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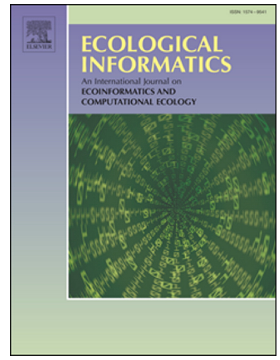

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Modelling informal Sand Forest harvesting using a Disturbance Index from Landsat, in Maputaland (South Africa)

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Abstract

Indigenous forests and savannah provide numerous benefits for rural communities and are utilised as a source of firewood, building material and for woodcraft production. Currently, there is insufficient information on the magnitude of human pressure affecting one such important forest community, namely Sand Forest, particularly in communal areas. The temporal monitoring of the spatial structures of forest areas, such as Sand Forest, within landscapes has been recommended in order to detect and model deteriorating trends in the forest structures and functioning. Remote sensing is critical in the generation of data that enables the identification and quantification of degraded and deforested areas.

The constrained distribution and fragmented patches associated with Sand Forest, and the effects of a declining canopy closure, resulting from selective wood harvesting, requires the use of remote sensing techniques and procedures that could potentially account for these characteristics. A spectral index that has been widely successful in monitoring disturbances in forests is the Disturbance Index. The success of the Disturbance Index in detecting changes could be attributed to the components that comprise the Disturbance Index, in that it takes into account the relationship that exists between soil; vegetation; and canopy & soil moisture. The suitability of determining changes could also be attributed to the approach taken by the Disturbance Index i.e. monitoring disturbance versus a component of vegetation, such as the Normalised Difference Vegetation Index (biomass). The rates of change derived for the study period (1998 to 2014) provided quantified information on the magnitude of human pressure affecting Sand Forest throughout Maputaland. The rates of change showed that the accumulated total loss in the extent of Sand Forest, across the South African section of Maputaland, was 15.53 km^2 over a period of 16 years.

Key Words: Sand Forest, informal wood harvesting, remote sensing, Disturbance Index, socio-ecological system, Maputaland.

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1. Introduction

Biodiversity is currently being lost at rates significantly higher than those revealed by fossil records. The loss of biodiversity has the potential to greatly affect human well-being, economic and informal utilisation of natural resources, and more importantly, ecosystem functioning (Biggs *et al*., 2008).

Sand Forest, which is also referred to as Licuáti Forest in Mozambique, is a type of forest that has a very idiosyncratic floral and faunal component (Matthews, 2007). Sand Forest is regarded as being critically endangered (Mucina & Rutherford, 2006; Gaugris *et al*., 2008) and is considered to hold various endemic species, several of which are viewed as being rare and atypical (Kirkwood & Midgley, 1999; Gaugris & Van Rooyen, 2007; Matthews, 2007). As a result of the constrained distribution of Sand Forest and the uncommon species composition, Matthews (2007) perceives Sand Forest as one of the most important habitat types in Maputaland, thereby forming the core of the Maputaland Regional Centre of Endemism (Mucina & Rutherford, 2006). Sand Forest occurs as fragmented patches, occurring only in South Africa and Southern Mozambique, from False Bay (KwaZulu-Natal, South Africa) in the south to Maputo (Mozambique) in the north (Kirkwood & Midgely, 1999; Mucina & Rutherford, 2006; Matthews, 2007).

Sand Forest has been observed as having a low rate of regeneration due to having a relic forest-like character, with few seedlings and saplings (Mucina *et al*., 2003). In a fragmented and dynamic landscape, species that are unable to colonise new habitats productively, at the same rate at which the species is lost, are more vulnerable to loss of biodiversity and fragmentation (Hermy *et al*., 1999). This characteristic, therefore, increases the susceptibility of Sand Forest to being adversely affected by activities that open up the forest edge and canopy, such as wood harvesting.

Indigenous forests and savannah, such as Sand Forest, provide numerous benefits for rural communities (Pote *et al*., 2006; Shackleton *et al*., 2007) and are utilised as a source of firewood, building material and for woodcraft production (Lawes & Obiri, 2003; Mucina &

Rutherford, 2006; Gaugris & Van Rooyen, 2010). The increase in human population within Northern Maputaland has also increased the use of wooded ecosystems to meet basic household needs. This increase in population has raised concerns regarding the fragmentation and loss of Sand Forest, particularly in communal areas (Gaugris & Van Rooyen, 2007). The fragmented patch occurrence of this rare and valuable forest type, combined with the lack of necessary knowledge and prior interest in its management, has resulted in the Sand Forest being subjected to uncontrolled utilisation within communal areas (Matthews *et al*., 2001). However, a significant concern is the lack of information on the magnitude of human pressure affecting Sand Forest in communal areas (Mucina *et al*., 2003).

Elevated human utilisation of woody vegetation may lead to a general change in the vegetation community, degradation and fragmentation and the extinction of species (Schmidt-Soltau, 2003; Ndangalasi *et al*., 2007). This is exacerbated further through the depletion of wildlife and wildlife habitat, leading to changes in wildlife densities and affecting the natural vegetation dynamics (Babweteera *et al.,* 2007). The long-term effects of large tree harvesting on forest community composition are not entirely understood. However, it is evident that the decline in canopy closure due to selective wood harvesting and the resultant increase in the amount of light reaching the forest floor can lead to a change in the species composition of the regenerating forest and in the functioning of the ecosystem (Lawes *et al*., 2007).

Sand Forest is especially susceptible to resource utilisation as it is not considered a resilient vegetation type (Matthews, 2007). Sand Forest has been observed by Matthews (2007) as being unable to recover after being adversely impacted upon. The low resilience of Sand Forest is additionally demonstrated by Gaugris *et al*. (2008) who cite various authors (Van Rensburg *et al*., 1999; Van Rensburg *et al*., 2000; Botes *et al*., 2006; Matthews, 2007) who were in agreement that, under the current climatic conditions, Sand Forest patches that are adversely impacted upon, may be changed into a woodland ecosystem.

Deforestation and forest degradation, such as those associated with the informal harvesting of firewood, building material and woodcraft, are considered to be associated and progressive processes (Panta *et al.*, 2008). These processes have resulted in the conversion of forest areas into a mosaic of forest fragments and degraded habitats. The temporal monitoring of the spatial structures of forest areas, such as Sand Forest, within landscapes has been recommended in order to detect and model deteriorating trends in the forest structures and functioning. Remote sensing is critical in the generation of data that enables the identification and quantification of degraded and deforested areas, potential areas for conservation (Panta *et al.*, 2008) and information for setting strategies for managing natural resources. As a result of scarce conservation resources, identifying priority areas for conservation is of great importance (Rouget *et al*., 2003). Remote sensing, therefore, can be used to identify and quantify the effects of informal wood harvesting of Sand Forest by rural communities. A remote sensing technique that has been successful in monitoring disturbances in forests is the Disturbance Index (DI), which was first applied by Healey *et al.* (2005). Healey *et al.* (2005) tested TC (Tasseled Cap) variants (e.g. DI) in the St. Petersburg region of Russia as well as in two ecologically dissimilar regions of Washington State in the US. In the majority of cases, the TC variants produced more precise change classifications than multi-date stacks of the raw Landsat reflectance data. The DI was the most accurate for the St. Petersburg region of Russia which was characterised by lower succession rates, similarly to Sand Forest. In addition, Deel *et al.* (2012) used a Cumulative Disturbance Index in determining changes in the forest canopy, an aspect which has significant consequences for Sand Forest. Subsequently, the spatial information derived from remote sensing techniques can be used for decisions regarding the future management of Sand Forest.

Matthews (2007) estimates that the area in which the Sand Forest occurs, covers a narrow 500 km zone, of which only 150 km occurs within South Africa. The study is limited to the Sand Forest areas within the South African section of Maputaland, which is situated in Northern KwaZulu-Natal. Due to the vast size of the study area, reference sites were selected for detailed observations to be discussed in this paper. A comparative and indicative approach was taken in determining the Sand Forest areas selected as reference sites and was based on precise characteristics relating to each specific site.

2. Methodology

2.1 Data Collection

Remotely sensed data used in the study comprised of three Landsat images from two different sensors and from three different dates. Landsat 5 TM was selected for the 1998 and 2004 images, while Landsat 8 OLI was selected for the 2014 image. The images selected for these dates were in the winter months i.e. June to July. This seasonal approach was incorporated for two reasons; mainly to increase the probability of attaining useable cloudless images and, as Sand Forest is evergreen, to attempt to reduce the influences of surrounding deciduous vegetation during analysis. It should be noted that data availability (i.e. useable cloudless images within winter months) also dictated the time-period utilised for this study.

GIS data was utilised in the form of existing data on the known extent and distribution of Sand Forest in South Africa, provided from the study undertaken by Mucina and Rutherford (2006). GIS data provided a base map of the maximum extent of Sand Forest that could be examined during the analysis stage of the study. However, to ensure accuracy, the Mucina and Rutherford (2006) dataset was modified to include information provided on isolated Sand Forest patches within the Phinda Nature Reserve. The use of auxiliary GIS data ensured a higher degree of accuracy in determining the changes relating to Sand Forest. Furthermore, the GIS data provided accurate zones from which an area of interest (AoI) could be derived. This increased the accuracy of the information produced during analysis stage of the study.

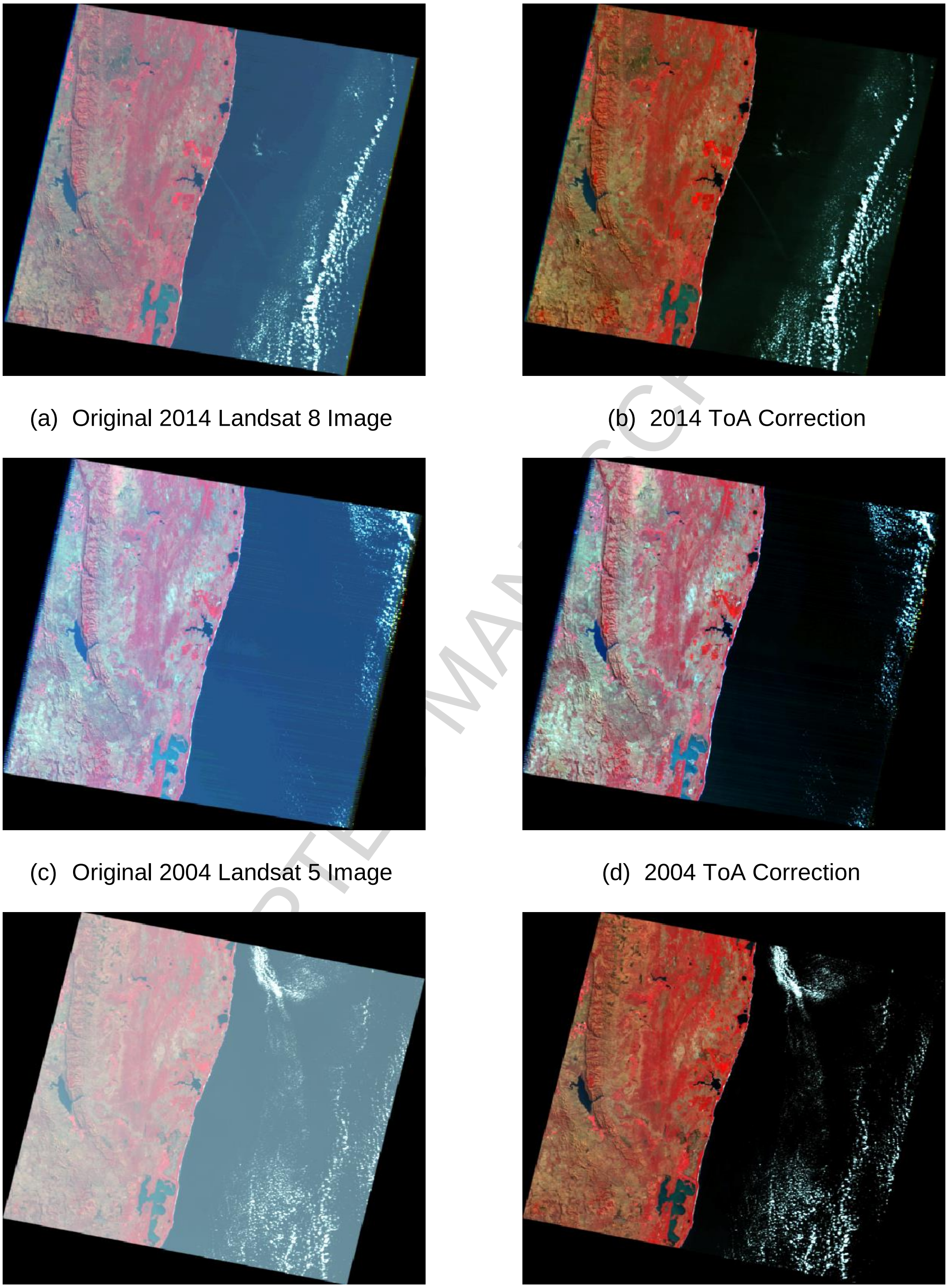
2.2 Pre-processing

2.2.1 Top of atmospheric correction

To ensure that the radiance of the images used in the study was a true representation of the actual values of the features on the ground, a top of atmospheric (ToA) correction was undertaken for each image using ATMOSC in IDRISI Selva (refer to Fig. 1). The ATMOSC uses a

COST model for atmospheric correction. The information used for the atmospheric correction is reliant on information derived from the image itself in order to estimate the path of radiance of each spectral band. A comparative study by Mahiny and Turner (2007) showed that the COST method performed well in comparison to other methods and produced overall stable results. Therefore, due to the availability of data, this method was selected as all the information required for the model could be derived from the images and associated metadata.

Atmospheric correction was selected for two main reasons, considering the close proximity of the ocean to the study area. Firstly, in order to undertake a ratio of values between two bands, i.e. for undertaking of an index, the effects of scattering were required to be reduced. This was especially necessary for indices that exploit shorter-wavelengths (e.g. Tasseled Cap Transformation), as these are affected more adversely by scattering than bands within the longer wavelengths. Secondly, ground measurements made at a singular location, though at different points in time, will have significant differences in scattering and absorption. To achieve a higher degree of accuracy, these differences are corrected to produce images that are more comparable (Lillesand *et al.,* 2007; Mather, 2009). The use of indices and temporal analysis are key components of the study; therefore atmospheric correction was required.



(a) Original 2014 Landsat 8 Image
(b) 2014 ToA Correction
(c) Original 2004 Landsat 5 Image
(d) 2004 ToA Correction
(e) Original 1998 Landsat 5 Image
(f) 1998 ToA Correction

Fig. 1. Landsat images before and after ToA correction (False Colour)

2.2.2 Tasseled Cap Transformation

The key purpose in undertaking an image transformation is to re-express the information recorded in an image, subsequently providing a new set of data that can be further analysed. The Tasseled Cap Transformation (TCT), which utilises six bands within the Landsat TM dataset, effectively derives data within three dimensions. The first dimension is the plane of soil, which is regarded as Brightness. The second dimension is the plane of vegetation and is regarded as Greenness. Lastly, a transition zone, which exists between these planes, is associated with canopy and soil moisture, namely Wetness (Lillesand *et al*., 2007). TCT is regarded as a valuable method for analysing phenological and ecological information (Lobser & Cohen, 2007).

To create images (refer to Fig. 2) based on soil; vegetation; and canopy & soil moisture, a TCT procedure was undertaken for the Landsat images using the Tasseled Cap model in ERDAS Imagine. However, the model within ERDAS Imagine, at the time of the research, had been developed to undertake the TCT for Landsat MSS (Landsat 1, 2 and 3), Landsat TM (Landsat 4 and 5) and Landsat ETM+ (Landsat 7) sensors. In order to ensure continuity within the study, a TCT would be required for the fairly new (at the time of the research) Landsat 8 OLI sensor. To overcome this, the standard TCT model in ERDAS Imagine was modified with the Landsat 8 OLI TCT coefficients (refer to Table 1) that were derived in a study by Ali Baig *et al*. (2014) to produce Brightness, Greenness and Wetness images for the 2014 Landsat 8 OLI image.

Table 1

Landsat 8 OLI Tasseled Cap Transformation coefficients (Ali Baig *et al.*, 2014)

Landsat 8 TCT	Band 2 (Blue)	Band 3 (Green)	Band 4 (Red)	Band 5 (NIR)	Band 6 (SWIR 1)	Band 7 (SWIR 2)
Brightness	0.3029	0.2786	0.4733	0.5599	0.508	0.1872
Greenness	−0.2941	−0.243	−0.5424	0.7276	0.0713	−0.1608

Wetness	0.1511	0.1973	0.3283	0.3407	−0.7117	−0.4559
TCT 4	−0.8239	0.0849	0.4396	−0.058	0.2013	−0.2773
TCT 5	−0.3294	0.0557	0.1056	0.1855	−0.4349	0.8085
TCT 6	0.1079	−0.9023	0.4119	0.0575	−0.0259	0.0252

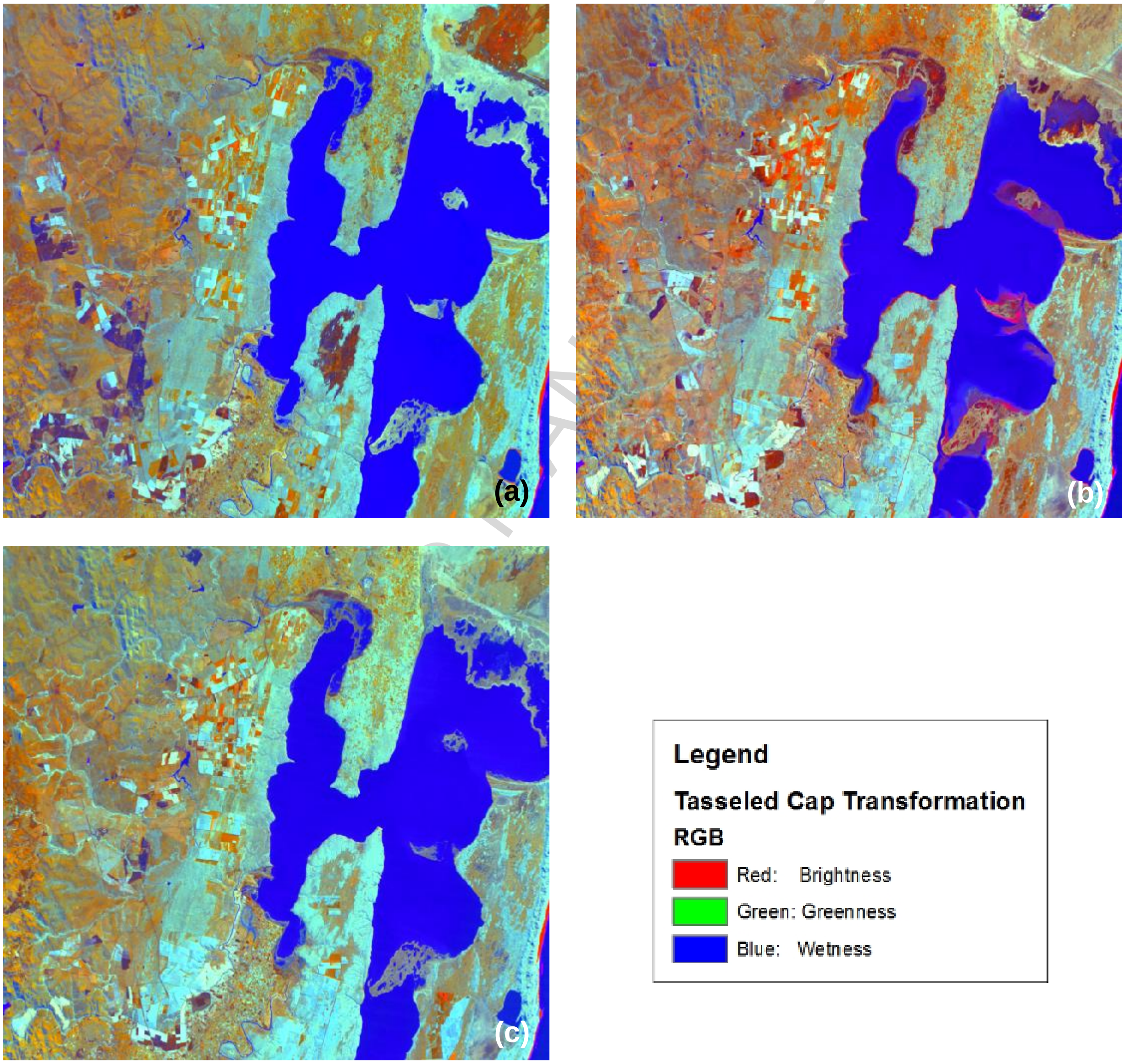


Fig. 2. Tasseled Cap Transformation of (a) 2014 Landsat 8 OLI, (b) 2004 Landsat 5 TM and (c) 1998 Landsat 5 TM

2.2.3 Classification of historical disturbances

Although classification is typically not considered as a pre-processing technique, in the context of this study, classification was required as a step before analysis could be undertaken. A k-means unsupervised classification was undertaken within the AoI provided for by the auxiliary GIS data on the 1998 TCT image. The reason for classifying the known Sand Forest areas was to differentiate between Sand Forest and existing disturbances within these zones. This provided a historical disturbance dataset i.e. disturbances prior to 1998, which provided advantageous information for use in the subsequent procedures and increased the accuracy of the changes observed within the study's specified period.

2.3 Disturbance Index

As previously mentioned, a spectral index that has been widely successful in monitoring disturbances in forests is the Disturbance Index (Healey *et al.,* 2005). The Disturbance Index utilises three components of the TCT: Brightness, Greenness and Wetness. The equation for the Disturbance Index is as follows:

$$\mathrm{DI} = \mathrm{Brightness} - (\mathrm{Greenness} + \mathrm{Wetness})$$

The values derived from the Disturbance Index are based on the concept that forests which have been highly disturbed have a higher reflectance of Brightness and a lower reflectance of Greenness and Wetness than undisturbed forests. The Disturbance Index was chosen for its potential sensitivity to detect the anthropogenic disturbances experienced from informal wood harvesting within Sand Forest. The Disturbance Index is generally normalised (i.e. correcting values measured on dissimilar scales to an ideally mutual scale) for use in detecting changes (Healey *et al.,* 2005), however, this study used a more simplistic un-normalised Disturbance Index, in such that the standard (i.e. raw) Brightness, Greenness and Wetness components of the TCT were used as opposed to using normalised inputs.

The Disturbance Index underwent a standard change detection procedure to develop change detection datasets for 1998-2004 and 2004-2014. These datasets were used as a point of departure for analysing the rates of change within Sand Forest. The change detection procedure may be considered as having a hybrid component, as the results from the change detection underwent a subset using the modified GIS Sand Forest dataset as an AoI. This was done in order to isolate the changes that occurred within the known Sand Forest, subsequently providing 'change maps' that were used in determining rates of change that are specific to Sand Forest.

2.4 Trends Analysis (Rates of Change)

Prior to analysing trends of informal Sand Forest wood harvesting, the change maps generated in the change detection procedure required additional processing. To ensure the accuracy of the rates of change, and to establish that the rates represented the actual changes occurring within the time periods being investigated, certain aspects within the change maps needed to be excluded. A historical disturbance dataset was created from the classification of disturbances that occurred prior to 1998 and was combined with the 2004 change map using an arithmetic function to exclude historical disturbances from the determination of forest cover for 2004. A similar exercise was conducted for the 2014 change map; however, for the 2014 change map, both the historical disturbances dataset and a Boolean dataset of the changes that occurred from 1998 to 2004 were combined using an arithmetic function. This excluded all historical disturbances and disturbances that occurred prior to 2004, for the 2004 to 2014 change map. These exclusions ensured that the rates of change would be exclusively for the time-periods under investigation, i.e. 1998 to 2004 and 2004 to 2014. These time-periods were selected as they correspond with the Landsat images available for the study area, providing two time-periods for comparative purposes. A visual representation of the analysis is shown in Fig. 3.

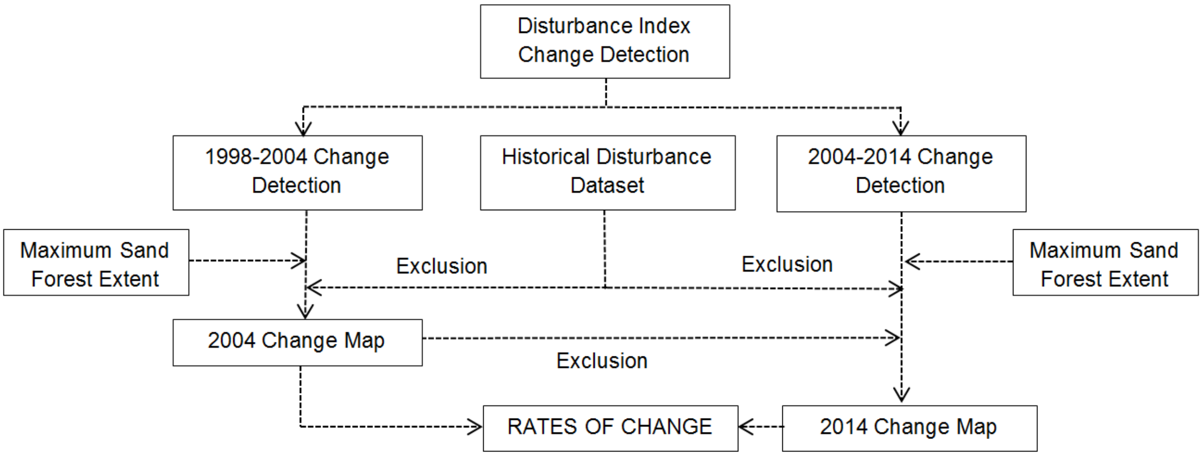


Fig. 3. Rates of change process flow diagram

To determine the rates of change, standard statistical analysis was used. The information developed during the statistical analysis included the net rate at which the extent of Sand Forest was disturbed and the annual rate of disturbance. The rates of change were calculated from the change maps for the changes occurring between 1998 and 2004 (6-year period), 2004 and 2014 (10-year period) and an overall accumulated change from 1998 to 2014 (16-year period). The time series selected were as a result of the limitations experienced in the data, however, it also provided information that could allow for analysing trends. The relative net change (RNC) was calculated as the difference in forest cover (FC) between the respective years, by means of an equation proposed by Kuemmerle *et al.* (2009):

$$\mathrm{RNC} = \left(\frac{\mathrm{FC}_{\mathrm{End\ Date}}}{\mathrm{FC}_{\mathrm{start\ Date}}} - 1\right) * 100$$

Kuemmerle *et al.* (2009) also proposed the following equation for determining annual disturbance rates (DR) for FC change. Within the equation 'D' is regarded as the sum of the disturbances of the time period (j) under consideration. FCB signifies forest cover at the beginning of time period (j) and (a) is the number of years between the datasets.

$$\mathrm{DR}_{\mathrm{j}} = \left(\frac{\mathrm{D}_{\mathrm{j}}}{\mathrm{FCB}_{\mathrm{j}}}\right) * \left(\frac{100}{\mathrm{a}}\right)$$

3 Results

3.1 Disturbance Index

The success of the Disturbance Index (refer to Fig. 4) in detecting changes could be attributed to the components of the Disturbance Index, in that it takes the relationship that exists between soil; vegetation; and canopy & soil moisture into account. The suitability of determining the changes could also be attributed to the approach taken by the Disturbance Index. The Disturbance Index responds to changes in disturbance, through having an inverted purpose as opposed to the other spectral indices. The Disturbance Index detected an increase in disturbance, which provided a more robust change detection procedure, as it highlights changes in disturbance, which is considered to produce a high degree of accuracy and confidence in the results. Consequently, the Disturbance Index was selected and used for determining the trends of informal Sand Forest wood harvesting.

For the Disturbance Index it should be noted that, although the decrease in disturbance that is referred to in the images is associated with an increase in vegetation (i.e. “increased” refers to an increase in disturbance, while “decreased” refers to a decrease in disturbance) it was excluded from the remaining Sand Forest in the proceeding evaluations. This is due to the low regeneration rate of Sand Forest; thereby the increase in vegetation is more likely to represent successional species from surrounding vegetation types rather than Sand Forest saplings.

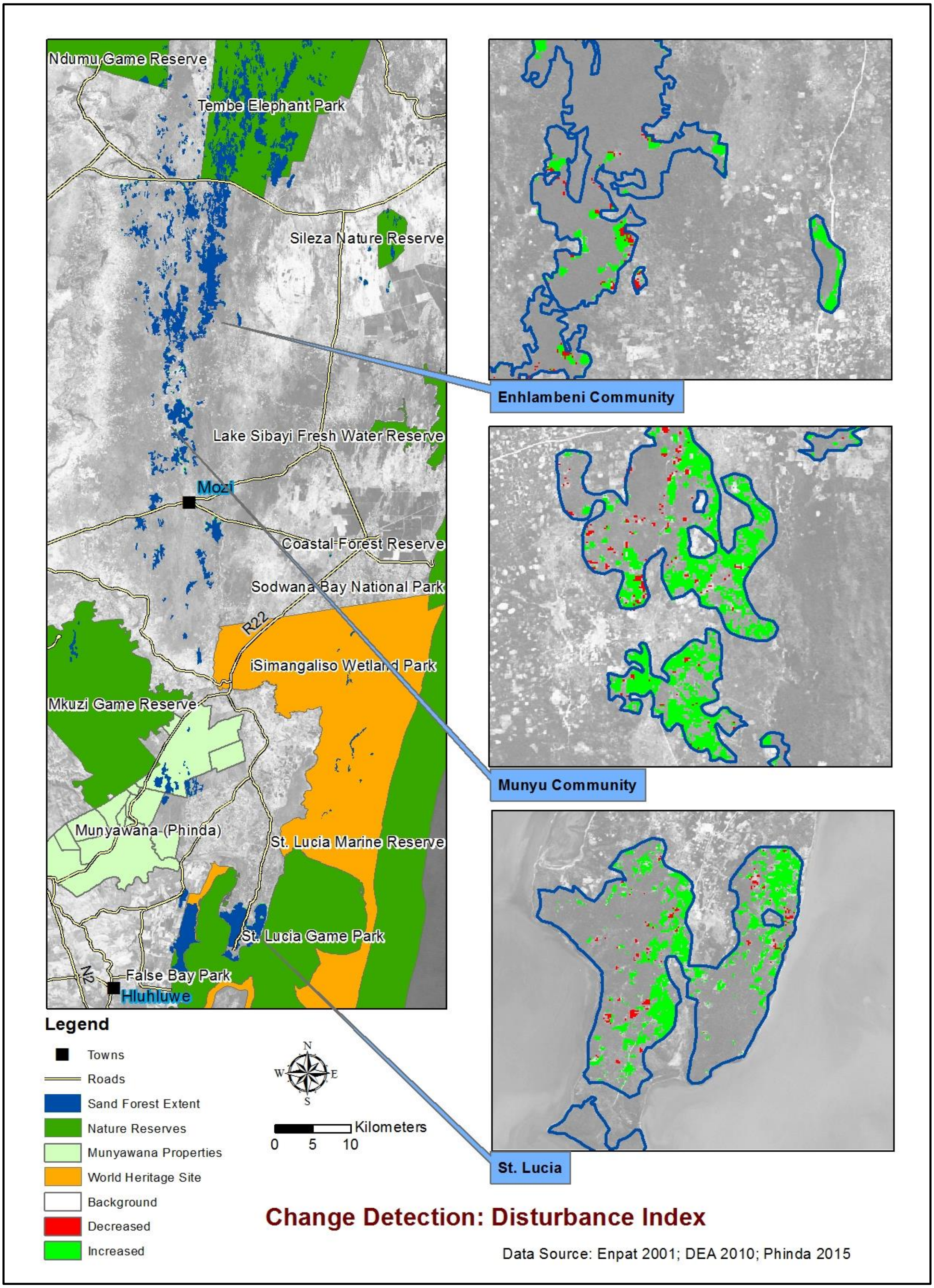


Fig. 4. Change detection: Disturbance Index (1998-2004 & 2004-2014)

3.2 Trends analysis

The rates of change determined include an overall net change and the annual rate of disturbance. The rates of change for Sand Forest were determined between 1998 and 2004, and between 2004 and 2014, as well as cumulative rates of change occurring between 1998 and 2014. The current rates of change for Sand Forest are detailed in Table 2.

Table 2

Current rates of change

Year	1998-2004	2004-2014	1998-2014
Disturbance (km^2)	5.02	10.51	15.53
Net Change (%)	-2.123	-4.539	-6.566
Annual Rate of Disturbance (%)	0.354	0.454	0.4102

As demonstrated in Table 2, the loss in extent of Sand Forest that occurred from 1998 to 2004 and from 2004 to 2014 was 5.02 km^2 and 10.51 km^2 respectively, over the South African section of Maputaland. This amounts to a total loss in extent of 15.53 km^2 of Sand Forest within Maputaland over a period of 16 years, resulting in a –6.566% net change. The annual disturbance for 1998 to 2004 was calculated at 0.345% per annum, while the annual disturbance for 2004 to 2014 was calculated at 0.454% per annum. This illustrated an increase of 0.1% annual disturbance between the two datasets and corresponding time series. The graph in Fig. 5 provides a visual representation of the actual loss of Sand Forest between 1998 and 2014.

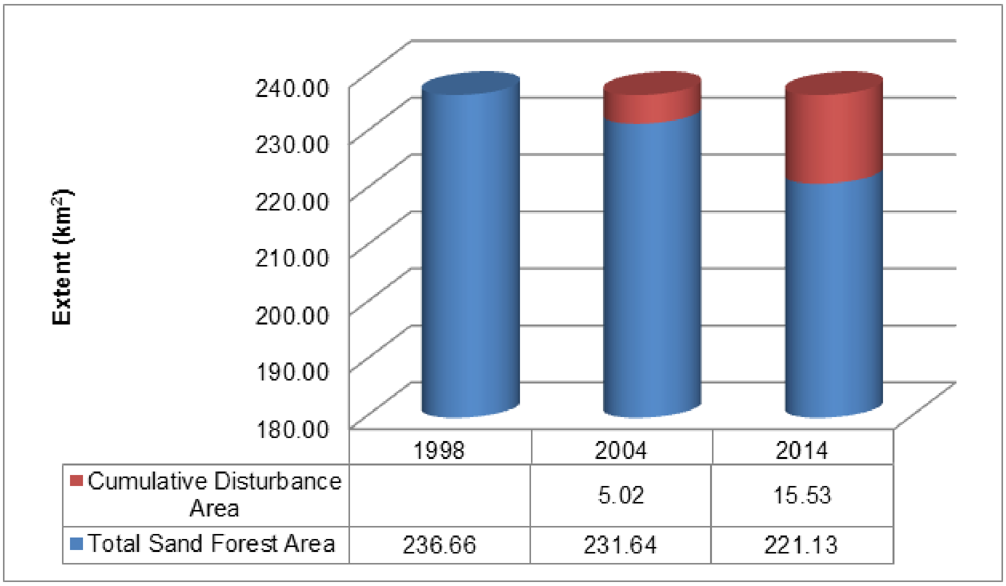


Fig. 5. Sand Forest extent vs. cumulative disturbance

4 Discussion

Illustrated in Fig. 6 is the regional distribution of Sand Forest in Maputaland, including 1998 to 2014 'change maps' of the St. Lucia and Mozi community reference sites. The Sand Forest in close proximity to St. Lucia and to the Mozi community are some of the most affected and provide a good representation of the extent of disturbance experienced by Sand Forest within Maputaland.

The loss in extent of Sand Forest is considered quite significant. The total loss of 15.53 km^2 of Sand Forest over Maputaland has been observed between 1998 and 2014. Considering that in South Africa the Environmental Impact Assessment Regulations, 2014 (Government Notice No. R 982, 983, 984 and 985 of 2014), promulgated in terms of Section 24(5), 24M and 44 of the National Environmental Management Act, 1998 (Act No. 107 of 1998) make provision for a Scoping and Environmental Impact Assessment to be conducted for any development that results in the loss of more than 20 ha (0.2 km^2) of indigenous vegetation, an average annual disturbance of 0.4102% (0.97 km^2) from 1998 to 2014 is quite considerable.

Furthermore, through analysing the trends relating to the changes, it was observed that minimal loss occurred through the development of infrastructure, as the significance of Sand Forest would generally be considered and the footprint of the development limited. The losses are most likely to be predominantly associated with informal wood harvesting, with an insignificant amount expected to be lost due to elephant-induced disturbance, as changes will be confined to nature reserves that contain these mega-herbivores. The anthropogenic changes occur mainly in close proximity to roads and settlements, such as the Mozi community and the KwaNibela community at St. Lucia. Changes relating to fire and climate may also have an effect on the results of the study. However, no evidence of complete loss of a forest patch was observed, as would be expected from a fire affecting a Sand Forest patch. Furthermore, the effects of climate change on the Sand Forest were not considered due to the lack of information on this occurrence. Additionally, a study by Gaugris and Van Rooyen (2011), which investigated the effects of herbivores and humans on Sand Forest, indicated that within the sites under observation the effects of fire and climatic changes did not feature in the disturbance of Sand Forest. The disturbances within the Tembe Elephant Park and in the neighbouring Manqakulane rural community were attributed to herbivores and anthropogenic causes. However, whether these results could be extrapolated to the entire Maputaland would only be clear if information on factors such as climate change were available for the complete study area.

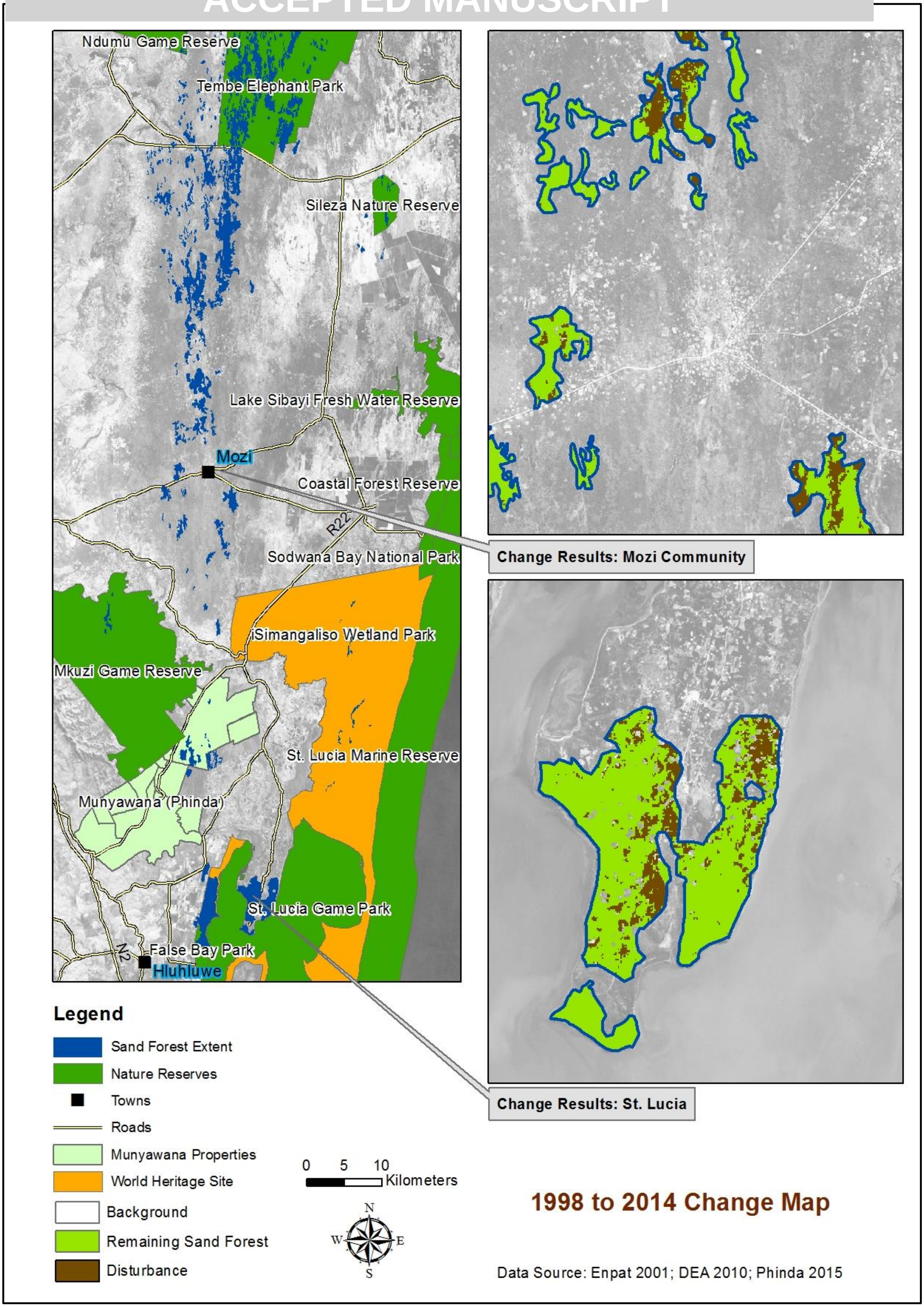


Fig. 6. 1998 to 2014 Change map

The Licuáti Forest (Sand Forest) in Mozambique is a forest reserve that has been significantly affected by logging over the last 20 years (Pereira *et al.,* 2001). According to Izidine *et al.* (2008) the average rate of deforestation for the last few years in and around the Licuáti Forest is 1.1% per annum and the author attributed this loss to the lack of implementation and enforcement of laws as well as the generally impoverished living conditions in Mozambique. In a comparison of the rates of change occurring in Sand Forest between South Africa and Mozambique, it was observed that the annual disturbance (1.1%) in the Mozambique Licuáti Forest (Sand Forest) was more than double the annual disturbance for South Africa. This illustrates the scale of human pressure that is being experienced on the entire Sand Forest population and also demonstrates the need for effective measures for conservation and sustainable utilisation.

The need for such measures is rationalised by the possible effects that continued uncontrolled informal wood harvesting of Sand Forest will have on biodiversity, communities and on the social-ecological system of Maputaland. These effects may include loss of genetic diversity, impacts relating to the edge effect, reduction in the abundance and distribution of Sand Forest, effects of the overall ecological functioning, depletion of wildlife habitat, effect on communities' livelihood security and climate resilience, and the reduction of the ecological infrastructure supporting the social-ecological system.

5 Conclusions

Sand Forest is considered as being an important vegetation unit, for both its conservation value (rare and atypical in nature) and as it forms an integral part of the ecological infrastructure that is entrenched in the livelihood security and resilience of the communities within Maputaland. The extensive and continued utilisation of Sand Forest for fuelwood, building materials and woodcraft through informal wood harvesting has resulted in sustained pressure on this natural resource.

Literature has extensive information on the structure, conservation importance and the economic importance of Sand Forest. However, little information was available on the extent of Sand Forest harvesting and the potential effects informal wood harvesting of Sand Forest would have on the social-ecological system in Maputaland. The results of the study revealed the value of remote sensing, in being able to determine changes not only over a long period of time but also over a large distance. The study was able to quantify changes that have taken place over a 16-year period. This provides current and historic data that can be analysed, thereby developing trends observed in Sand Forest. However, once the historic and current changes to Sand Forest have been quantified. Through these quantified trends, a clearer understanding of the processes affecting Sand Forest could be derived, subsequently allowing for notions to be formed on the impacts that could emerge from these trends. In particular, the information determined is a first step towards understanding the potential effects informal wood harvesting of Sand Forest would have on the social-ecological system in Maputaland.

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Modelling informal Sand Forest harvesting using a Disturbance Index from Landsat, in Maputaland (South Africa)

Research Highlights

- Temporal monitoring to detect and model deteriorating trends
- Success of the Disturbance Index in detecting changes
- Magnitude of informal wood harvesting affecting Sand Forest quantified
- Accumulated loss of Sand Forest was 15.53 km^2 over a period of 16 years