Monitoring The Restoration of Mangrove Ecosystems from Space

REPORT - NOVEMBER 2014

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Contents

Executive summary

Mangrove establishment and rehabilitation projects have had varying levels of success at different locations around the world. Given the money that has been invested in restoring mangrove coverage, it is useful to map, monitor and compare results and experiences in different parts of the globe to compare the success of such projects. This study conducted temporal analyses for 24 mangrove sites from 10 different projects in six different countries (Senegal, the United Arab Emirates, Madagascar, Kenya, Solomon Island and Indonesia) using satellite imagery and GIS technology to map and monitor their status. Given that many of the sites were small, very high-resolution satellite imagery (0.45, 0.6 and 1 metre resolution from Worldview, Quickbird and Ikonos, respectively) was used.

Compared with ground surveys, remote sensing provides a synoptic view and, using ancillary data, makes it possible to look at historical data. However, it may preclude gaining a clear understanding of reasons for failure and successes of projects.

Given the time and financial resources for this project, it was not possible to conduct ground surveys. However, the results were sent to the mangrove recovery project managers. As it turned out, results were mostly unchallenged. The results provided include a quantitative evaluation of the mangroves restoration (in both absolute number of ha and in percentage of the total). An analysis of the change in other vegetation coverage was also included where relevant. Additionally, the results show a range of various degrees of success. Half of the projects were very successful, 20 per cent were successful, 20 per cent show limited or no change, and in one project a decline of mangroves was observed.

Several limitations for detecting mangrove recovery from space have been highlighted, the main one being that the satellite images should be taken at least three to four years after the complexion of the mangrove recovery, as the size of the mangrove canopy would otherwise not be large enough to be detected. It also has to be noted that mangroves and tropical vegetation can be easily confused, and such distinction from space therefore remains challenging. Overall, the study showed that remote sensing is a good tool for monitoring mangrove recovery.

1. Introduction

Mangrove establishment and rehabilitation projects have been given increasing attention in recent years. The general impression is that the level of success for replanting of mangroves has varied significantly. However, until now there has been little effort to map, monitor and compare results and/or experiences throughout the world and to analyse what makes a sustainable mangrove (re-)development succeed or fail.

This study conducted temporal analyses for 10 projects (24 sites in six countries (the United Arab Emirates, Madagascar, Kenya, Senegal, Solomon Islands and Indonesia) to assess mangrove recovery after the implementation of restoration projects. It was conducted to map and monitor the loss and/or increase of mangrove forest areas via satellite imagery and GIS technology, and tries to assess the potential benefit of these methods.

1.1 Literature review

Mangrove ecosystems

The term mangrove is both used for the tree itself, and the overall habitat. Mangroves are small to medium evergreen trees or shrubs (Kuenzer et al., 2011) usually with a complex root system. They grow in the intertidal zone of marine coastal environments and estuarine margins between approximately 30° N and 30° S (Giri et al., 2011). Mangrove habitats are forests of mangrove trees. They grow in high salinity, high temperature and extreme tidal zones, which have high sedimentation rates and muddy anaerobic soils (Giri et al., 2011). In this report, the word "mangrove" refers to the habitat, but it has to be kept in mind that in the literature it can be also referred to as a "tidal forest" or a "mangrove forest" (Giri et al., 2011).

Mangrove ecosystems are represented by a large variety of plant families that are salt tolerant and found in brackish waters (Field, 1998). "Mangrove" can also refer to the ecosystem itself; a differentiation that will be used in this publication.

The importance of mangrove forests

Globally, mangroves are among the most productive of coastal ecosystems. About 75 per cent of all tropical commercial fish species and associated ecosystems, such as seagrass meadows and coral reefs, depend on mangrove forests as nurseries, and for shelter and food. Additionally, mangroves protect coasts from waves and wind—helping to reduce the risk of flood damage and erosion—and support soil stabilization, nutrient retention, filtration of sediment and pollutants, and the sequestration of carbon dioxide. For people living in coastal areas, mangroves provide firewood, medicine, fibres and dyes, food and building material.

Mangroves are influenced by tidal levels, salinity, and rainfall, and are threatened by human pressure, (through wood/timber extraction, pollution, and reclamation), global warming, and rising sea level.

Mangroves have recently been recognized as a key component of the global carbon cycle. They are the most carbon-rich forests in the tropics and are able to sequester carbon at a faster rate than terrestrial forests (Donato et al., 2011; Ray et al., 2011; Matsui et al., 2012; Kauffman et al., 2014). If their overall coverage is combined with that of marshes and seagrass meadows, they only account for approximately 0.5 per cent of the seabed area but for more than 50 per cent of the earth's blue carbon sinks, and for 71 per cent of all carbon storage in ocean sediments (Nellemann et al., 2009). The annual economic value of coastal wetlands (mainly based on mangrove ecosystems) is estimated to be between US$2,000 and US$200,000 per hectare (Van der Ploeg et al., 2010).

Current status of mangroves

Giri et al. (2011) made the most recent comprehensive, global survey of mangrove coverage (using Landsat archives to estimate the total surface of mangroves in the year 2000 for 137,760 km^2), including data from 118 tropical and subtropical countries. Approximately 75 per cent of this area is concentrated in 15 countries[1]. While there are no accurate estimates of the original cover, there is a general consensus that it would have been over 200,000 km^2 and that considerably more than 50,000 km^2 or one quarter of original mangrove cover has been lost as a result of human intervention (Spalding et al., 2010), with at least 35 per cent disappearing within the past two decades (Valiela et al., 2001). This rate is four times greater than the loss of terrestrial rainforest (Duarte, 2009) and it is expected that it will further accelerate (Waycott et al., 2009).

The destruction of mangroves is closely linked with human activities such as urban development, aquaculture, mining and overexploitation for timber. The greatest threats come from the development of fish and shrimps farms, and overexploitation of fisheries. Alteration of hydrology, pollution and global warming are also contributing to the loss of mangroves, but to a lesser extent (Alongi, 2002).

Mangrove restoration

The definition of the term "restoration" is generally restricted to the process of assisting the recovery of an impaired ecosystem (Clewell and Aronson, 2007). In this document, the term has been broadened to encompass all associated components of the ecosystem, including hydrology, soils, water quality, and all plant and animal species (Lewis, 2011). Planting mangroves in bare areas where there were no previous mangroves is "afforestation", whereas planting in other vegetated surfaces is referred to as "habitat conversion" (Erftemeijer and Lewis, 1999).

In mangrove restoration projects, the following parameters need to be assessed for the whole watershed during the site selection: stability of the site, siltation rate, soil characteristics (i.e. salinity, pH, nutrients and grain size), exposure to waves and currents, tidal height, height of water table, water salinity, availability of fresh water, presence of pests, availability of propagules, and signs of natural regeneration (Field, 1996; Venugopal et al., 2008). An understanding of the causes of ecosystem degradation of the selected sites (i.e. past use as a shrimp farm or paddy field) is compulsory, as they will differentially affect soil quality and other parameters and potentially affect the success rate of a restoration project (Field, 1998).

Achievable and measurable success criteria need to be defined and incorporated into a monitoring programme prior to its initiation. The status of adjacent mangroves should also be evaluated: healthy mangroves will maximize the chances of success of the restoration. Land clearing should be undertaken before planting, as debris movement on the site can potentially destroy young plants (Field, 1998). Even with successful restoration projects, at least two decades are needed to evaluate this success, based on the vegetation's structural attributes (Luo et al., 2010). Simple planting success is the first short-time step in the restoration process (Rovai et al., 2012).

1 The dataset is available at http://data.unep-wcmc.org/datasets/21.

1.2 Remote sensing

The crown width of adult mangrove tree species varies from 3 to 15 metres (Wannasiri et al., 2013). When young, mangroves (i.e. less than three years old) do not have a crown canopy that can be detected with satellite imagery. In a typical Landsat image (with a medium spatial resolution of 15 to 30 metres) single trees cannot be identified. According to literature cited in this study, the most frequent type of remotely sensed data employed to monitor mangrove ecosystems are either high-resolution (0.45 m to 1 m resolution) (e.g. WorldView, Quickbird or IKONOS), or medium-resolution (such as Landsat, ASTER, IRS or SPOT) satellite imagery. High-resolution imagery is most appropriate for visual interpretation, using on-screen delineation classification methods (see Table 1 in Kuenzer et al., 2011), whereas medium-resolution imagery is mainly processed by pixel-based classification techniques; although it has also been the subject of visual interpretation and on-screen delineation. Few studies employ object-based image analysis using either high-resolution or medium-resolution imagery.

Nevertheless, Kuenzer et al. (2011) indicate medium-resolution imagery as the most useful type of data for assessing reforestation and conservation success. However, medium-resolution imagery is too coarse for local observations. Additionally, Selvam et al. (2003) monitored a "successful effect of restoration conditions and reforestation status on degraded areas"—they used Landsat TM and Indian Remote Sensing Satellite IRS 1D LISS III datasets acquired in 1986 and 2002 that surveyed the Pichavaram mangrove wetlands in India. Their findings indicated that the mangrove forest cover increased by about 90 per cent over the 15-year span, which they mainly attributed to the combined

science-based and community-centred approach to reforestation, supported by the Tamil Nadu government as well as the mangrove users themselves. In current times, remotely derived products display an increased relevance to supporting local conservation planning tasks.

Seto and Fragkias (2007) presented a methodology for systematic monitoring of mangroves that is within the context of the Ramsar Convention on Wetlands[2]. They analysed a time series of Landsat MSS and TM data from the Red River Delta, Vietnam, between 1975 and 2002, calculating mangrove extent and density, extent of aquaculture, and landscape fragmentation, to assess the land cover condition as a function of time. Based on the results of artificial neural network classification—characterization of the amount of fragmented landscapes—pattern metrics, such as patch size and patch density, fragmentation and isolation patterns have been calculated. Their findings indicated that the Ramsar Convention did not diminish aquaculture development, but that the total extent of mangroves remained unchanged as a result of extensive reforestation efforts.

2 The Ramsar Convention on Wetlands is based in Gland, Switzerland. More information can be found here: http://www.ramsar.org/cda/en/ramsar-home/main/ramsar/1_4000_0__.

2. Sites considered

DEPI (the Division of Environmental Policy Implementation) of the United Nations Environment Programme (UNEP) provided a list of projects for monitoring the progress of mangrove restoration. This list included the names of the organizations responsible for the different restoration projects, names of the sites and, in some cases, their precise location. A first selection of sites was made based on the year the mangrove restoration project was finalized, as mangrove crowns need three to five years to attain a minimum size to be detected by satellite imagery. Thus, many projects were too recent, and could not be included.

Access to precise site locations was a second parameter that turned out to be problematic and which led to a restriction on an additional number of sites.

Finally, project sites were subdivided according to their investors and/or location. If several sites were present in the same imagery and the project supported by the same institution, the sites were merged into one. Figure 1 displays all locations used for this study, comprising 24 selected sites distributed within 10 projects across a wide range of regions:

- Madagascar (1 project, 1 site)
- Kenya (1 project, 1 site)
- Solomon Islands (1 project, 1 site)
- United Arab Emirates (1 project, 1 site)
- Indonesia (5 projects, 5 sites)
- Senegal (1 project, 15 sites)
- Mexico (1 project, 1 site; but this analysis was not fruitful and therefore not further included)

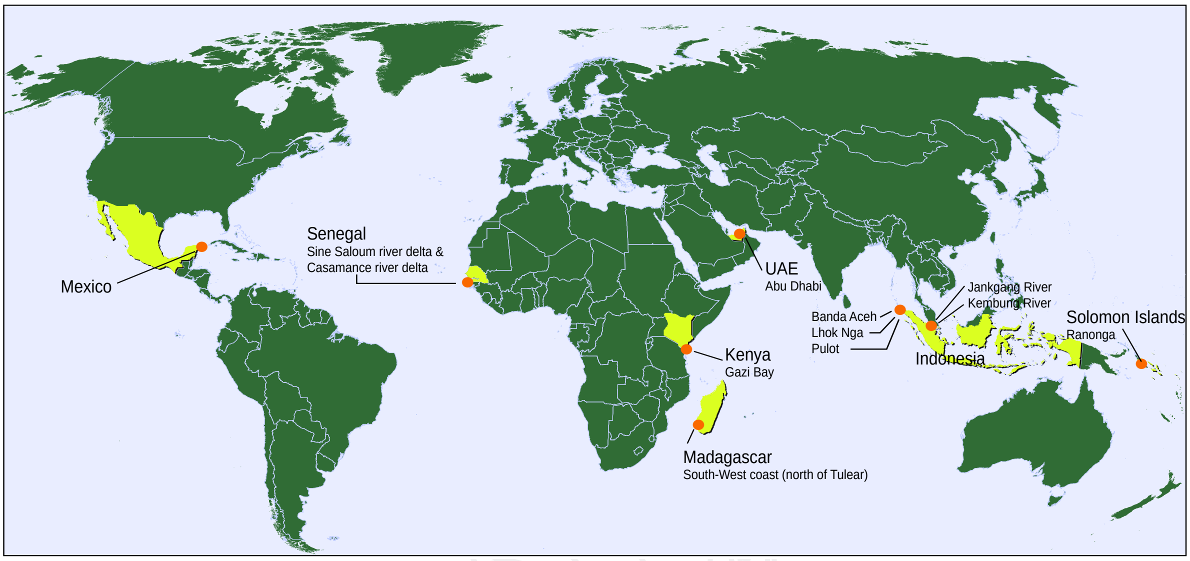


Figure 1: Map showing the locations of the mangrove restoration projects (project countries are given in pale green, the exact area of the project site is marked in orange).

Most sites provided on the list were, unfortunately, too small for assessment via Landsat data (i.e. at a 30-metre spatial resolution); hence, imagery from high-resolution satellite sensors was used (WorldView, Quickbird and Ikonos). These sensors have a resolution of 45 cm, 60 cm and 100 cm, respectively. However, as these sensors are fairly recent, the archives are limited. (Landsat provides a 30-metre spatial resolution and has been available since 1982 (Landsat 4 with TM sensor)). Worldview was launched in 2007, Quickbird in 2001, and Ikonos in 2000. This means that no high-resolution satellite images are available prior to 2000. In this study, for larger sites, the use of Landsat images was possible but, in most cases, high-resolution images were needed and thus the study was limited to using imagery between 2000 and 2010.

2.1 Major challenges

In most cases, the precise location of mangrove restoration projects could not be provided. The challenge was to identify where progress had been made, and where not. Therefore, an analysis of the whole area had to be undertaken, and mapping changes included not only mangroves but also other surrounding vegetation types. The difference between mangroves and other dense tropical coastal vegetation is not clearly visible at first sight, especially without ground truthing. The texture and shape of mangroves can change from one site to another.

Different external datasets were used to help with the identification of vegetation types, including a digital elevation model from NASA's Shuttle Radar Topography Mission. Additionally, a global dataset of mangroves (United States Geological Survey, 2011) was used, which helped to find known mangroves for calibrating the remote sensing algorithms. Mostly, high-resolution imagery was used, which not only allows for image characteristics to be taken into consideration (e.g. size and shape), but also enables mapping of smaller areas. Finding available "cloud free" images was more time consuming. The tropics are often cloudy, meaning that the availability of imagery is low for passive sensors (i.e. optical sensors as opposed to radar imagery). Clearly identifying and estimating the extent of the sites under consideration was not always easy, especially for small-scale actions.

Furthermore, the precise extent of recovery projects needed to be identified, as processing of full images requires differentiation of mangroves from non-mangrove forests without post-analysis field validation. The lack of standardized reporting complicated the synthesis task, and imposed site-specific processing.

Extent and size

Estimating the size of a site is critical. Very small and small sites (e.g. 20 ha to 500 ha and 500 ha to 20,000 ha) are best visually interpreted by an analyst using high-resolution imagery (0.45 m to 1 m resolution), whereas medium to larger sites (bigger than 20,000 ha) can be more easily assessed by means of digital image processing techniques using broader resolution (5 m to 30 m).

Shape and texture

Having some knowledge of the shape and texture of a site is useful, as uniform, continuous and compact shapes are generally more easy to process digitally (i.e. to extract useful information and map changes). Describing the shape and texture of a site can be quite challenging, as natural mangrove ecosystems can vary enormously in their characteristics. The more non-continuous and mixed the composition and texture of a site is, the more difficult it is to automatically assess changes.

Age

There was no common reference date that could be used for all project sites. Therefore, each project site had to be treated independently. This added to the complexity of this study. Because young mangroves can only be identified three to four years after being planted, projects that have been launched recently could not be used in this analysis. The lack of historical imagery close to the projects' launch dates was an extra difficulty. Additionally, differences in sun elevation and related factors (e.g. shadowing and differences in luminosity) needed to be taken into consideration in the selection of the imagery and in the remote sensing processes.

2.2 Remote sensing processes

Generally, small-scale sites require high-resolution imagery. Pan sharpening is also required, which is undertaken through some multi-spectral satellite sensors that are equipped with coarser bands and one panchromatic band at a higher resolution. By using relevant remote sensing techniques, it is possible to introduce the brightness information of the high-resolution panchromatic band into the other bands, thus generating a multi-spectral high-resolution image.

Pan sharpening was performed in this study to support further land cover classification, as well as visual interpretation tasks. A hybrid approach was used that consisted of object-based image analysis (image segmentation to derive homogeneous image regions), and unsupervised pixel-based classification (to extract unique land cover classes), followed by visual verification and class labelling of the results. This process improved the classification, and eased the change detection, in particular with high-resolution satellite sensors. Hence, the difference could be computed between the classified images. Analysis was implemented based on logical conditions (e.g. distance from shore or elevation), samples, or a combination of both. Context analyses identified features that were not solely based on spectral or textural attributes. As a result, on-screen working (visual interpretation, on-screen delineation) was applied for specific sites (e.g. Ourong site 3 in Senegal), especially as the elongated and thin shape of the sites posed additional challenges (as narrow bare land strips in a forest can potentially appear as forested or bare depending on the tilt of the image).

3. Data

3.1 Identification of sites

The location of sites was provided by the UNEP Division of Environmental Policy Implementation, Climate Change Adaptation Unit, although the precise geographic coordinates were not always available. Further contact with mangrove restoration project managers for some sites was necessary.

3.2 Satellite imagery

In total, 22 satellite images were processed. Only six of them were of medium resolution (15 m and 30 m, ASTER or Landsat); the other 16 used high-resolution sensors (Quickbird, Ikonos and Worldview) with resolutions ranging from 0.45 m to 2.4 m. This was necessary given the small size of the rehabilitation sites, where medium-resolution satellites would not have been able to identify the changes with the required level of detail. As most high-resolution satellites use technology dating from after 2000, only land-cover changes between 2000 and 2013 could be assessed. As expected for remote sensing analysis conducted in the tropics, cloud cover was also an issue and made the image selection process more complex.

3.3 Other data

Additional data that were used for this study include the following:

- The Digital Elevation Model from Shuttle Radar Topographic Mission V4.1 (NASA), available at: *http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1*.
- The Global Distribution of Mangroves database (United States Geological Survey, 2011), available at: *http://data.unep-wcmc.org/datasets/21*.

4. Analysis

4.1 United Arab Emirates: Jubai

Information about the project

Project funded by:	Abu Dhabi Government
Amount:	US$1,800,000
Restoration run by:	UNEP-World Conservation Monitoring Centre, Forest Trends, UNEP and UNEP/GRID-Arendal
Project start:	October 2012
Project end:	October 2013
Purpose:	Develop carbon payment and payment for ecosystem services schemes for mangroves.
Location (centre point):	24.50° N; 54.52° E
Size of study area:	22.3 km x 11.7 km

Image data sources

Figure 2: Composite visible bands of Jubai project area in 2000 (left) and 2013 (right).

Sensor name:	Landsat 7 ETM	Sensor name:	Landsat 8 OLI
Date of acquisition:	19 May 2000	Date of acquisition:	31 May 2013
Resolution:	30 m	Resolution:	30 m

Results summary

Table 1: Mangrove extent and change in Jubai, 2000 to 2013.

	Dense mangroves	Sparse mangroves
Extent in 2000 (ha)	535.1	1527.4
Extent in 2013 (ha)	378.5	2729.4
Change (ha)	-156.5	+1201.9
Change (percentage)	-29.3[3]	+78.7

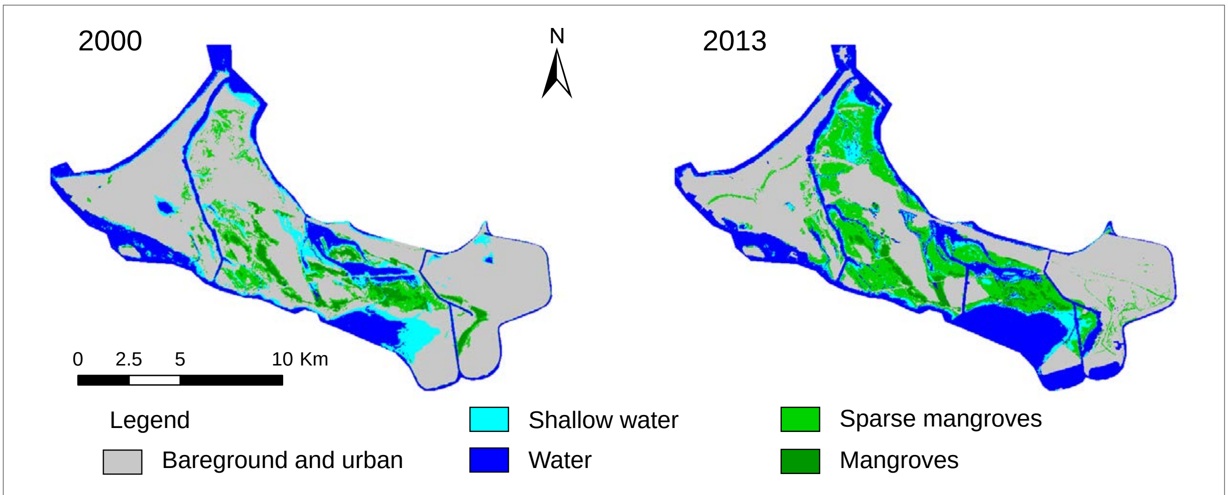
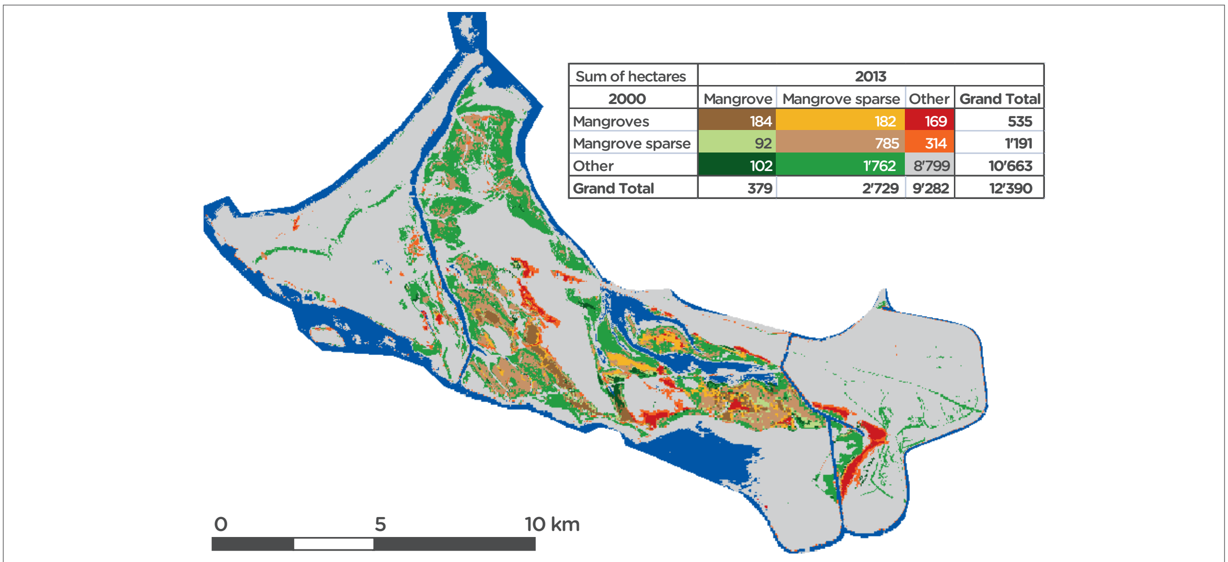


Figure 3: Classified land cover of Jubai project area in 2000 and 2013. [3]



Sum of hectares	2013			
2000	Mangrove	Mangrove sparse	Other	Grand Total
Mangroves	184	182	169	535
Mangrove sparse	92	785	314	1'191
Other	102	1'762	8'799	10'663
Grand Total	379	2'729	9'282	12'390

Figure 4: Detected change in land cover (2000 to 2013) for Jubai project area. While mangroves declined in some areas (yellow, orange and red), the mangrove cover has clearly improved in many more areas (light to dark green).

3 Percentages are computed by using the formula: (past coverage−new coverage)/past coverage. A positive value represents an increase in coverage, a negative one a decrease.

Note: The embedded table shows changes in area of vegetation cover between 2000 and 2013. Reading from top left, 184 ha of mangroves in 2000 were still mangroves in 2013, 182 ha of mangroves in 2000 had become sparse mangroves by 2013, and 169 ha of mangroves in 200 and become another land cover by 2013. Colours correspond to colours in image.

Comments

The regrowth of mangroves has been successful. Although coverage of dense mangroves declined, the new plantations seem to have succeeded. The overall area covered by mangroves increased by 50.7 per cent to reach 3,018 ha.

4.2 **Madagascar:** Mamelo Honko

Information about the project

Project funded by:	**World Wildlife Fund, Rufford Small Grant Foundation, Marineland Foundation, Municipality of Schoten, ING Lease Belgium, Lions Club Middelheim, OLV College, Private donations through Koning Boudewijn Stichting**
Amount:	Unknown
Restoration undertaken by:	Honko, five villages of Mamelo and Blue Ventures (technical advisor)
Project start:	2008
Project end:	On-going
Purpose:	To implement an ecosystem services project using mangrove afforestation and reforestation.
Location (centre point):	23.25° S, 43.63° E
Size of study area:	3.1 km x 0.35 km

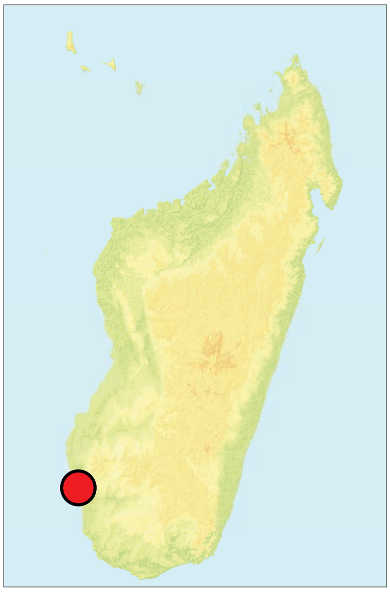


Image data sources

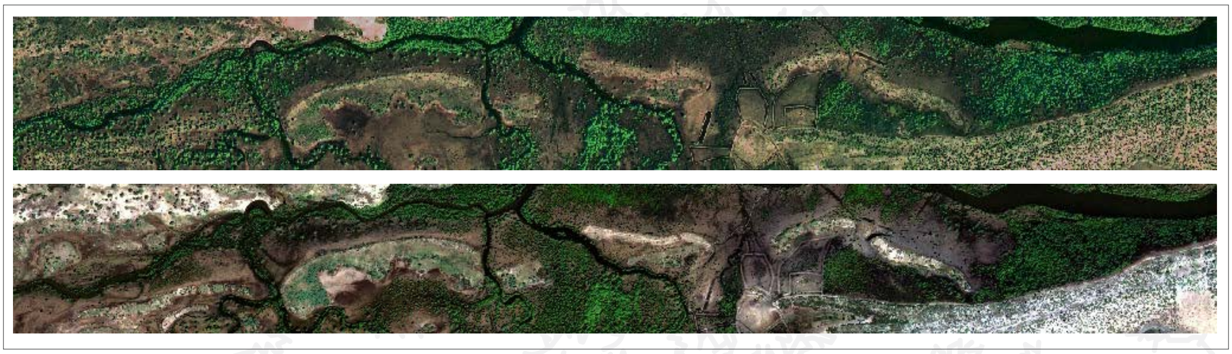


Figure 5: Composite image (RGB) of vegetation cover in the Mamelo Onko project area in 2003 (top) and 2013 (bottom). Overall greenness has declined.

Sensor name:	WorldView 2	Sensor name:	WorldView 2
Date of acquisition:	4 July 2003	Date of acquisition:	10 April 2013
Resolution:	2.4 m	Resolution:	2.4 m

Results summary

Table 2: Extent and change of vegetation cover in the Mamelo Onko project area.

	Mangroves	Other vegetation	Shadow (including some mangroves)
Extent in 2003 (ha)	21.44	32.53	11.61
Extent in 2013 (ha)	24.87	8.54	15.04
Change (ha)	+3.43	-23.99	+3.44
Change (percentage)	+16.0	-73.8	+29.6

Sum of hectares	2013				
2003	Mangroves	Other Vegetation	Shadows (incl. Some Mangroves)	Other	Grand Total
Mangroves	10.0	0.4	3.9	5.9	20.2
Other Vegetation	2.9	5.8	1.6	20.0	30.3
Shadows (incl. Some Mangroves)	4.0	0.1	2.4	4.7	11.1
Other	8.0	2.3	7.2	37.8	55.3
Grand Total	24.8	8.6	15.1	68.4	117.0

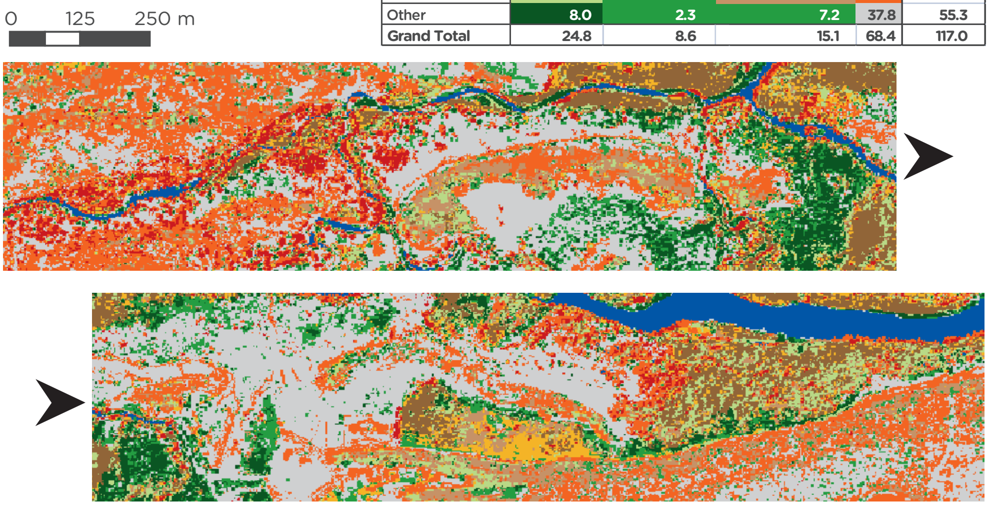


Figure 6: Detected change in vegetation cover (2003 to 2013) in the Mamelo Onko project area. Given the length of this image, it has been split into two. While mangrove cover has slightly improved (+3.4 ha), overall there is a decline in natural vegetation cover (orange and red dominate). Loss of mangrove coverage is in red (strong) and decline in orange. Status quo is represented in brown (dark for mangroves, light for mixed mangroves). Recovery of mangroves or a change to mixed mangroves are represented in dark and light green. Water is shown in blue.

Comments

Located in the north of Toliara (south-west Madagascar), the mangrove forest monitored is a narrow stretch less than 350 m wide and 3.1 km long that covers more than 500 ha. Unfortunately, the analysis identified only 3.4 ha of additional mangrove coverage. Of more concern was the fact that the other vegetation types seemed to have undergone a significant decrease (-73.8 per cent). Despite a planned project start in 2008, actual plantation and restoration actions started in the period of 2011–2012. This furthermore explains the lack of progress visible by means of remotely sensed imagery, as young mangroves need at least three years of growth to form a visible crown.

In 2013, the Rufford Small Grant Foundation published a progress study that reported a total of 50,000 mangrove propagules being collected and planted with the help of the local communities. Furthermore, in March 2012, the region of Honko planted an additional 10,000 mangrove propagules.

4.3 **Kenya:** Gazy Bay

Information about the project

Project funded by:	Carbon Credit
Amount:	Unknown
Restoration run by:	Earthwatch International, Kenya Marine and Fisheries Research Institute, Kenya Forest Service, and the Mikoko Pamoja Community Organization (Gazi Community). Academic institutions including Bangor and Edinburgh Napier Universities (CAMARV), the Plan Vivo Foundation.
Project start:	2009
Project end:	2029
Purpose:	Restoring, protecting and replanting mangroves.
Location:	4.44° S, 39.51° W
Size of study area:	1,554.5 ha

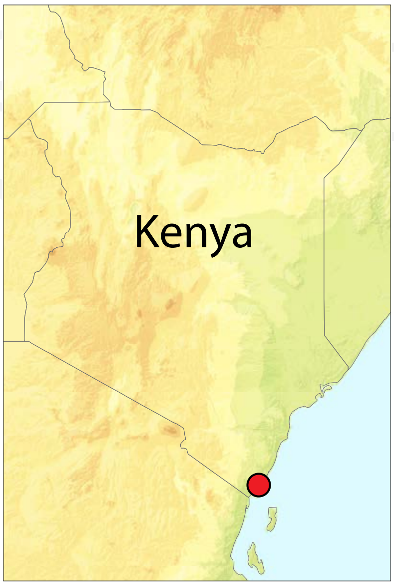


Image data sources

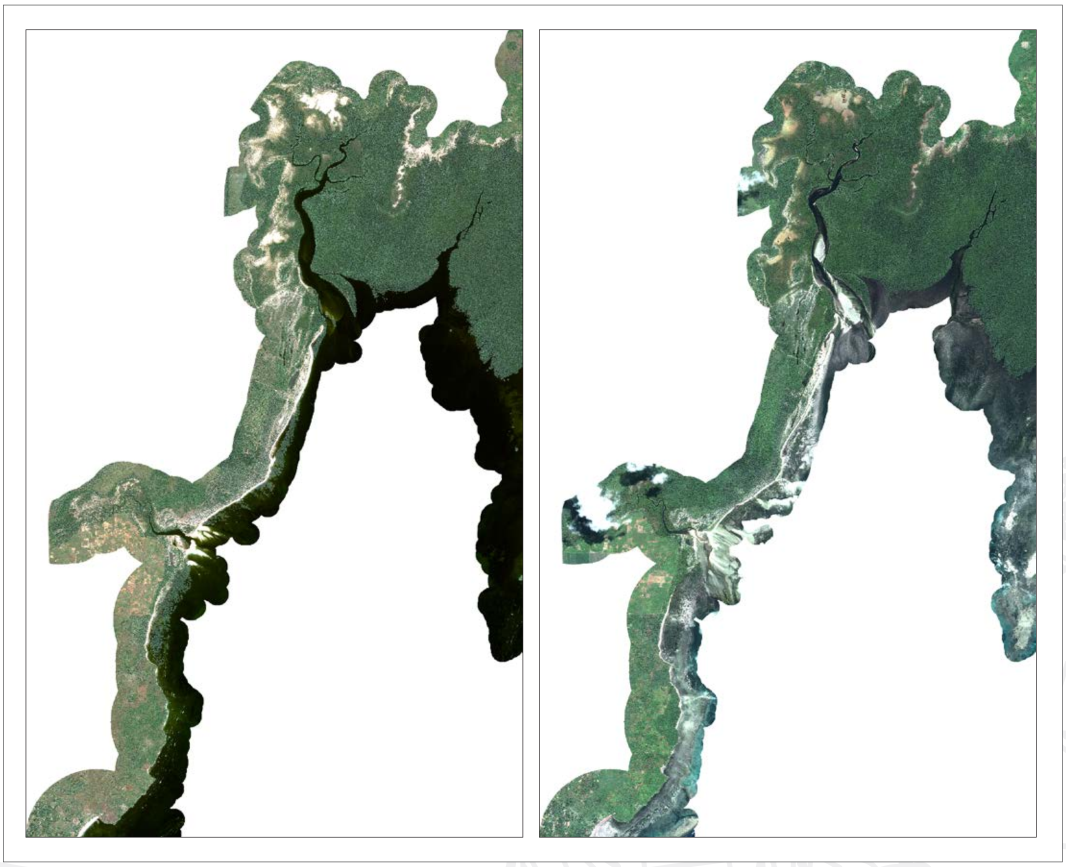


Figure 7: Composite image of Gazy Bay in false colours for 2002 (left) and for 2011 (right). The image is masked.

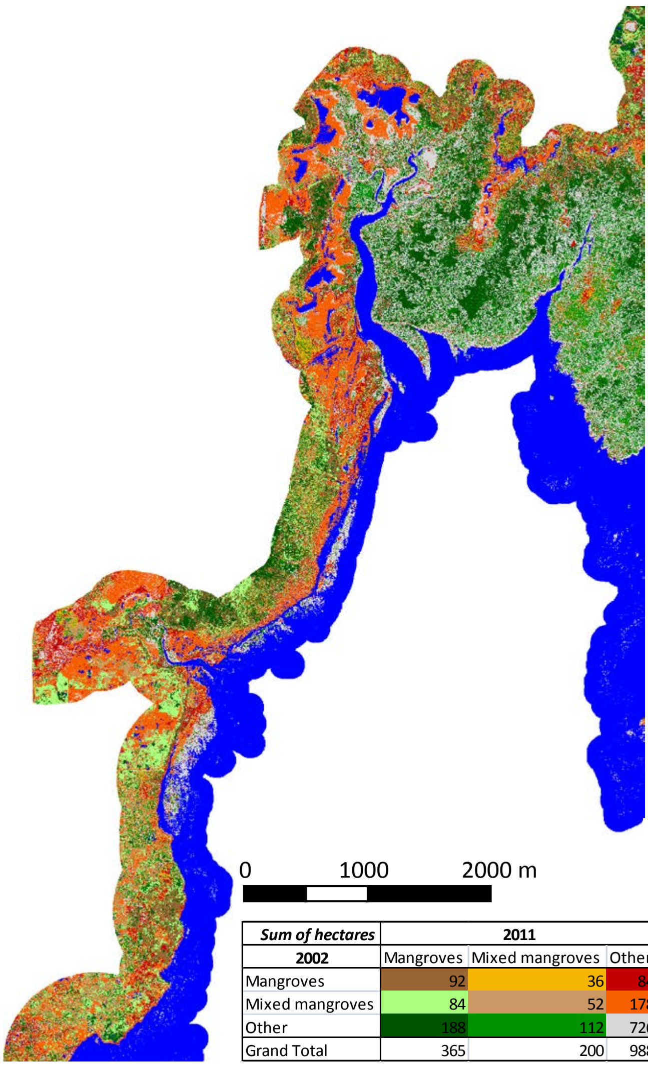
Image data sources

Sensor name:	Quickbird 2	Sensor name:	IKONOS
Date of acquisition:	10 October 2002	Date of acquisition:	15 June 2011
Resolution:	0.60 m	Resolution:	1.0 m

Results summary

Table 3: Results of the Gazy Bay analysis.

	Mangroves further inshore	Mangroves near shoreline	Mangroves mixed with other natural vegetation	Vegetation mixed with mangroves
Extent in 2002 (ha)	224.3	489.6	0.0	313.9
Extent in 2011 (ha)	137.7	630.5	54.5	68.3
Change (ha)	-86.6	+140.9	+54.5	-245.6
Change (percentage)	-38.6	+28.8	-	-78.2



Sum of hectares	**2011**			
2002	Mangroves	Mixed mangroves	Other	Grand Total
Mangroves	92	36	84	213
Mixed mangroves	84	52	178	314
Other	188	112	726	1'026
Grand Total	365	200	988	1'553

Figure 8: Detected change in land cover in Gazy Bay (2002 to 2011) showing a significant improvement in mangrove cover in the northern part of the study site (green). Given the large size of the area and the high resolution, buffers using distance from water and elevation were used to reduce the duration of the analysis. This map shows loss of mangrove coverage in red (strong) and decline in orange. Status quo is represented by brown (dark for mangroves, light for mixed mangroves). Recovery of mangroves or a change to mixed mangroves are represented in dark and light green. Water is shown in blue and masked areas in white.

Comments

Overall, vegetation cover reduced (-136.8 ha). In contrast, the coverage of mangroves increased in the northern part of the site (+149.1 ha, see green areas); however, the mangroves seemed to have decreased in the central to southern part of the area (orange and red).

4.4 **Senegal:** Cabrousse

Information about the project

Project funded by:	Group Danone, Yves Rocher Foundation
Amount:	US$6,301,080
Restoration run by:	Oceanium, Fondation Internationale du Banc d'Arguin.
Project start:	2008
Project end:	On-going
Purpose:	Co-benefit.
Location:	16.7° W, 12.4° N
Size of study area:	1,700 ha

Image data sources

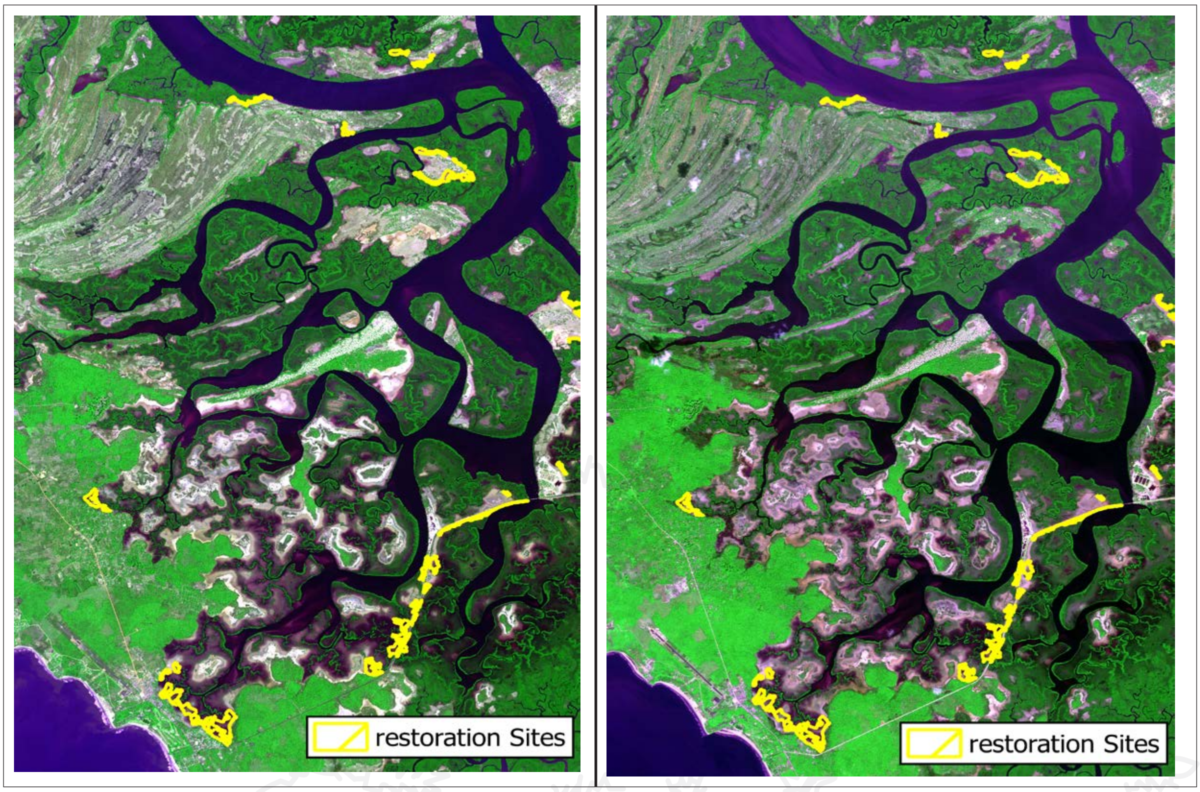


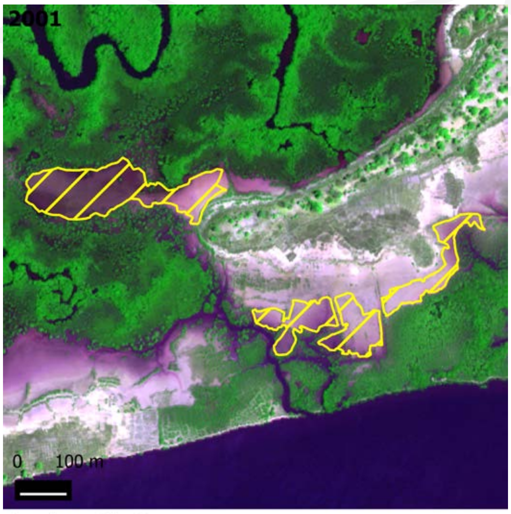
Figure 9: Composite image of Cabrousse in false colours for 2001 (left) and 2010 (right). Vegetation appears in green.

Sensor name:	WorldView	Sensor name:	QuickBird
Date of acquisition:	13 March 2001	Date of acquisition:	6 November 2010
Resolution:	0.54 m, 2.17 m	Resolution:	0.61 m, 2.44 m

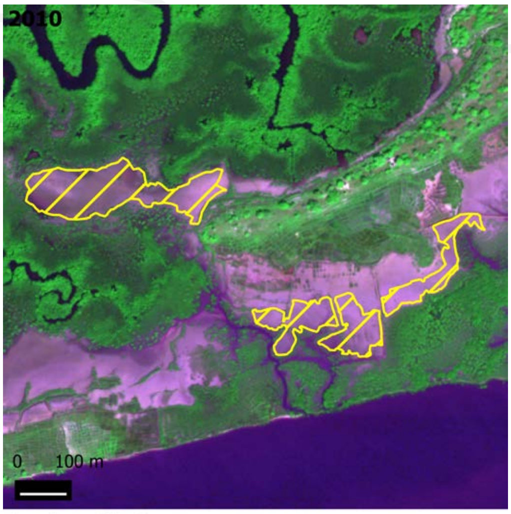
Results summary

The reforestation project sites were mostly located on bare land, and the project started in 2008. No, or only a slight, change could be detected for the 40 sites analysed (see examples in Figure 10), although some reforestation was visible in close proximity to restoration site Carabane site 2 (see first two images in Figure 10).

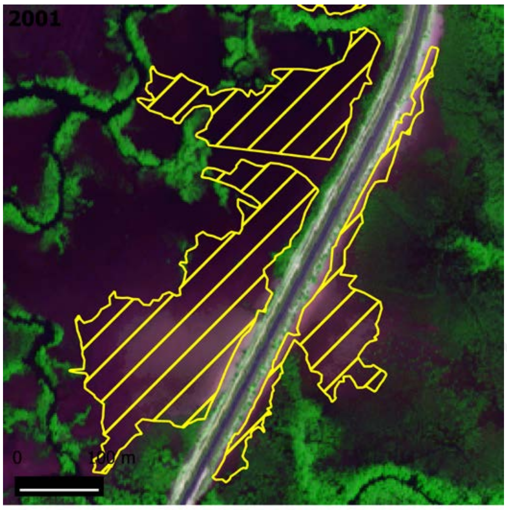
Comments



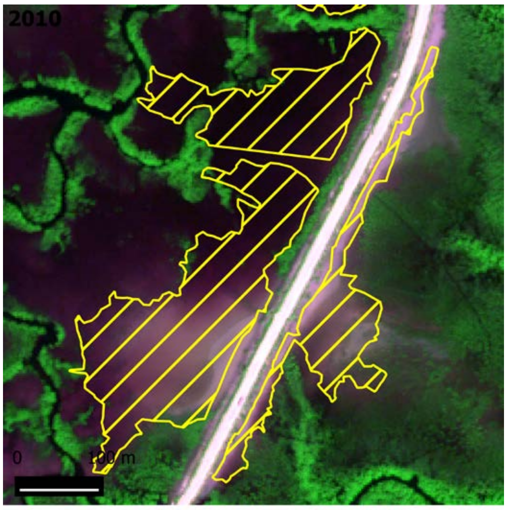
Carabane Site 2



Carabane Site 2



Kayite Site 1 to 2 and Katakalousse Site 5



Kayite Site 1 to 2 and Katakalousse Site 5

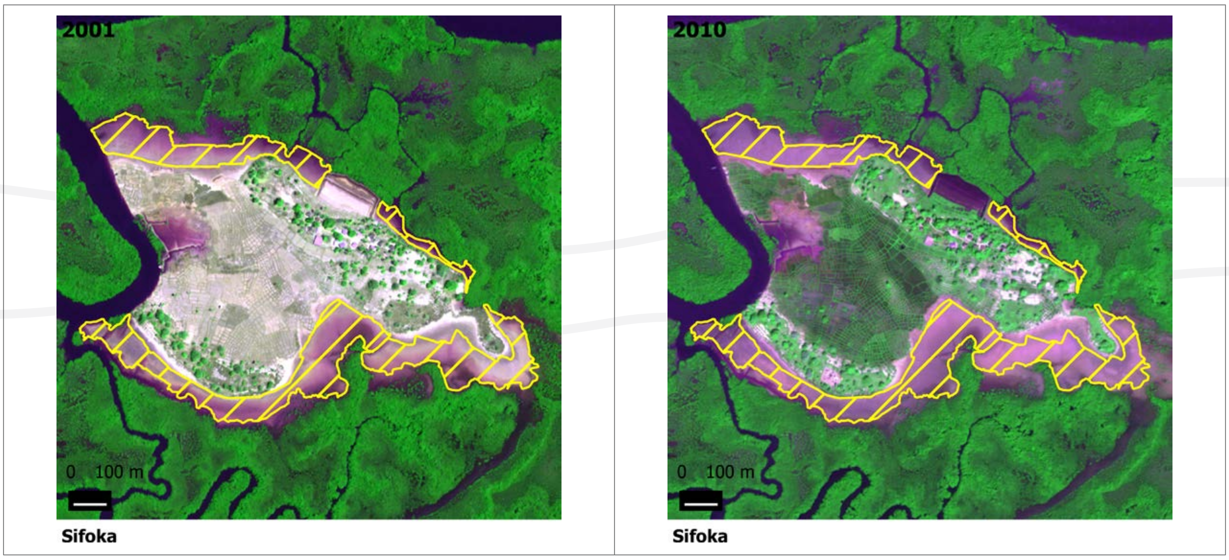


Figure 10: Satellite imagery of different areas within the Cabrousse site. Areas of mangroves are outlined in yellow.

Data comparison of 2010 versus 2001 shows no, to only a slight, change in mangrove cover. As the most-recent available imagery for the area is from 2010, and the restoration project only started in 2008, no change in mangrove cover was detected. Further analysis of vegetation cover would require updated imagery.

4.5 **Solomon Islands:** Ranonga

Information about the project

Project funded by:	**WorldFish Center; AusAID; Ministry of Environment, Conservation and Meteorology, Solomon Islands**
Amount:	US$302,000
Restoration run by:	WorldFish Center; AusAID; Ministry of Environment, Conservation and Meteorology, Solomon Islands
Project start:	2009
Project end:	2012
Purpose:	Poverty alleviation and the global carbon market. Also, replanting to replace vegetation lost in an earthquake.
Location (centre point):	7.93° S, 156.53° E

Image data sources

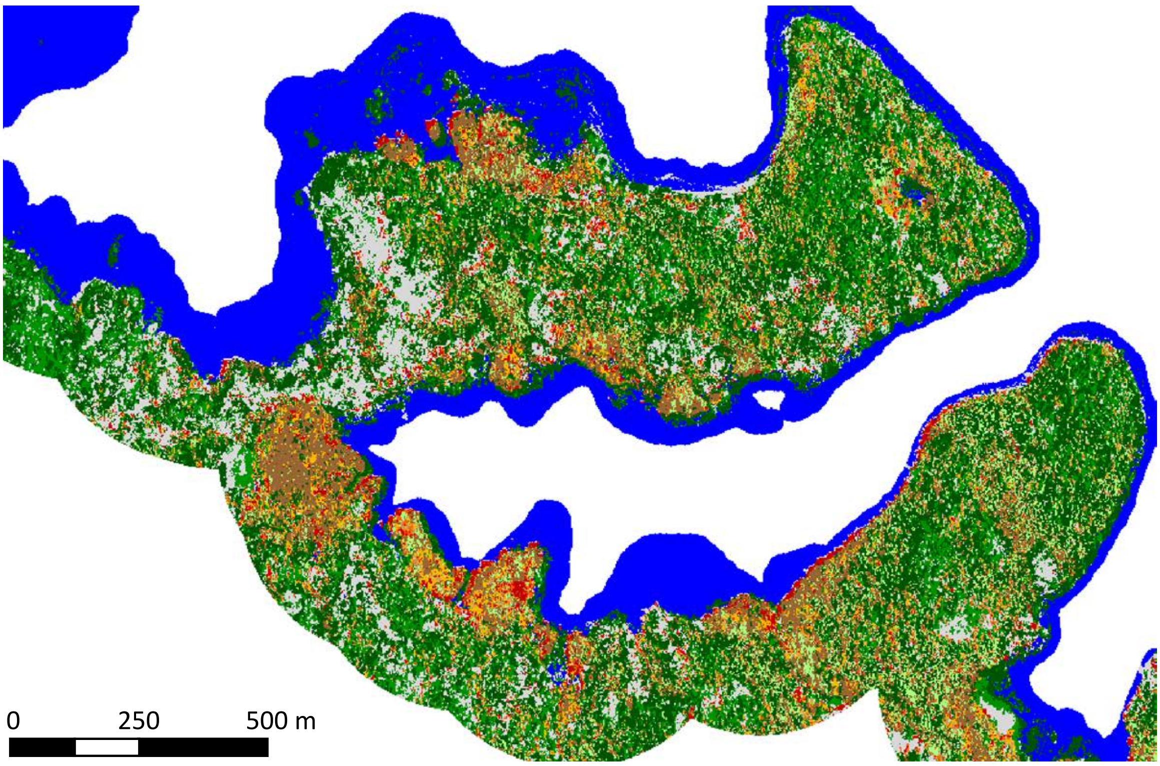
Figure 11: The Ranonga project area in 2002 (left) and 2012 (right).

Sensor name:	QuickBird 2	**Sensor name:**	WorldView 2
Date of acquisition:	26 April 2002	**Date of acquisition:**	7 May 2012
Resolution:	0.60 m	**Resolution:**	0.45 m

Results summary

Table 4: Extent and change of vegetation cover in the Ranonga project area.

	Dense mangroves	Sparse mangroves	Other natural Vegetation
Extent in 2002 (ha)	63.71	16.54	57.2
Extent in 2012 (ha)	81.7	6.55	43.4
Change (ha)	+17.99	-9.99	-13.8
Change (percentage)	+28.2	-60.4	-24.1



Sum of hectares	Cat_2012			
Cat_2002	Mangroves	Mixed Mangroves	Other	Grand Total
Mangroves	18.7	6.9	5.2	30.8
Mixed Mangroves	10.3	4.0	2.3	16.5
Other	52.7	27.8	21.0	101.5
Grand Total	81.7	38.7	28.4	148.8

Figure 12: Classification of changes in vegetation cover in the Ranonga project area between 2002 and 2012. Loss of mangrove coverage is in red (strong) and decline in orange. Status quo is represented in brown (dark for mangroves, light for mixed mangroves). Recovery of mangroves and/or mixed mangroves is represented in dark and light green, respectively. Water is shown in blue and masked areas in white.

Comments

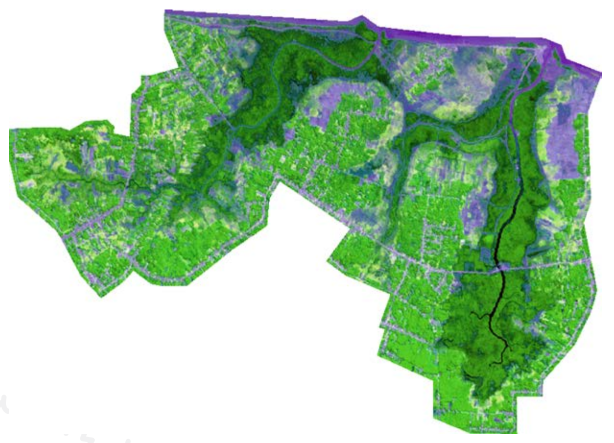
Although the project itself is fairly recent, changes in land cover and vegetation are already visible. Given the right conditions, eight hectares of sparse mangroves could be improved to dense mangroves in a short time.

4.6 **Indonesia:** Bengkalis Island, Jankgang River

Information about the project

Project funded by:	**Danone, the United Nations Development Programme-Global Entrepreneurs Council, the International Union for Conservation of Nature-Ecosystems and Livelihoods Group, and the US Department of Forestry.**
Amount:	US$21,000
Restoration run by:	YL Invest Co. Ltd, Indonesia. The main implementing organization is Mangrove Action Project, Indonesia.
Project start:	2010
Project end:	On-going
Purpose:	Rehabilitation, conservation and restoration.
Location:	1.53° N, 102.22° W

Image data sources



Sensor name:	Landsat 7	**Sensor name:**	ASTER
Date of acquisition:	14 July 2002	**Date of acquisition:**	9 July 2012
Resolution:	15 m (30 + pan sharpened)	**Resolution:**	15 m

Results summary

Table 5: Extent and changes in vegetation cover for the Jankgang River project site.

	Dense mangroves	Other vegetation and rubber plantations	Urban and wet ground
Extent in 2002 (ha)	1 250.9	3 045.9	883.3
Extent in 2012 (ha)	1 214.9	2 772.4	2 772.4
Change (ha)	-35.9	-273.5	+1 889.0
Change (percentage)	-2.9	-9.0	+213.9

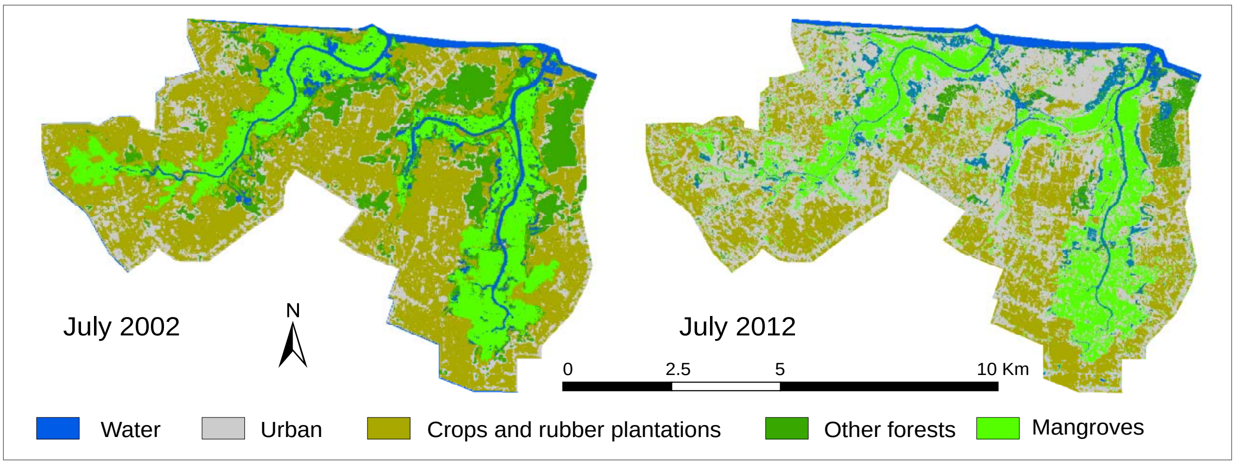


Figure 14: Classified land cover for the Jankgang River site in 2002 and 2012.

Comments

The area has undergone a significant development in recent years, and urban features have increased three-fold. The main roads are clearly visible in the 2012 ASTER image. Mangrove coverage remains about the same (-2.9 per cent, which is within the margin of error), but other natural vegetation (as well as rubber plantations) have decreased in area. The restoration project only started in 2010 and so most of the changes in mangrove coverage and the potential recovery may not be visible in the 2012 imagery (as mangrove crowns may still be too small to be detected).

4.7 Indonesia: Bengkalis Island, Kembung River

Information about the project

Project funded by:	**Danone, the United Nations Development Programme-Global Entrepreneurs Council, the International Union for Conservation of Nature-Ecosystems and Livelihoods Group, and the US Department of Forestry.**
Amount:	US$21,000
Restoration run by:	YL Invest Co. Ltd, Indonesia. Main implementing organization is Mangrove Action Project, Indonesia.
Project start:	2010
Project end:	On-going
Purpose:	Rehabilitation, conservation and restoration.
Location (centre point):	1.415° N, 102.430° W

Image data sources

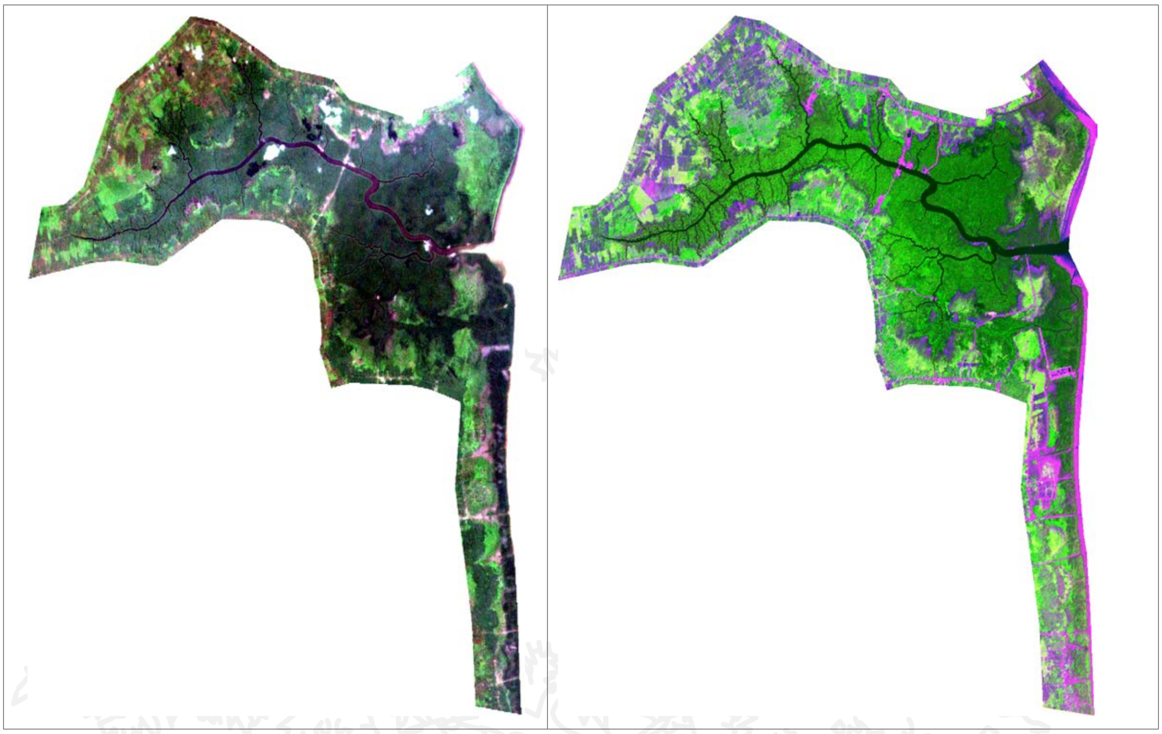


Figure 15: Pre-restoration and post-restoration images for the Kembung River project site.

Sensor name:	Landsat 7	Sensor name:	ASTER
Date of acquisition:	14 July 2002	Date of acquisition:	9 July 2012
Resolution:	15 m (30+ pan sharpened)	Resolution:	15 m

Results summary

Table 6: Extent and change in vegetation cover for the Kembung River project site.

	Mangroves	Other vegetation
Extent in 2002 (ha)	3 109.0	2 056.8
Extent in 2011 (ha)	3 546.9	2 854.1
Change (ha)	+437.9	+797.3
Change (percentage)	+14.1	+38.8

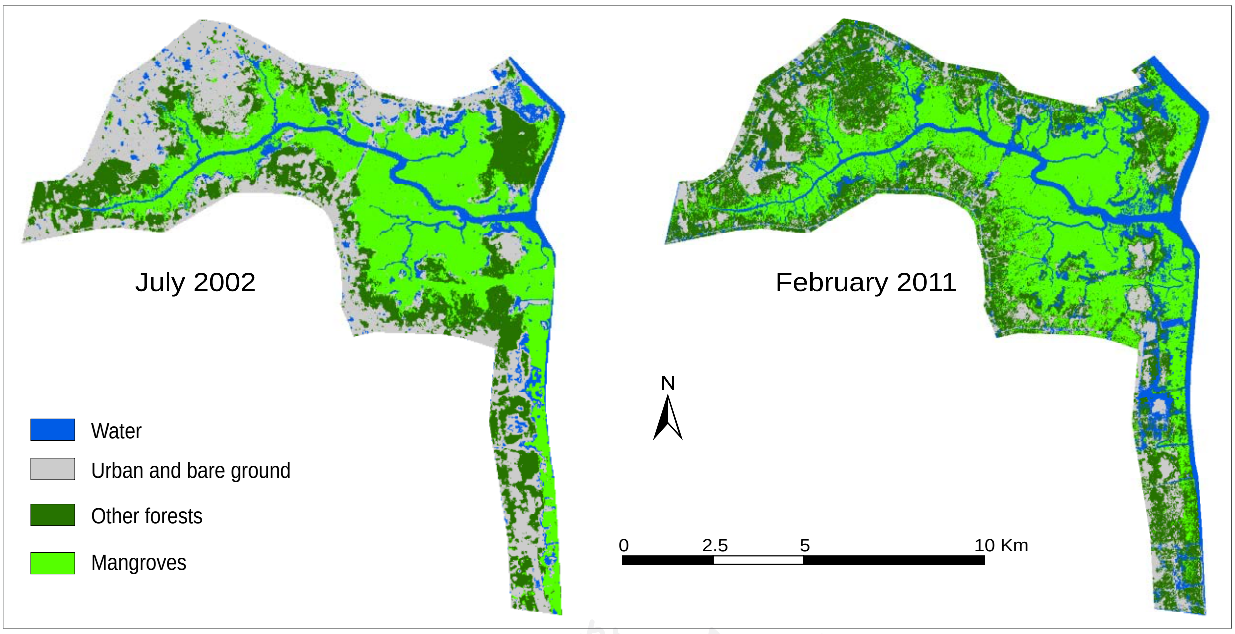


Figure 16: Classified land cover for the Kembung River project site for 2002 and 2011 showing significant recovery of mangroves and other vegetation.

Comments

As opposed to the nearby Jankgang River site, the Kembung River site shows large recovery for both mangroves (+14.5 per cent) and natural vegetation (+38.8 per cent).

4.8 **Indonesia:** North Sumatra, Aceh Besar, Banda Aceh

Information about the project

Project funded by:	**Oxfam Novib with back donor SHO (a consortium of humanitarian NGOs in the Netherlands which raised money from the Dutch public after the 2004 Indian Ocean tsunami).**
Amount:	US$456,600 (€1 million for three sites)
Restoration run by:	Wetlands International, the World Wildlife Fund, the International Union for Conservation of Nature, and Both ENDS.
Project start:	2005
Project end:	2009
Purpose:	Restore and manage damaged coastal ecosystems to restore livelihoods and increase resilience to the impacts of climate change.
Location (centre point):	5.606° N, 95.379° W
Size of study area:	Unknown

Image data sources

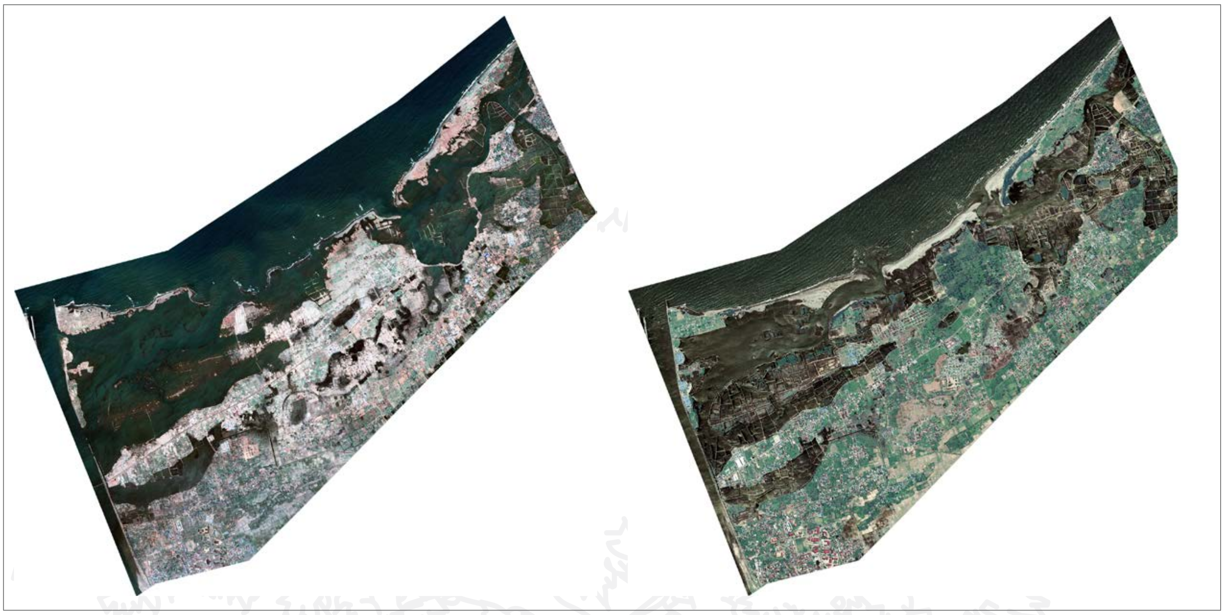


Figure 17: Pre-restoration and post-restoration images for the Banda Aceh project site.

Sensor name:	QuickBird 2	**Sensor name:**	QuickBird 2
Date of acquisition:	6 August 2005	**Date of acquisition:**	15 June 2012
Resolution:	1.0 m	**Resolution:**	1.0 m

Results summary

Table 7: Extent and change in vegetation cover for the Banda Aceh project site.

	Mangroves	Other vegetation
Extent in 2005 (ha)	112.50	219.18
Extent in 2012 (ha)	218.54	597.86
Change (ha)	+106.05	+378.69
Change (percentage)	+94.3	+172.8

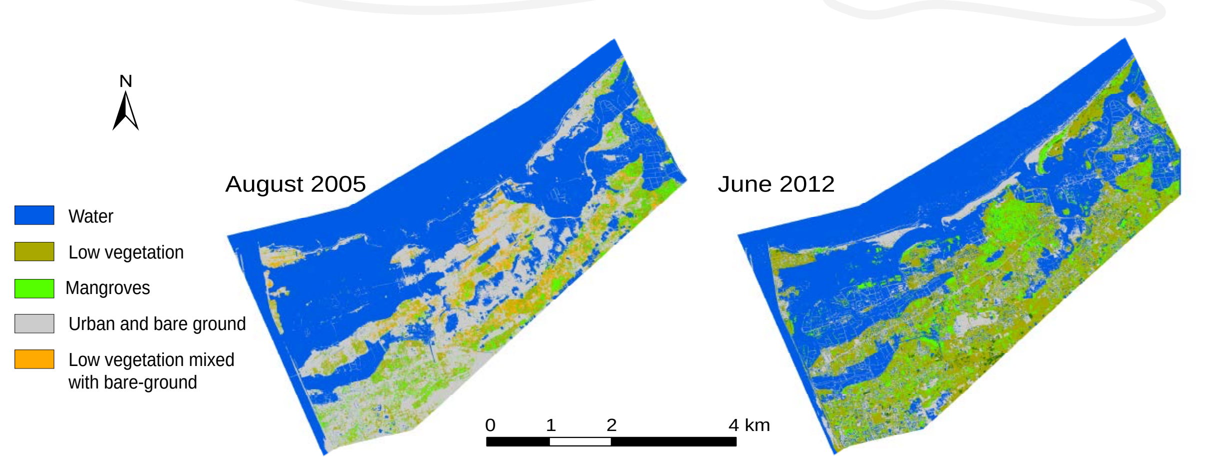


Figure 18: Classified land cover for the Banda Aceh project site for 2005 and 2012 showing a clear improvement in the mangrove and vegetation coverage.

Comments

The 2005 image was taken only a few months after the Indian Ocean tsunami. Bare ground and water coverage dominate the image. The 2012 image shows a significant increase in vegetation coverage (in green). Mangrove coverage has nearly doubled (+94.3 per cent), and the coverage for other vegetation has also increased drastically (+172.8 per cent). In the 2012 image, there is an obvious increase in the abundance of mangrove trees. Some of the signals for mangroves are mixed with natural vegetation.

In the 2005 image, very few mangroves are visible. The remaining trees cast shadows, which are captured in the classification process. Different kinds of bare ground were identified, from sand to concrete, which could be debris left over from the tsunami. The post-tsunami damage is well evident (a large amount of bare ground and little low vegetation cover).

4.9 **Indonesia:** North Sumatra, Aceh Besar, Lhok Nga

Information about the project

Project funded by:	**Oxfam Novib with back donor SHO (a consortium of humanitarian NGOs in the Netherlands which raised money from the Dutch public after the 2004 Indian Ocean tsunami).**
Amount:	US$456,600 (€1 million for three sites)
Restoration run by:	Wetlands International, the World Wildlife Fund, the International Union for Conservation of Nature, and Both ENDS.
Project start:	2005
Project end:	2009
Purpose:	Restore and manage damaged coastal ecosystems to restore livelihoods and increase resilience to the impacts of climate change.
Location (centre point):	5.445° N, 95.244° W

Image data sources

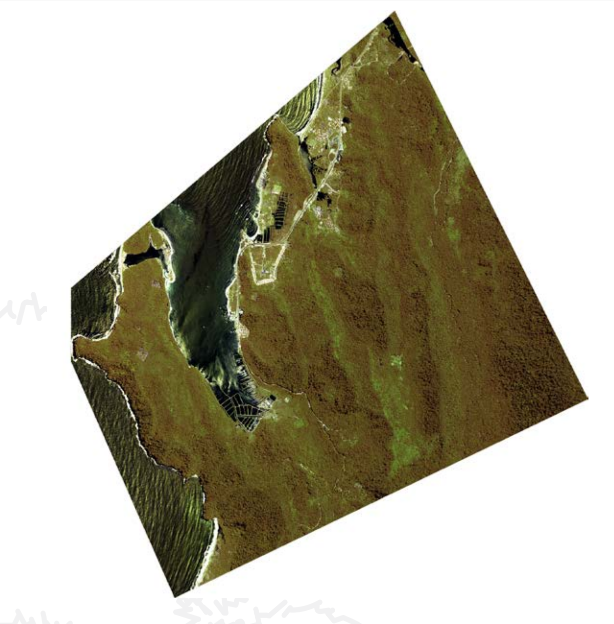


Figure 19: Pre- and post-restoration images for the Lhok Nga project site.

Sensor name:	QuickBird 2	**Sensor name:**	QuickBird 2
Date of acquisition:	2 January 2005	**Date of acquisition:**	15 June 2012
Resolution:	0.60 m	**Resolution:**	0.60 m

Results summary

Table 8: Extent and change of vegetation cover for the Lhok Nga project area.

	Mangroves	Forest	Low vegetation
Extent in 2005 (ha)	0.0	142.4	747.3
Extent in 2012 (ha)	36.3	945.2	129.5
Change (ha)	36.3	802.8	-617.8
Change (percentage)	100.0	563.8	-82.7

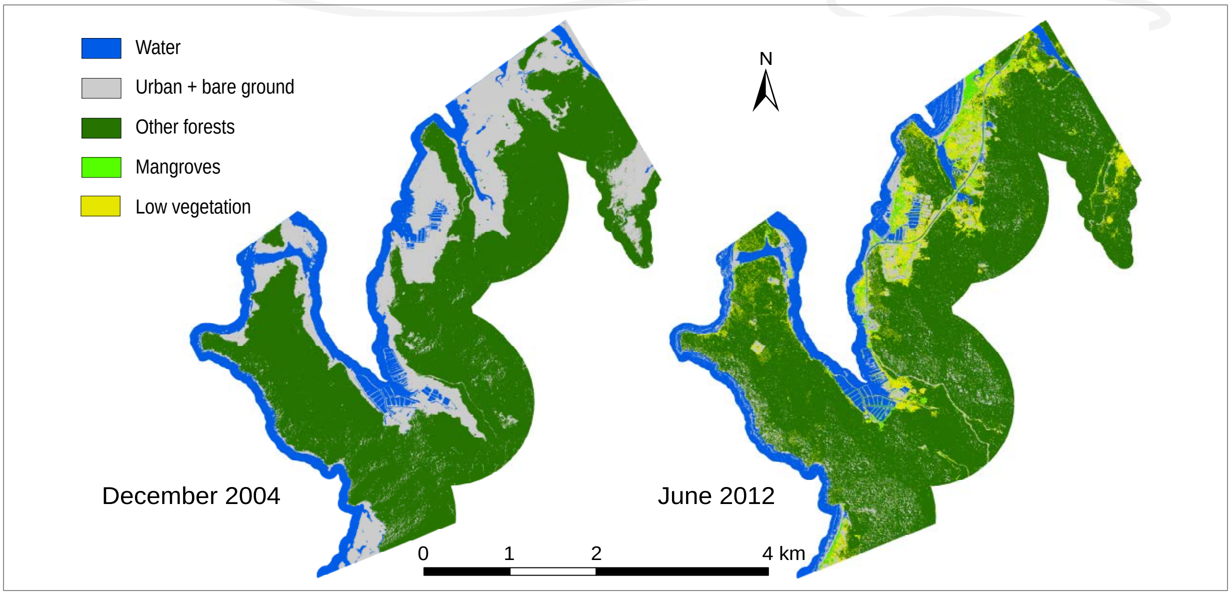


Figure 20: Classified land cover for the Lhok Nga project area for 2005 and 2012 showing significant improvement in vegetation cover. The dark area in the 2005 image is from a cloud and related shadow (and should be disregarded).

Comments

The presence of clouds on the 2004 image meant that it had to be masked. This improved the statistical analysis by concentrating it on the coastal areas, where mangroves are located. The mask was produced by using a buffer around the existing waterbodies.

The comparison between 2012 and 2005 shows significant improvements in mangrove coverage, as the low-lying areas were “shaved” by the 2004 Indian Ocean tsunami. Vegetation has recovered well. Almost 38 ha of mangroves have since been restored.

4.10 **Indonesia:** North Sumatra, Aceh Besar, Pulot

Information about the project

Project funded by:	**Oxfam Novib with back donor SHO (a consortium of humanitarian NGOs in the Netherlands which raised money from the Dutch public after the 2004 Indian Ocean tsunami).**
Amount:	US$456,600 (€1 million for three sites)
Restoration undertaken by:	Wetlands International, the World Wildlife Fund, the International Union for Conservation of Nature, and Both ENDS.
Project start:	2005
Project end:	2009
Purpose:	Restore and manage damaged coastal ecosystems to restore livelihoods and increase resilience to the impacts of climate change.
Location:	5.356° N, 95.246° W

Image data sources

Figure 21: Pre and post-restorarion images of the Pulot roject site.

Sensor name:	QuickBird 2	**Sensor name:**	QuickBird 2
Date of acquisition:	28 December 2004	**Date of acquisition:**	15 June 2012
Resolution:	0.60 m	**Resolution:**	0.60 m

Results summary

Table 9: Extent and change in vegetation cover for the Pulot project site.

	Mangroves	Low vegetation	Forest
Extent in 2004 (ha)	0.0	8.4	8.4
Extent in 2012 (ha)	+135.0	90.2	169.2
Change (ha)	+135.0	+81.9	+160.8
Change (percentage)	-	+975.7	+1 917.2

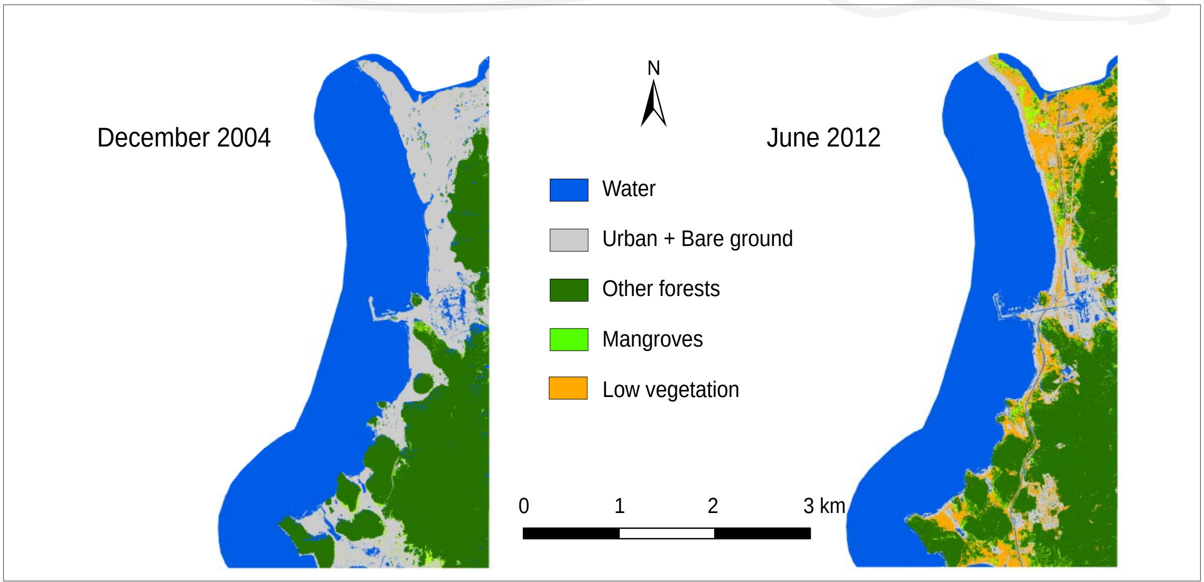


Figure 22: Classified vegetation cover for the Pulot project site for 2004 and 2012. Mangrove recovery can be seen, mostly in the north of the image.

Comments

The first image was taken on 28 December 2004, only two days after the Indian Ocean tsunami hit the area. Bare ground dominates in low-lying areas. Post-tsunami damage is evident. The second image, from 2012, shows a significant recovery of the overall vegetation, with only slight degradation of the inland forest (small patches of deforestation). Although mangroves could not be detected in the first image, the 2012 image shows their recovery in the northern part of the study site close to the shore. Some of these signals were mixed with natural vegetation and, without ground truthing, it was not possible to determine whether this was a signal for mangroves, palm trees or other tropical vegetation.

In both images, blue inland is not necessary water: the signals from the shadows of an industrial site and a road were classified as water. This could be corrected, but was disregarded for this study as the main focus was on vegetation cover.

5. Discussion

5.1 Changes in mangrove cover

This study provides a quantitative evaluation of the status of 10 mangrove restoration projects using satellite imagery. The pre-restoration status of mangrove cover was assessed using satellite images acquired between 2000 and 2005. The post-restoration status was assessed using images acquired between 2010 and 2013.

With three exceptions (Abu Dhabi, and the two Indonesian sites on Bengkalis Island), where the size of the projects allowed for the use of medium-resolution satellite sensors, high-resolution sensors (Quickbird, WorldView or IKONOS) were used. Consequently, only post-2000 data could be assessed, as the high-resolution sensors did not exist prior to that date. The "trends" found in this study are therefore only a change between two points in time.

Despite these limitations, trends could clearly be identified. Overall, most sites showed improved mangrove recovery (see Table 11). Only in Jankgang River (Indonesia) was there a decline in both mangrove and vegetation cover. All other Indonesian sites showed visible and significant improvements. The restoration project in Abu Dhabi also appears to be a success. Changes in mangrove cover in Senegal could not be identified, however, as no imagery beyond 2010 (only a year after the restoration project started) could be obtained. In the Solomon Islands, Kenya and Madagascar, some improvements in mangrove cover have been achieved, but there is also a decline in the cover of other detectable vegetation.

Table 11: Progress made in restoring mangrove cover for the locations analysed in this report.

Sites	Change
United Arab Emirates: Abu Dhabi	Very good
Madagascar: Mamelo Honko	Little improvements
Kenya: Gazi Bay	Good
Senegal: Cabrousse	No change
Solomon Island: Ranonga	Good
Indonesia: Bengkalis Island, Jankgang River	Decline
Indonesia: Bengkalis Island, Kembung River	Very good
Indonesia: North Sumatra, Aceh Besar, Banda Aceh	Very good
Indonesia: North Sumatra, Aceh Besar, Lhok Nga	Very good
Indonesia: North Sumatra, Aceh Besar, Pulot	Very good

This assessment has been done without ground surveys, and thus the results cannot be validated. Improvement of data could be made for three locations. In Senegal, better assessments could be made if more recent imagery was available.

One problem that arose in this assessment was that the signal for both mangroves and tropical vegetation was very similar and could be confused. Ground truthing would overcome this issue.

5.2 Details on the technical process

The workflow used in this project was the following:

1. Search for precise locations of mangrove restoration projects.
2. Consolidate the data and metadata related to the identified projects.
3. From the identified projects, select eligible sites that can be assessed using remotely sensed data (the size of the area should be detectable from space, and the start date should fall within the time span of available imagery).
4. Search for appropriate satellite imagery (with a resolution appropriate for the size of the project area, no cloud cover, and availability for both past and recent dates with comparative quality).
5. Analyse the remote sensing data to identify and quantify changes in land cover.
6. Evaluate the results.

As the sites in this project were globally widespread, it was impossible to set up a "one size fits all" methodological approach. Instead, a general workflow was applied to the different types of satellite data, which were then prepared for further processing. The general steps applicable in all cases were:

- Standard remote sensing pre-processing techniques were performed in order to utilize the spectral properties of the land cover.
- Various vegetation indices were derived that could improve the extraction of mangrove cover from the satellite images.
- Image segmentation was undertaken to obtain object-based image statistics to increase the accuracy of subsequent image classification techniques.
- Unsupervised classifications of objects into separate land cover categories were made (where possible).
- Finally, a visual control of land cover classes was made to produce a meaningful class nomenclature with mangroves as the main class of interest.

Fine spatial resolution is important in enabling precise mapping of mangroves. Its necessity becomes even clearer when the dotted-like pattern that mangrove plantations generally form in remotely sensed imagery is considered. Despite their richer spectral capabilities and number of bands, medium-resolution data, such as from Landsat, cannot compensate for the loss of spatial detail needed to analyse small-scale changes in land cover (from a few tenths of a hectare) in mangrove restoration projects.

5.3 Limitations

An important obstacle in retrieving clear satellite imagery for the studied areas was the frequent and heavy cloud contamination. This had to be expected, as mangroves mainly grow in the tropics. The use of radar imagery might provide a solution for the frequent cloud cover; however, high-resolution passive sensors offer a much-needed visual screen interpretation, which cannot be provided by radar sensors. For remote analysis without suitable knowledge of the study area and without ground truthing, the use of radar imagery is very difficult, especially given the mixture of other tropical vegetation with mangroves. Although the "texture" of new mangrove plantations might be detected, old growth mangroves are every difficult to discriminate from all other natural vegetation.

A major limitation of this project was the lack of information on the exact geographic extent of the restoration actions taking place. Having a clear knowledge of the areas where mangroves were being planted would have allowed for a much more precise assessment of the progress made. On the other hand, assessing the entire area did provide a better picture of the general improvement (or decline) of forest and mangrove coverage.

To overcome this limitation, it was decided that the assessment should cover larger areas than originally planned. This enabled easier reprocessing of the data to get highly accurate statistics on the subject. One drawback, however, was the increased presence of mixed classes (e.g. mangroves mixed with other forest vegetation). Nevertheless, this did not diminish the accuracy and importance of the trends reflected in the final statistics.

5.4 Access to data and reports

Access to reports and data to be used as a baseline, and further documents to assess the success of the project, were rare, non-standardized and difficult to find. This was because:

- Scientists or organizations have been reluctant to report or document unsuccessful (or only partially successful) projects.
- Reports and data were not centralized and/or properly referenced.

Consequently, numerous mangrove restoration programmes are being carried out without proper reference to lessons learnt from past experiences.

The Abu Dhabi site is a good example of biased access to data and lack of access to the reality in the field. The selection of the site to be monitored was made according to spatio-temporal data from the Division of Environmental Policy Implementation, UNEP.

6. Conclusion

6.1 The use of remote sensing

The study has shown that mangrove restoration actions can be effectively assessed using remotely sensed data. It shows that, even without clear identification of the study area capturing the surfaces of interest, or without ground truthing, it is possible to map land cover changes.

The difficulties encountered here in accessing cloud-free satellite images are being eased by the increase in the number of satellite sensors, which are increasing the number of images available for a given location. Compared with ground truthing, remote sensing provides a comprehensive view of land cover and, using ancillary data, makes it possible to look at its past status. However, satellite imagery does not allow an understanding of reasons for failure and successes of different land cover restoration projects. Ground survey and remote sensing are necessary complementary processes. In this project, no ground surveys were planned, due to the lack of time and resources. They would have allowed a better calibration of the satellite imagery, as well as a check on the accuracy of the classifications made. Ground surveys would also assist in understanding the reasons for success or failure of restoration projects.

For future monitoring, the availability of precise locations, provided as shape files or keyhole markup language, would ease the process. In the absence of such information, the analysis had to be performed over large areas, which was a time-consuming process given the high resolution of the data (0.45 m and 0.6 m).

6.2 Uncertainties

Without ground truthing, the accuracy of the study classifications could not be further assessed. Direct visual interpretation of the high-resolution satellite sensors was used to perform quality checks of the algorithms. The use of other datasets, such as the Global Distribution of Mangroves (United States Geological Survey, 2011) and the Shuttle Radar Topographic Mission (NASA), proved helpful. It has to be noted that mangroves and other tropical vegetation, both coastal and inland, can be easily confused in satellite image interpretation, and distinguishing them from space remains challenging.

6.3 Restoration efficiency

Common mistakes of past initiatives of mangrove restoration include: planting the wrong species, planting at the wrong place, planting at wrong time, and planting without involving local communities (Check, 2005). Furthermore, Field (1998) established a list of activities to monitor restoration activities:

- Take regular aerial photographs of the site
- Monitor the evolution of the distribution of mangrove species
- Monitor growth as a function of time
- Monitor growth characteristics
- Record level of failure of seedlings
- Record impact of pests and diseases
- Record levels of rubbish accumulation

- Record the impact of grazing, cutting, fish ponds and fishing
- Adjust density of seedlings and saplings to an optimum level
- Estimate cost of rehabilitation project
- Monitor impact of any harvesting
- Assess characteristics of a rehabilitated mangrove ecosystem
- Measure the success of the rehabilitation project against the original criteria established

It can be hard for to get support from local communities, as they are mostly not the owners of the wetlands in question. Decisions for mangrove recovery projects often lie within the hands of local governments. Field (1998) noted that the success of a restoration project depends more on the implication to local communities than any politically driven ecological goal. In order to guarantee a wide dissemination and application of lessons learnt from such projects, it is also necessary to publish reports not only in the English, but also local languages.

Lewis wrote in 2009 that "funding agencies typically fund mangrove restoration projects with minimal funds dedicated towards quantitative monitoring and reporting over a reasonable and ecologically based time period (five years minimum). Both failures and successes thus go undocumented, and mistakes are repeated and lessons learnt are lost… These efforts to date have been hampered, however, by the lack of application of uniform methodologies of sampling and reporting". Lewis continued in 2011, saying that "the evidence for successful restoration of mangroves on any large scale, however, is nearly non-existent."

Field (1998) wrote: "One of the challenges is to gauge how successful rehabilitation projects have been and what lessons have been learnt from failures. It is clearly impossible to carry out such a critical review without access to the myriad of reports that must be hidden in the archives of the many sponsoring agencies… There is a real need for an archival system to be established where reports on mangrove rehabilitation can be lodged and accessed easily by interested people… The result is that there are many mangrove rehabilitation programmes being carried out without any reference to lessons that might be learnt from other similar programmes".

In 2013, the situation remains unchanged and no standardized protocols and reporting have been developed yet. Additionally, funding problems often cause monitoring and replanting projects to operate on a short-term basis.

Making an independent assessment of the success or failure of mangrove recovery projects cannot only be based on reports provided by the organizations that are operating the projects. Hence, there are three potential ways of following up – the use of ground surveys, monitoring from space or, if finance allows, a combination of both. Ground surveys provide a better understanding of the context, which can explain the progress (or lack thereof) of a project. They can also further assess the quality of the recovery. However, remote sensing analysis provides a synoptic view, as well as the possibility of going back in time (with the limitations explained above). Both techniques can be used, and ideally should be used, in combination, as they are highly complementary.

The relationship between success of mangrove restoration projects and the amount of funding (i.e. more funding yielding better results) could not be assessed in this project because we could only monitor the restoration projects over a short time frame. Due to their relative small size, most of the sites required very high-resolution satellite sensors which started to be available only in recent years. Given that the canopy of a mangrove tree cannot be detected until after three to four years of growth, our analysis could only be performed on projects which have started after 2000 and were fully completed by 2009. For projects which were completed (or well-advanced) by 2000, the initial situation could be assessed. Within the projects which satisfied this condition, we only assessed progress made on projects which were completed by 2009. This narrow time span restricted us to only a selection of sites within a project (projects usually include several sites).

Precise locations (e.g. such as from the keyhole markup language files received for Madagascar) really helped to monitor the progress made for the project. For most of the projects, we received only general information regarding their location, and the analysis was then made on the overall area. This meant that decline or increase in mangrove coverage outside the project were also taken into consideration.

This in itself is not necessarily a significant limitation, as having a project for restoring mangroves should also raise awareness in the region and therefore should (in theory) have a broader impact in the surrounding areas.

In this analysis, 70 per cent of the sites showed good to very good recovery. This is an encouraging result. Although the start and end dates of projects limited site selection, where these dates were between 2000 and 2009, the monitoring process was successfully applied. Overall, monitoring mangrove restoration from space is a valid approach and could be applied in other locations, although each project would need to be calibrated individually.

Annexes

Glossary

Object-based analysis: image analysis based on groups of pixels with similar spectral properties (i.e. colour, size, shape and texture), as well as context from the neighbourhood surrounding the pixels.

Pan sharpening: process of transforming a low-resolution multi-spectral image to high-resolution multi-spectral image, by fusing a co-registered low-resolution panchromatic image.

Post-analysis field validation: process of validating results from remote analysis in the field, with the aim of refining the methodology applied.

Segmentation: process of grouping pixels for object-based analysis.

Unsupervised pixel-based classification: process of classifying an image based on natural groupings of the spectral properties of the pixels, without the user specifying how to classify any portion of the image using training areas.

More detailed explanations on processing techniques

The small-scale sites in this project required high-resolution imagery. Pan sharpening was initially performed to support further classification, as well as visual interpretation tasks. A hybrid approach was used that consisted of object-based image analysis (image segmentation to derive homogeneous image regions) and unsupervised pixel-based classification (to extract unique land cover classes), followed by visual verification and class labelling of the results.

This process improved the classification, and eased the change detection, in particular with the high-resolution satellite sensors.

Pan sharpening

Multi-spectral satellite sensors produce multi-dimensional data. These comprise images that capture various narrow portions of the electromagnetic spectrum (known as multi-spectral bands), plus a panchromatic band, which is wider. The multi-spectral bands are (technologically and/or financially) of coarse spatial resolution, though they have a finer radiometric resolution. The panchromatic band is of high spatial, but coarser radiometric, resolution.

By using advanced image processing techniques, it is possible to fuse the low- and medium-spatial resolution multi-spectral bands, with the high-resolution pixels of the panchromatic bands. This process produces artificial multi-spectral images of high spatial resolution. This adopted hybrid approach of classifying the satellite images of interest involved the unavoidable standard image pre-processing tasks that concern the spatial projection and the radiometry of the images.

Next, segmentation was performed to derive objects for which various image statistics were calculated. Multi-dimensional data sets were built that combined the images' radiometric information, as well as some of the statistics that provided additional descriptive information.

These multi-dimensional images were subjected to a pixel-based image classification. The resultant classified pixels were visually interpreted and manually assigned to a certain category that described the land cover classes of interest. The final classification maps were compared and analysed.

Image pre-processing: five steps

Image pre-processing involves accurate projection of images, importation into a geospatial database and conversion of digital numbers to reflectance (top-of-canopy or top-of-atmosphere, depending on the acquisition's clarity).

The following five steps may be used:

1. Atmospheric correction. This enables an estimation of the actual amount of energy reflected from the top of the canopy, and is not always required because each acquisition (one pre- and one post-implementation of mangrove restoration in a site) is treated individually. Thus, there is no unavoidable need for a relative atmospheric correction between the pre- and post- implementation pairs of scenes for the site. The comparison of the abundance of mangroves is performed at the final classification (using thematic raster maps that describe the same surface, but at different times). In one case of a cloud- and haze-contaminated image, advanced filtering was performed to enhance the spectral profile of the captured surface by using principal components analysis.
2. Segmentation to derive homogenous objects. Using an advanced algorithm, pixels are grouped to form segments (objects), based on their spectral similarity across all available multi-spectral bands. Optionally, the segmentation also considers various descriptive statistics derived from their spectral profile.

The multi-dimensional input data for the segmentation process is a composition of some of the following layers that corresponded to the image(s) to be classified: reflectances (panchromatic and multi-spectral bands), pan-sharpened reflectances (fused multi-spectral bands with their corresponding panchromatic band), selected principal components derived from reflectances (spectrally enhanced synthetic layers), vegetation indices (NDVI or EVI2), object-based statistics (average, average deviation, standard deviation, variance, minimum, maximum) and textural features.

3. Pixel-based classification of objects based on maximum likelihood.
4. Visual interpretation, verification and manual labelling of classes.
5. Optionally, in some cases of very high-resolution images, an additional geo-referencing of the pre- and post-restoration (high-resolution) classification maps can be made before applying the final step of image differencing.

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