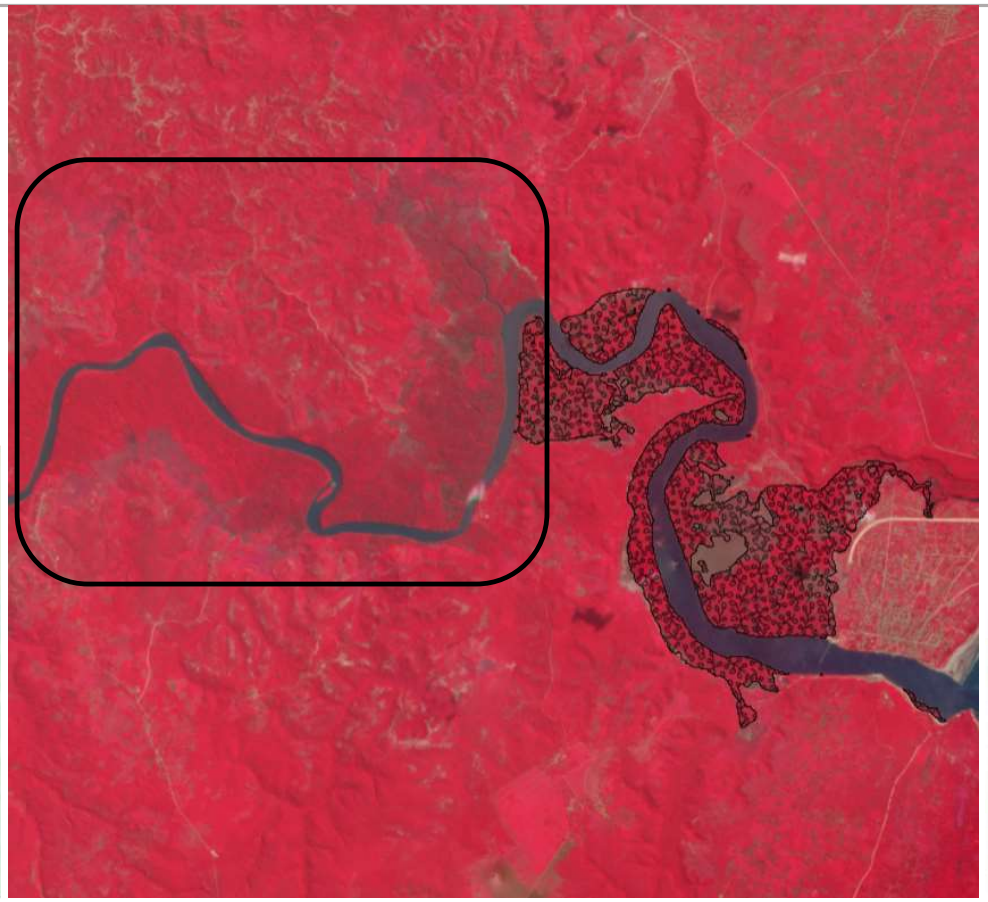
	Closed-Canopy Mangroves	Open-Canopy Mangroves	Non-mangrove Vegetation	Built up/bare	Water	Total	User's Accuracy
Closed-Canopy Mangroves	298	8	7	2	0	315	0.95
Open-Canopy Mangroves	6	39	1	0	0	46	0.85
Non-mangrove Vegetation	8	0	141	1	3	153	0.92
Built up/bare	0	0	1	42	0	43	0.98
Water	1	0	4	0	87	92	0.95
Total	313	47	154	45	90	649	
Producer's Accuracy	0.95	0.83	0.92	0.93	0.97		
Overall Accuracy	**0.94**						

	Closed-Canopy Mangroves	Open-Canopy Mangroves	Non-mangrove Vegetation	Built-up/ bare	Water	Total	User's Accuracy
Closed-Canopy Mangroves	69	0	6	0	0	75	0.92
Open-Canopy Mangroves	1	5	0	0	0	6	0.83
Non-mangrove Vegetation	3	0	129	0	2	134	0.96
Builtup/bare	0	0	2	46	0	48	0.96
Water	0	0	0	0	57	57	1.00
Total	73	5	137	46	59	320	
Producer's Accuracy	0.95	1.00	0.94	1.00	0.97		
Overall Accuracy	**0.96**						

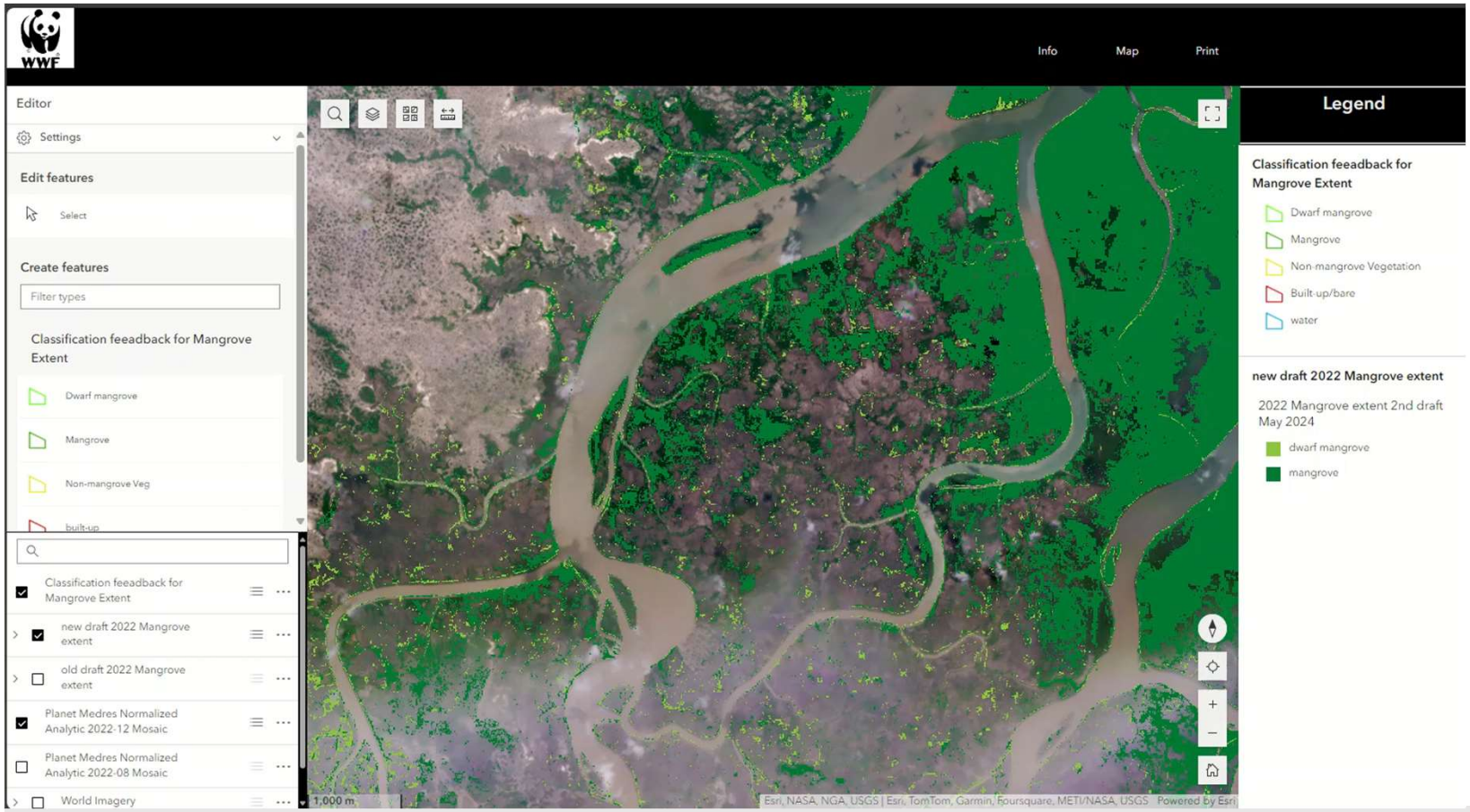
Results 2023



Can’t Tell a Coconut from a Mangrove without expert knowledge



Training & Validation data collection with Feedback online map app

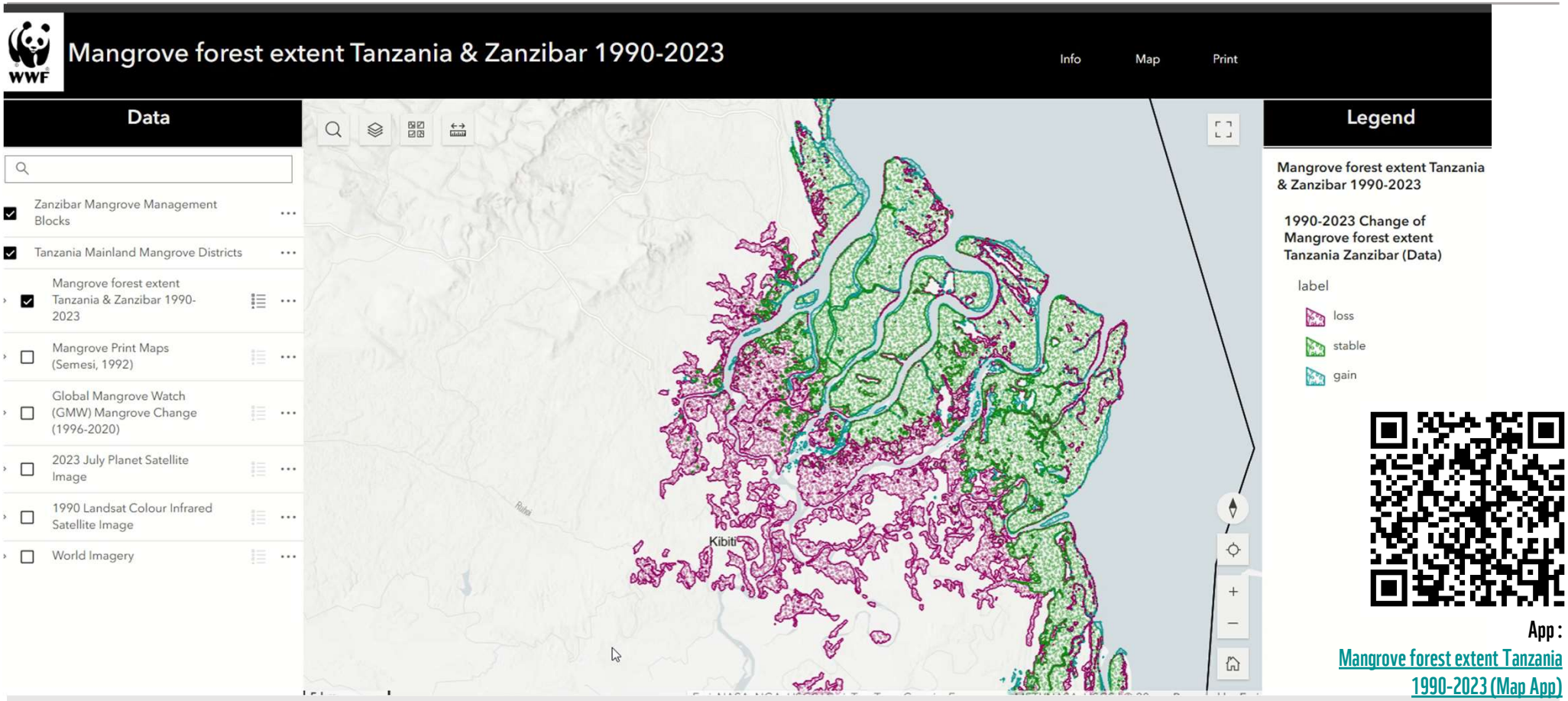


Feedback Apps :

Mangroves Tanzania 1990 Feedback tool

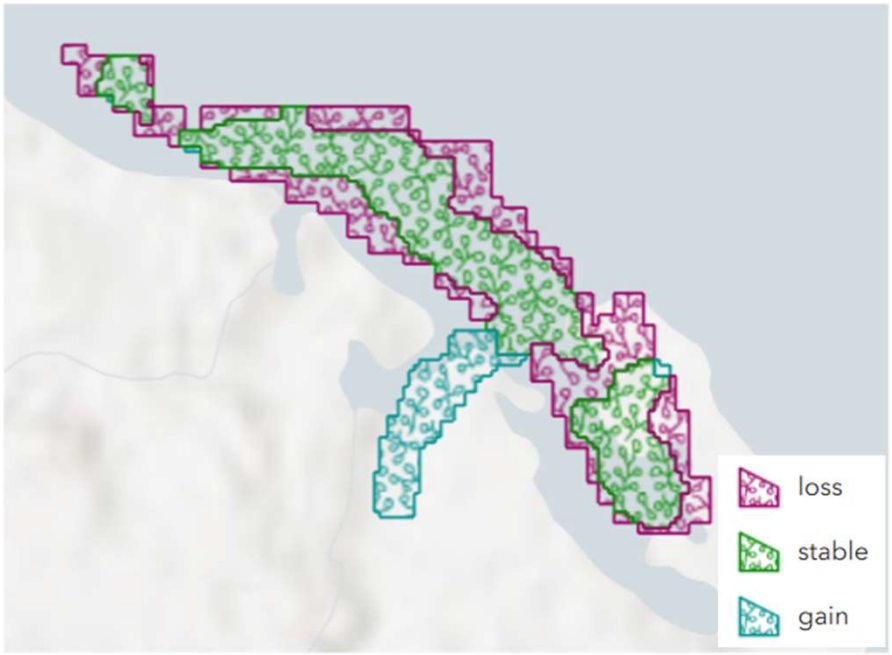
Mangroves Tanzania 2023 Feedback tool

Mangrove Loss & Gain Over 30+ Years



App :
[Mangrove forest extent Tanzania 1990-2023 (Map App)]

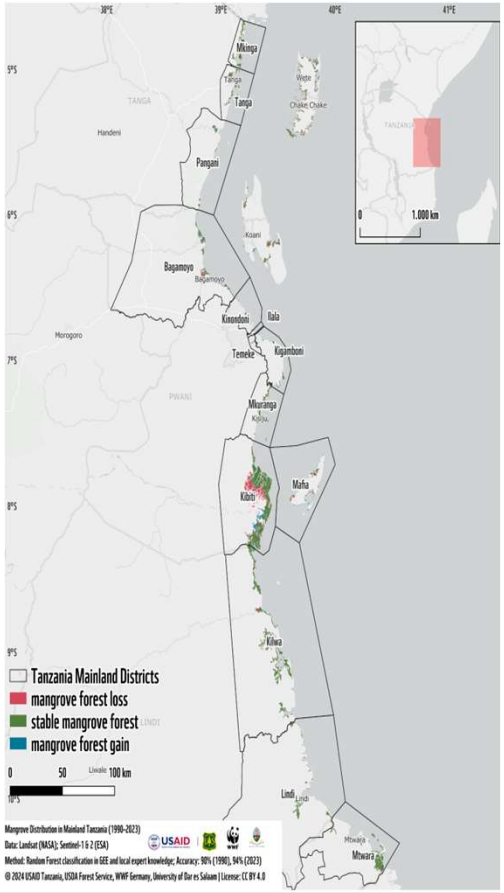
Mangrove restoration



Mangrove Loss & Gain Over 30+ Years

Mangrove Forest Area [ha] in the Mainland Districts

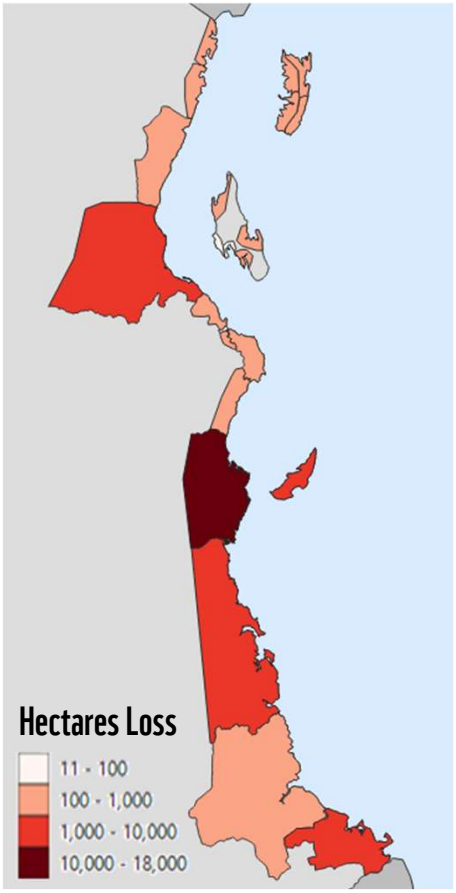
District	1990		2023			
	Landsat	Digitized Maps		Stable	Gain	Loss
Mkinga	6,067.3	5,435.9	5,789.3	5,350.6	438.7	716.7
Tanga	3,795.6	3,259.7	3,278.8	3,028.3	250.5	767.3
Pangani	1,773.4	1,801.6	2,192.1	1,457.1	735.0	316.3
Bagamoyo	6,015.4	5,458.5	5,013.6	3,901.8	1,111.6	2,113.5
Kinondoni	196.7	201.5	221.3	92.8	128.6	103.9
Ilala	19.0	13.7	14.7	8.2	6.4	10.7
Temeke	333.4	266.9	251.9	227.9	24.0	105.5
Kigamboni	1,401.9	1,249.1	1,246.9	1,081.8	165.1	320.2
Mkuranga	5,306.3	4,516.0	4,934.8	4,404.2	530.5	902.2
Kibiti	54,202.2	50,862.8	42,264.5	36,598.5	5,665.7	17,604.0
Mafia	4,082.9	3,617.7	3,345.7	2,621.1	724.5	1,461.9
Kilwa	25,518.6	26,913.6	23,652.9	22,116.7	1,536.3	3,401.9
Lindi	5,400.7	5,094.4	4,781.3	4,411.7	369.5	989.1
Mtwara	9,908.2	8,945.5	9,066.1	8,460.2	605.8	1,448.1
TOTAL	**124,021.6**	**117,636.9**	**106,053.7**	**93,760.9**	**12,292.2**	**30,261.2**

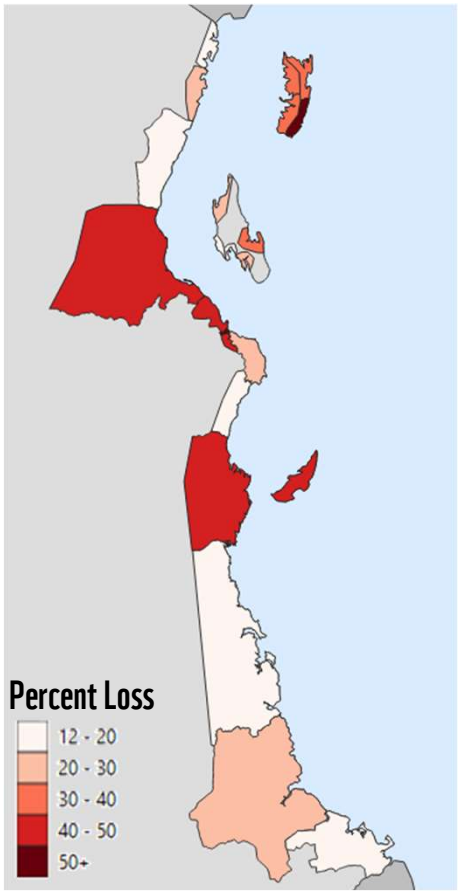


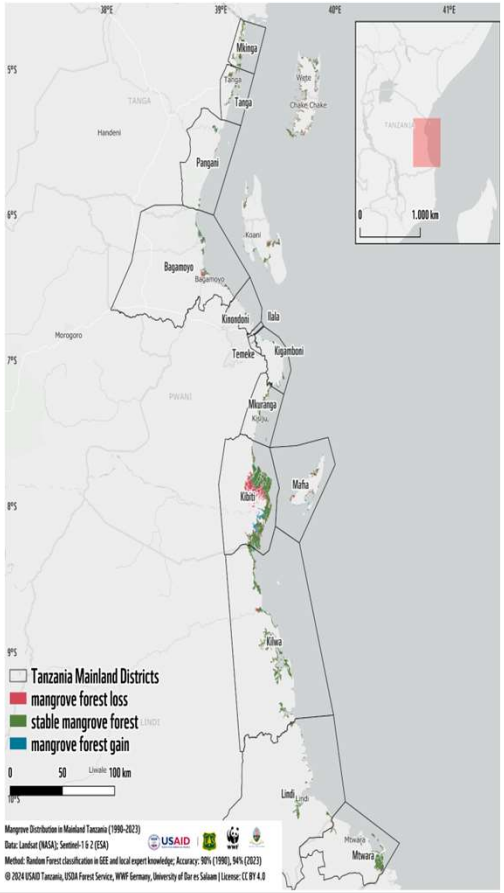
Mangrove Loss & Gain Over 30+ Years

Mangrove Forest Area [ha] in the Mainland Districts

→ Net loss 14.5%
or 545 ha/year

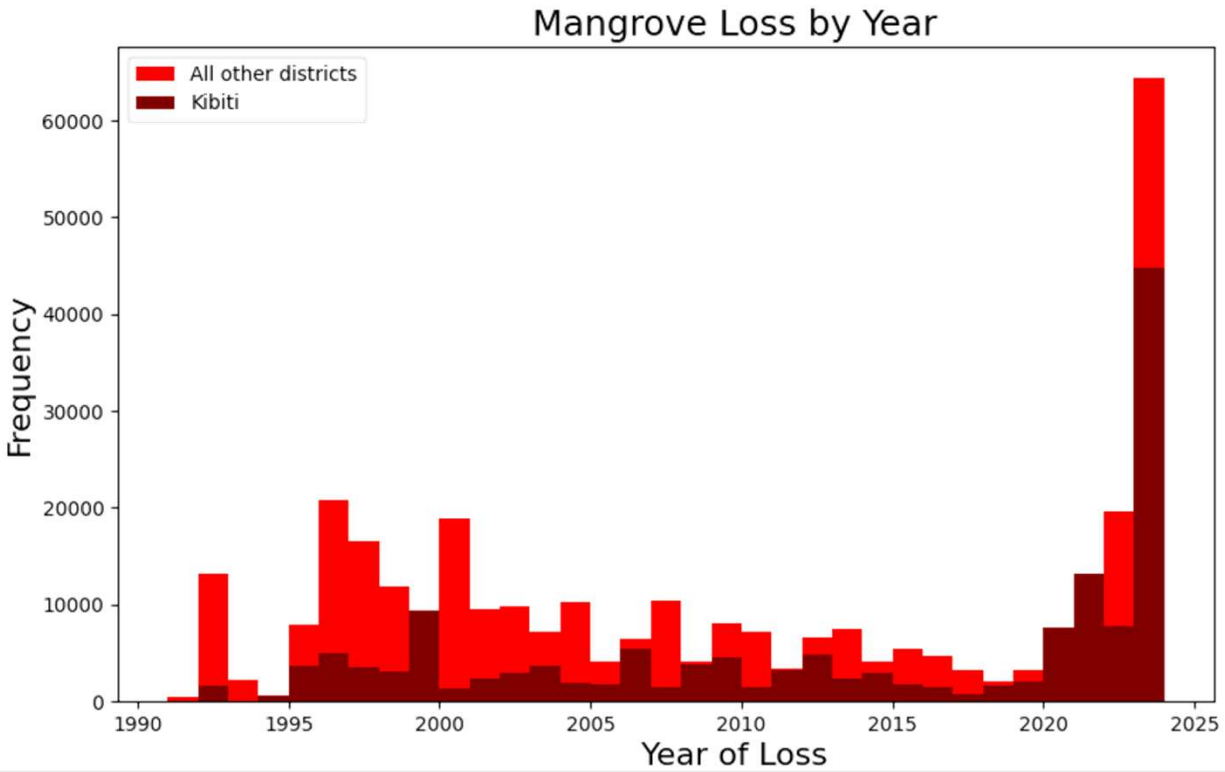


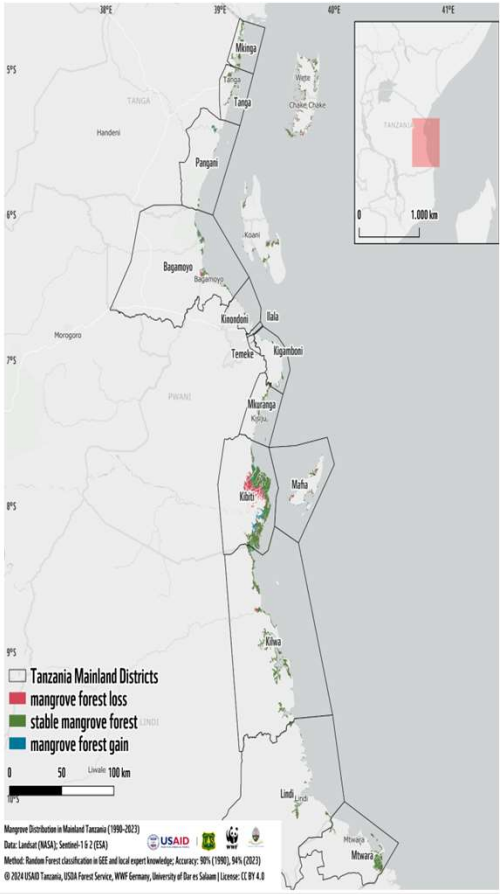




Mangrove Loss & Gain Over 30+ Years Mangrove Forest Area [ha] Year of Change in the Mainland Districts

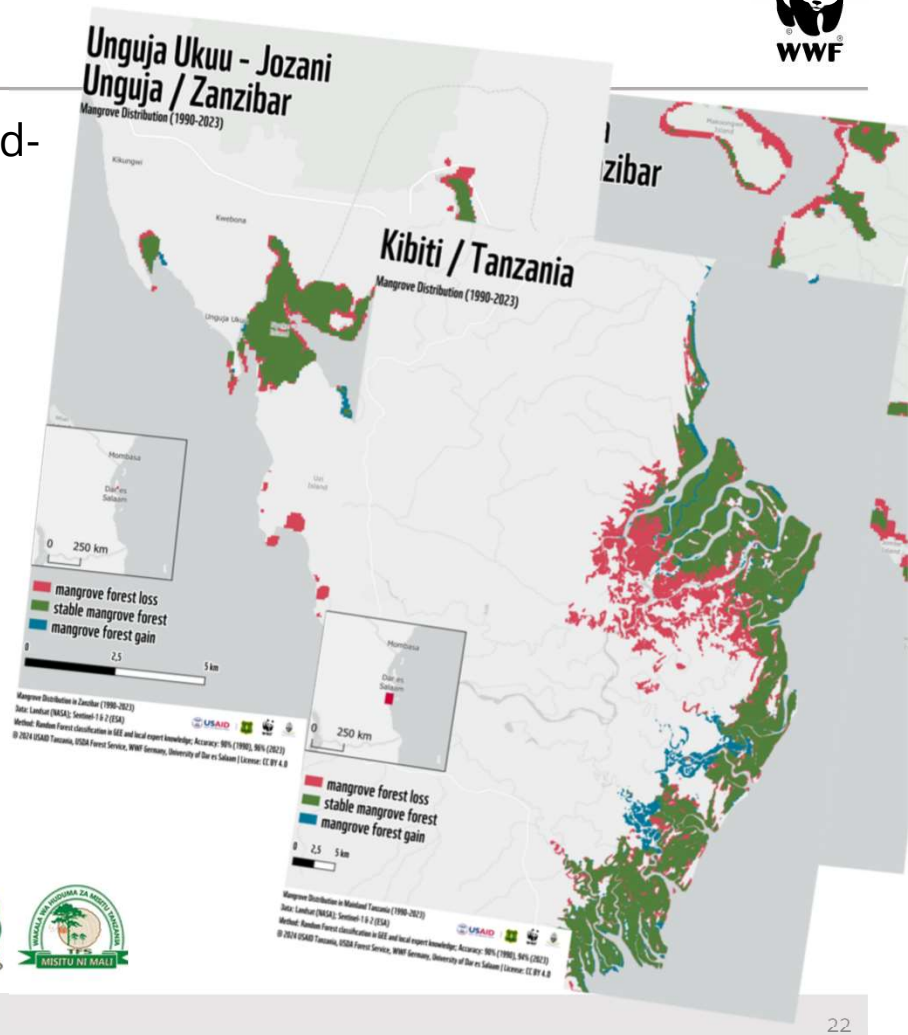
→ Most loss in past 5-10years





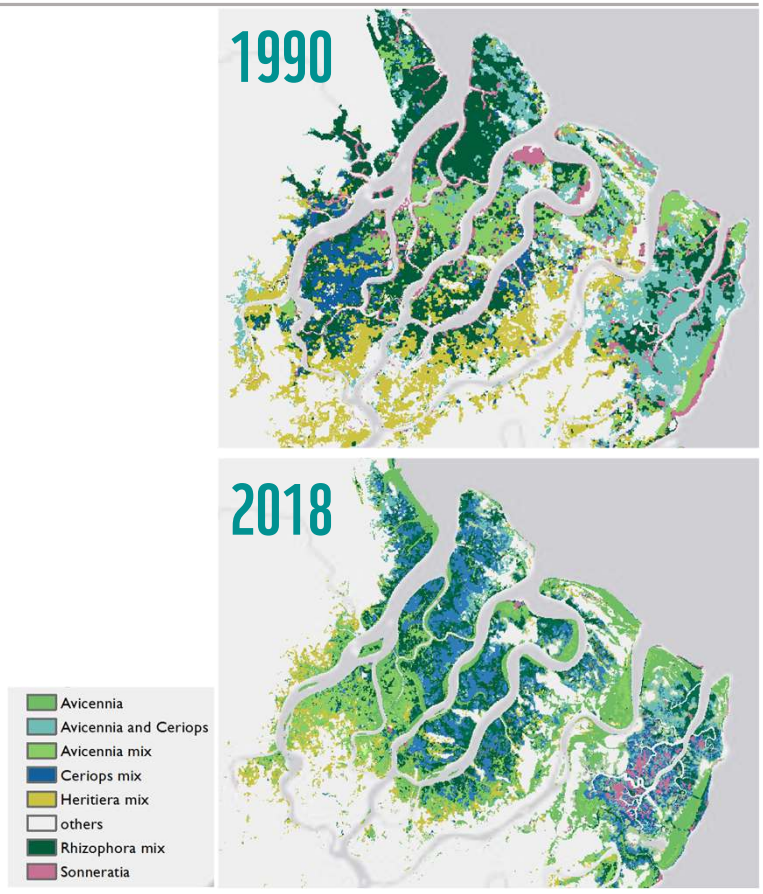
From Research to Real-World Impact

- Government agencies want to adopt our dataset for land-use planning
- Integrated into Tanzania's National Forest Inventory & Climate Reporting
- Potential update to Global Mangrove Watch with improved data
- [Open Data Sharing on the WWF GLOBIL platform]



Next Steps / Future needs

- Government agencies want to adopt our dataset for land-use planning
- Integrated into Tanzania's National Forest Inventory & Climate Reporting
- Potential update to Global Mangrove Watch with improved data
- Species change (Rufiji analysis)
- Drivers of mangrove change
  (sea-level rise, sediment deposition, coastal development, and land-use changes)



Team effort

Carl C. Trettin
USDA Forest Service
Leading mangrove expert, USAID communication, project management

Helga Kuechly
WWF Germany
GIS tools, RS method, technical communication, project management

Kelvin J. Kamnde
UDSM/WIOMN
mangrove expert ,field surveys

Makemie J. Mabula
EACOP
mangrove expert old map digitization, field surveys

Mwita M. Mangora
UDSM/WIOMN
Leading mangrove expert , field survey governmental & USAID communication, project management

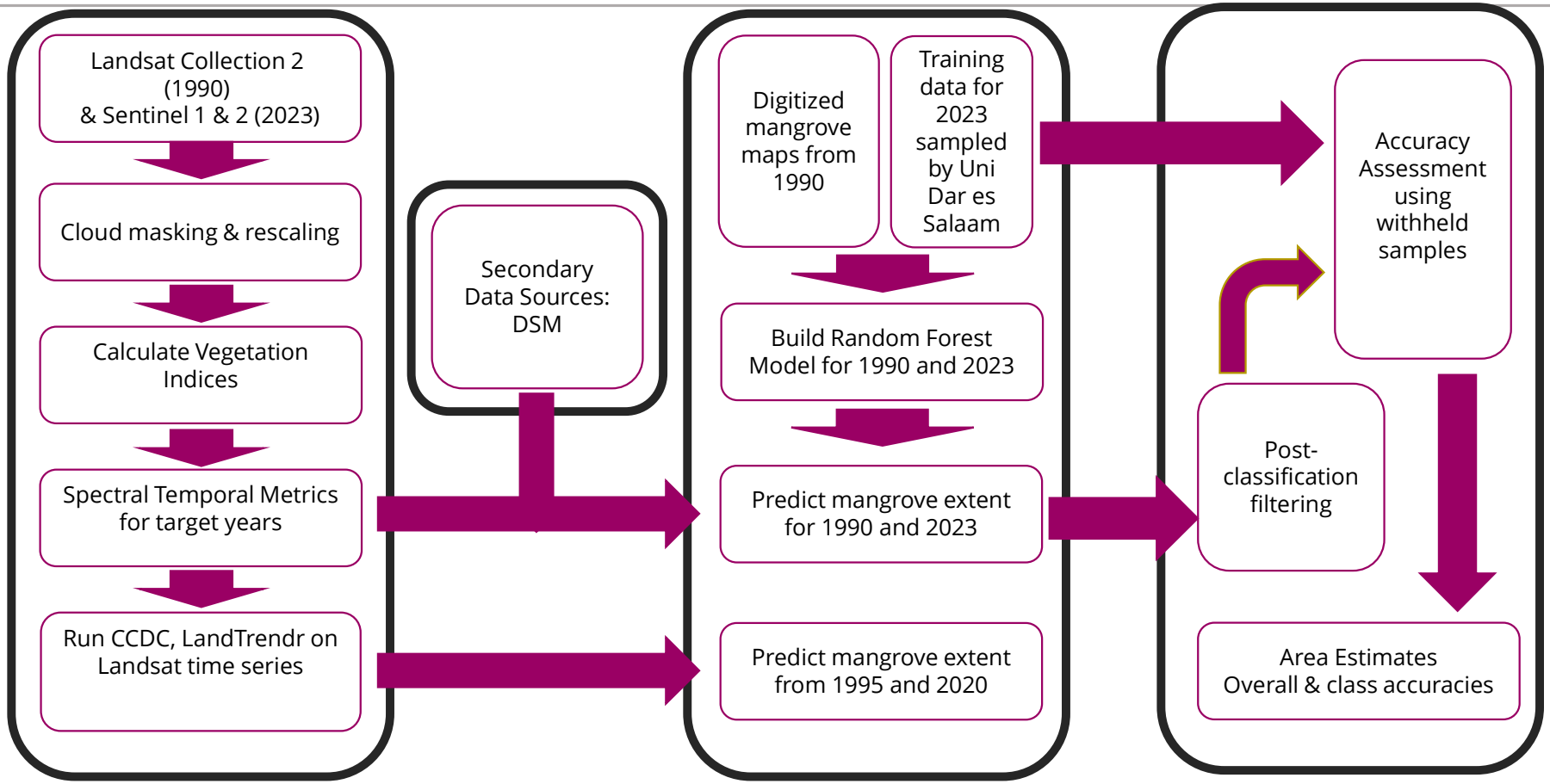
Sam Cooper
Humboldt-Universität zu Berlin
RS model, technical communication

Simon Spengler
WWF Germany
GIS analysis, GIS tools, RS model

Key Recommendations

1. Long term access for continuous monitoring and VHR services
   (e.g. Planet NICFI for training & validation)
2. Cloud-based processing environments for reduced reliance on GEE.
3. Global ground truth data catalogues & pretrained models
   just as important as satellite images.
4. Long term monitoring indicator vector products
   (long time-series, end-users prefer using vectors, but a lot of RS typically limited to raster products)

Workflow


Landsat Collection 2 (1990) & Sentinel 1 & 2 (2023)
Cloud masking & rescaling
Calculate Vegetation Indices
Spectral Temporal Metrics for target years
Run CCDC, LandTrendr on Landsat time series
Secondary Data Sources: DSM
Digitized mangrove maps from 1990
Training data for 2023 sampled by Uni Dar es Salaam
Build Random Forest Model for 1990 and 2023
Predict mangrove extent for 1990 and 2023
Predict mangrove extent from 1995 and 2020
Accuracy Assessment using withheld samples
Post-classification filtering
Area Estimates Overall & class accuracies

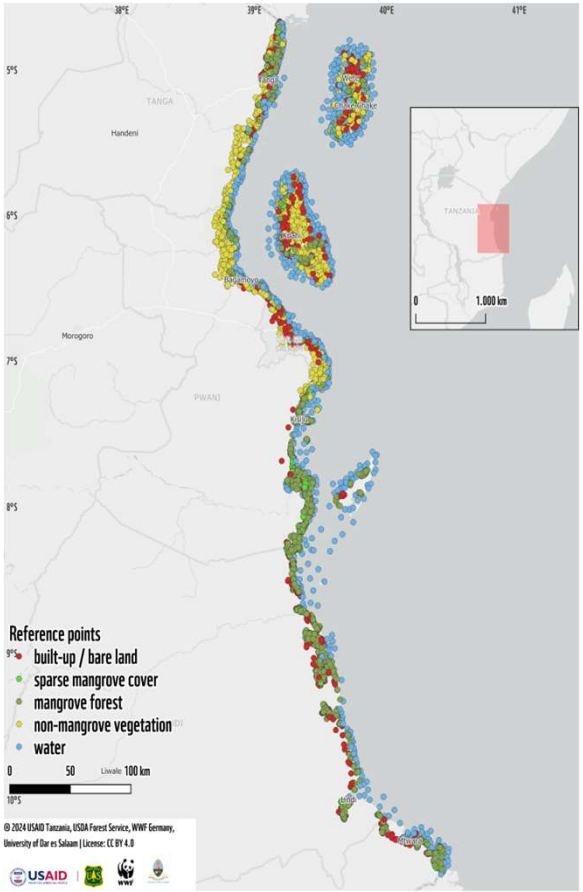
Training and Validation Data

2023 Reference Points per Class

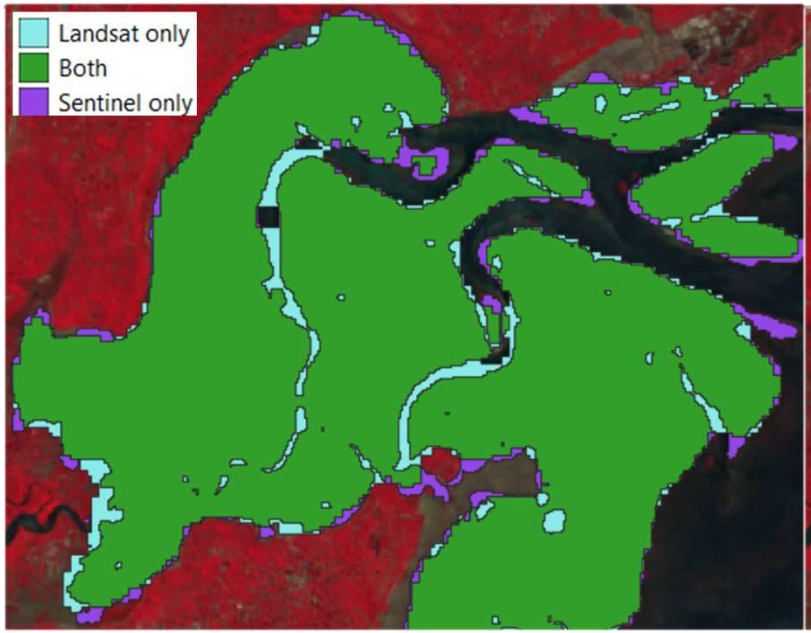
	Mainland		Zanzibar	
Class	n training	n test	n training	n test
Built-up/bare land, settlements	435	43	554	48
Open canopy mangrove	335	46	68	6
Closed canopy mangrove	2,913	315	560	75
Non-mangrove vegetation	1,303	153	1003	143
Water	734	92	490	57

1990 Reference Points per Class

	Republic of Tanzania	
Class	n training	n test
Mangroves	2,016	226
Non-mangroves	2,539	298
Water	166	22



2023 Landsat vs Sentinel



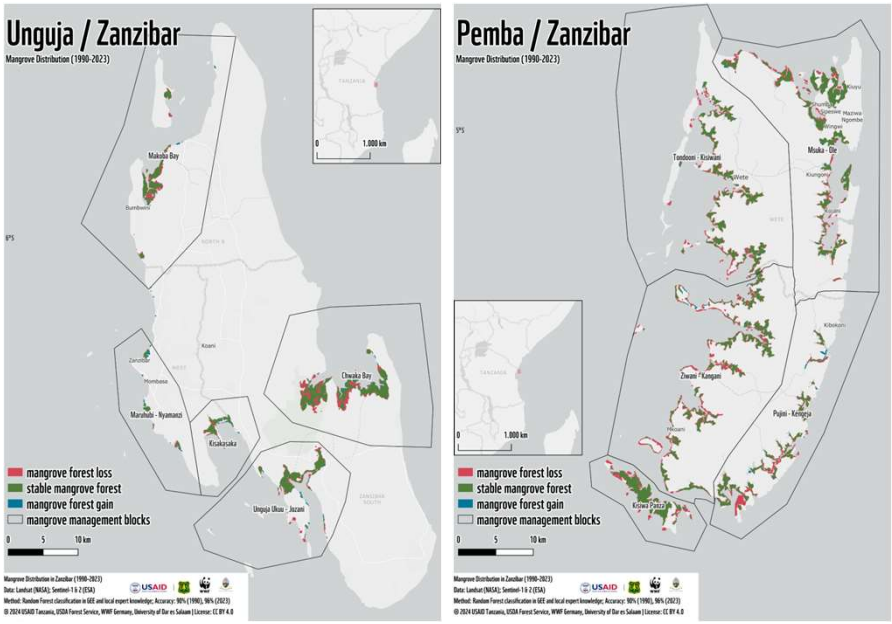
- Differences between Landsat and Sentinel models were 3,400 ha, or 4.8% of the total mangrove area
- Spatial resolution of sentinel allows more detail in canopy mapping
- Sentinel appears to handle water/vegetation mixtures better

USAID, USDA – Forest Service, Univ. Dar es Salaam – Inst. Marine Science and WWF-Germany

Mangrove Loss & Gain Over 30+ Years

Mangrove Forest Area [ha] in the management blocks of Unguja & Pemba (Zanzibar)

Management Blocks	1990	2023	Stable	Gain	Loss
Unguja					
Makoba Bay	1029.8	842.7	786.5	56.2	243.3
Chwaka Bay	2579.6	1,906.8	1,821.1	85.7	758.5
Maruhubi - Nyamanzi	152.6	185.4	123.1	62.4	29.5
Kisakasaka	328.1	313.5	264.8	48.7	63.3
Unguja Ukuu - Jozani	1096.0	897.6	842.0	55.6	254.0
Pemba					
Tondooni - Kisiwani	2537.2	2,005.9	1,886.1	119.9	651.1
Msuka - Ole	3246.8	2,538.3	2,417.1	121.1	829.8
Ziwani - Kangani	3162.3	2,373.7	2,205.1	168.6	957.1
Pujini - Kengeja	1659.3	1,141.5	1,034.8	106.8	624.6
Kisiwa Panza	1562.7	1,204.8	1,183.6	21.2	379.1
TOTAL	**17,354.2**	**13,410.2**	**12,564.1**	**846.1**	**4,790.3**



→ Net loss 23% or 120 ha/year

→ Positive Impact of Conservation Project visible

Mangrove Loss & Gain Over 30+ Years

of Unguja & Pemba (Zanzibar) Year of Change

Management Blocks	1990	2023	Stable	Gain	Loss	Mean Loss Year	Majority Loss Year	Mean Gain Year	Majority Gain Year
Unguja									
Makoba Bay	1029.8	842.7	786.5	56.2	243.3	2001	1995	1999	1995
Chwaka Bay	2579.6	1,906.8	1,821.1	85.7	758.5	2010	2021	2000	1995
Maruhubi - Nyamanzi	152.6	185.4	123.1	62.4	29.5	2001	1995	2000	1995
Kisakasaka	328.1	313.5	264.8	48.7	63.3	2003	2002	2004	1995
Unguja Ukuu - Jozani	1096.0	897.6	842.0	55.6	254.0	2008	2023	2002	1994
Pemba									
Tondooni - Kisiwani	2537.2	2,005.9	1,886.1	119.9	651.1				
Msuka - Ole	3246.8	2,538.3	2,417.1	121.1	829.8	2007	1995	2002	1995
Ziwani - Kangani	3162.3	2,373.7	2,205.1	168.6	957.1	2005	2001	2003	2001
Pujini - Kengeja	1659.3	1,141.5	1,034.8	106.8	624.6	2004	1995	2001	1995
Kisiwa Panza	1562.7	1,204.8	1,183.6	21.2	379.1	2002	1994	2003	1994
TOTAL	**17,354.2**	**13,410.2**	**12,564.1**	**846.1**	**4,790.3**	2003	1995	2000	1995

→ Most loss before 2005

If you can see it,
you can change it.