

Conservation-Driven Forest Recovery in Ise Forest Reserve, Nigeria: A Multiscale Analysis of Vegetation Structure and Land Cover

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Abstract

The forest ecosystems within the Ise Forest Reserve in Nigeria are under constant pressure from land-use conversion and timber exploitation. However, a portion of the enclave has been managed under the Southwest/Niger Delta Forest Project. This study investigated recovery trajectories by integrating systematic field sampling, remote sensing, and geographic information technologies. Eleven 25 × 25 m plots were established along 200 m transects in disturbed and undisturbed areas to evaluate species diversity and structural attributes. In total, 27 species (17 families) were recorded, with *Ricinodendron heudelotii* achieving the highest frequency ($n = 55$) and *Diospyros lotus* exhibiting the most significant mean height (12.20 ± 0.00 m), canopy cover (18.60 ± 0.00 m), and DBH (138.13 ± 0.00 cm). Significant differences ($p < 0.05$) in height, DBH, and canopy cover were observed between the two areas. The undisturbed area recorded higher Shannon-Wiener (2.73), Simpson concentration (0.91), and Margalef richness (4.74) indices than the disturbed area. Landsat imagery (2016, 2023) showed farmland expansion (1.20% vs. 13.60%) and an increase in degraded vegetation (52.61% vs. 52.26%) in the undisturbed and disturbed sites, respectively, alongside a secondary forest decline (-53.80% vs. -65.89%). Notably, the 10% lower forest degradation in the undisturbed zone reflects partial recovery. The findings revealed that the 2021 conservation program has brought beneficial changes to forest regrowth and demonstrates the necessity of continuing protective action.

1 Introduction

Multiple mounting threats arise from natural forces and human activities, such as climate change, invasive species, illegal logging, and agricultural expansion, affecting the global forest system [1, 2]. Over 1 million hectares of the Amazon rainforest were lost, while Australian forests burned 18 million hectares between 2018 and 2020 [3, 4]. Primate species diversity declines as the continent shifts from the third to the second-largest holder of tropical forests, and extreme damage trends intensify during loss in the Congo Basin [5, 6]. The lower species abundance in African forests compared to those in Asia and the Americas [7] does not diminish their essential role in protecting biodiversity that contains carbon stores and delivering key ecosystem functions [8, 9].

As a result of anthropogenic activities such as illegal logging, agricultural expansion, and infrastructure development, Nigeria is one of the countries with the highest deforestation rates in Africa, with less than 10 percent of its forest cover remaining [10]. Indeed, the country had extensive tropical rainforests that were severely degraded, and deforestation rates were 5% between 2010 and 2015 [11]. Deforestation also alters forest structure, wildlife habitats, and carbon sequestration capacity, exacerbating the impacts of climate change. Therefore, the trend underscores the need to adopt conservation and sustainable land management measures to mitigate the effects of forest loss on biodiversity and the stability of ecosystem services.

Ise Forest Reserve in the southwest of Nigeria is under threat from illegal loggers, while further pressure is exerted by farmers expanding their territories by clearing forestland and cultivating cannabis [12, 13].

The protected area designation does not stop persistent activities that endanger this area's ecological health. This area is crucial for the critically endangered Nigeria–Cameroon chimpanzee and supports numerous plant species, including *Gmelina arborea* and several other primate species, as well as *Tectona grandis* and *Mansonia altissima* [13]. The Ekiti State government, together with the Southwest/Niger Delta Forest Project, launched a restoration initiative to the reserve from within the reserve in 2021 after identifying its importance. The project uses active and passive restoration strategies to conserve biodiversity and reduce human pressure on forests through forest recovery [14, 15].

The emphasis on data-driven conservation poses the challenge of measuring restoration success, while evidence of ecological changes within the reserve is limited. Still relevant: One must also develop systematic, holistic methods of assessing vegetation composition, diversity, and changes in forest structure over time. This type of ecosystem monitoring is based on factors such as species richness, abundance, basal area, and canopy cover, as noted by both [16] and [17]. The measured parameters are used to assess the ecosystem's stability and its ability to support wildlife. The latter, however, serves as a reference point for determining the effectiveness of the protection measures taken. Quantitative ecological indicators will be used to support future restoration activities for forest ecosystems under increasing environmental pressures.

Remote sensing and geographic information systems help enhance field surveys to monitor large-scale forest changes [18, 19]. Vegetation landscape health can be effectively monitored using satellite indices such as NDVI and EVI [20, 21]. Satellite imagery enables scientists to detect changes in land-use conversions, producing spatial data that cannot be captured through conventional fieldwork [22, 23]. Remote sensing, combined with ground observations, provides insights into forest ecosystem recovery and supports the management of protected areas such as the Ise Forest Reserve.

This study examined recovery trends in disturbed and undisturbed areas of the Ise Forest Reserve and assessed the effects of recent restoration efforts by the Southwest/Niger Delta Forest Project. Specifically, it aims to (i) compare the species composition and richness between the disturbed and undisturbed plots, (ii) find out the impact of conservation strategies in the last decade, and (iii) evaluate the recovery rates from field data and satellite data. The results of this study can help conserve biodiversity, including the critically endangered chimpanzee, and contribute to global forest restoration initiatives such as the Bonn Challenge and the UN Decade on Ecosystem Restoration [24, 25]. Therefore, this research, which combines on-site data collection and remote sensing, can help improve restoration policies and guarantee the sustainable ecological recovery of tropical forest reserves.

2 Materials and Methods

2.1 Study area

The Ise Forest Reserve, situated in a tropical forest ecosystem in southwest Nigeria, lies within the coordinates 5° 20.804' E to 5° 25.331' E longitude and 7° 21.069' N to 7° 25.579' N latitude (Fig. 1). It is

approximately 9 km south of the reserve along the Akure-Benin expressway, near the Uso community in Ondo State [26]. The southwest Nigerian fragment preserves forests while enduring intense human activities, including farming, logging, and hunting, which degrade their condition [12, 27]. *Pan troglodytes ellioti* significantly benefits from this region despite ongoing human-induced deforestation [27]. The reserve's terrain elevation is approximately 366 meters above sea level, and, like many Nigerian forests, it is severely fragmented, with smaller fragments hosting fewer species than larger, contiguous ones. This situation calls for immediate habitat conservation initiatives, as this habitat is vital to biodiversity [13, 26].

The Ise Forest Reserve receives an average of 1380 mm of rainfall annually during the wet season, which lasts from April to October [13]. A small perennial stream is located near the eastern part of the reserve, and the Ogbese River is located on the western part [26]. The annual temperature range is 19°C-33°C, while the annual mean is 25°C–28°C [13]. *Gmelina arborea*, *Tectona grandis*, and *Khaya ivorensis* are some of the plants found in the reserve. At the same time, primates such as the Mona monkey (*Cercopithecus mona*) and the Nigeria-Cameroon Chimpanzee live there [12, 27]. This conservation area is a habitat for the African forest elephant (*Loxodonta africana cyclotis*) and many bird species, and it also protects the yellow-casqued hornbill (*Ceratogymna elata*) [12, 28]. Forest diversity indicates the area's ecological status and, therefore, the need to ensure the area remains protected for as long as possible.

2.2 Data collection

2.2.1 Vegetation assessment

Using a systematic sampling technique described by [29], a field survey was conducted in the Ise Forest Reserve to assess the vegetation structure and diversity. Sampling sites were selected along trails within the disturbed and undisturbed parts of the reserve. In the undisturbed areas, 12 transects were established, and 8 25m by 25m plots were systematically allocated, 200m apart, to capture the vegetation pattern [30]. Unlike the undisturbed areas, the disturbed areas lacked transects, and three sample plots were selected from different trails due to the limited area under investigation. Eleven sampling plots were set up for the woody species survey. All sample plots were located using a Global Positioning System (GPS) to record their geographic coordinates, facilitating further analysis [31].

2.2.2 Acquisition of imageries

Landsat 7 ETM + and Landsat 9 OLI/TIRS satellite images from January 2016 and January 2023, covering the Ise Forest Reserve, were obtained from the United States Geological Survey (USGS) archives at a 30-meter resolution [32]. These images, captured during the early dry season, served as the primary data source for identifying and characterizing the area's current land-use and land-cover patterns. Although the imagery contained a few scanline errors, these were corrected using the Landsat Toolbox in ArcGIS 10.8 (Esri, 2015). The masking process, applied during data extraction, overlapped the study area's shapefile onto the satellite scenes to clip and generate a new raster layer [33]. The

procedure implemented isolation techniques to extract the study area from extraneous image areas, producing an accurate, extensive map of the Ise Forest Reserve. This methodological approach ensured a precise representation and analysis of the region's land-use and land-cover dynamics.

2.2.3 Vegetation analysis

The analysis used PAST version 2.14, Microsoft Excel, and a t-test to evaluate interrelations among phytosociological variables. The study used the Shannon–Wiener diversity index to assess biological diversity because of its widespread recognition and ability to combine species richness and evenness [34]. The diversity index H' combines species counts and their population proportions in ecological communities. The Shannon diversity index was calculated using the standard formula to generate meaningful insights into species distribution patterns and environmental balance (Eq. 1).

$$H' = -\sum_{i=1}^s P_i \ln P_i, \quad (1)$$

Where H' = Shannon diversity index, s = the number of species, P_i = the proportion of individuals of the i th species expressed as a proportion of total cover in the sample, and $\ln$ = the natural logarithm. The Shannon Evenness Index (J) was calculated using the following formula:

$$J = \frac{H'}{H'_{max}} = \frac{H'}{\ln s}, \quad (2)$$

Where J = Shannon equitability or evenness index, H' = Shannon–Wiener diversity index, H'_{max} = the maximum level of diversity possible within a given population, which equals $\ln s$, s = the number of species, and $\ln$ = the natural logarithm. Margalef's index measured species richness [35].

$$\text{Margalef's index} = (S - 1) / \ln N \quad (3)$$

S = total number of species

N = total number of individuals in the sample

$\ln$ = natural logarithm.

2.2.4 Image Pre-processing, Ground Truthing, Validation, and Image Analysis

Landsat satellite imagery of the study area was pre-processed in ArcGIS, including clipping and geometric corrections to align with the Geographic Coordinate System-Minna Datum and Minna Universal Transverse Mercator Zone 31N [36]. The alignment process removed spatial variations to

match the imagery and geographic references precisely. The accuracy improved by incorporating calibration data comprising sensor specifications, altitude readings, position readings, and ground control points (GCPs). Landsat images from 2016 and 2023 were mosaicked to analyze temporal changes, enabling comprehensive land-use/land-cover (LULC) change detection. The analysis method for supervised classification involves grouping pixels into predefined land-use and land-cover categories through analyst-supervised evaluation of spectral features. Field data for classification accuracy were collected using a GARMIN 78S GPS receiver during ground truthing. The coordinates assisted in selecting the training site by converting land-use categories into numerical values, thereby enhancing classification precision [37].

2.2.5 Change detection analysis, transition measurement and measurement of restoration rate.

This research employed GIS analysis and post-classification comparison of satellite imagery to identify land-use and land-cover shifts. Each image was individually categorized, and classifications from various dates were contrasted to form a comprehensive change matrix [38]. The subsequent annual change rate for every vegetation class was then determined using the method outlined by [39].

$$r = \left(\frac{1}{t_2 - t_1} \right) \times \ln \left(\frac{A_2}{A_1} \right) \quad (4)$$

Where r is the change for each class per year, A_2 and A_1 are the class areas at the end and the beginning, respectively, for the period being evaluated (2016 and 2023), and t is the number of years spanning that period (7 years).

3 Results

3.1 Standout species reveal structural dominance

The phytosociological characteristics of woody vegetation in the Ise Forest Reserve showed notable variation among species (Table 1). *Diospyros lotus* exhibited the highest mean height (12.20 ± 0.00 m), the most extensive mean canopy cover (18.60 ± 0.00 m), and the greatest mean diameter at breast height (DBH) (138.13 ± 0.00 cm). *Funtumia elastica* recorded the lowest values, with a mean height (4.42 ± 0.63 m), canopy cover (1.46 ± 0.26 m), and DBH (9.31 ± 2.10 cm). Regarding species frequency, *Ricinodendron heudelotii* had the highest occurrence (55), while *Diospyros lotus* and *Milicia excelsa* appeared only 1) time each.

Table 1
Phytosociological characteristics of woody species in Ise Forest Reserve

Family	Species	Frequency	Height	Canopy	DBH
Fabaceae	<i>Albizia zygia</i>	27	8.15 ± 0.61	4.7 ± 0.52	19.36 ± 1.33
Apocynaceae	<i>Alstonia congensis</i>	3	9.40 ± 2.60	6.50 ± 1.56	20.21 ± 6.82
Sapindaceae	<i>Bligia sapida</i>	2	8.60 ± 0.40	3.00 ± 0.00	13.53 ± 0.16
Malvaceae	<i>Ceibal pentandra</i>	3	6.63 ± 1.98	4.20 ± 0.75	16.13 ± 1.49
Cannabaceae	<i>Celtis mildbraedii</i>	37	12.07 ± 3.47	4.54 ± 0.41	18.77 ± 1.71
Cannabaceae	<i>Celtis zenkeri</i>	5	10.24 ± 0.65	3.14 ± 0.87	19.50 ± 7.19
Sapotaceae	<i>Chrysophyllum albidum</i>	6	9.58 ± 1.37	4.10 ± 1.16	21.70 ± 5.26
Boraginaceae	<i>Cordia millenii</i>	6	9.17 ± 1.31	5.93 ± 1.79	24.31 ± 3.25
Ebenaceae	<i>Diospyros lotus</i>	1	12.20 ± 0.00	18.60 ± 0.00	138.13 ± 0.00
Meliaceae	<i>Entandrofrangma cylindricum</i>	3	8.60 ± 0.91	4.20 ± 1.50	28.33 ± 2.67
Rutaceae	<i>Fagara zanthoxyloidea</i>	6	9.55 ± 1.36	3.07 ± 0.77	22.37 ± 5.49
Rutaceae	<i>Fagara spp</i>	43	8.53 ± 0.44	4.16 ± 0.25	19.88 ± 1.11
Moraceae	<i>Fiscus exasperata</i>	13	7.10 ± 0.51	4.09 ± 0.55	21.19 ± 5.14
Apocynaceae	<i>Funtumia elastica</i>	5	4.42 ± 0.63	1.46 ± 0.26	9.31 ± 2.10
Ulmaceae	<i>Holoptelea grandis</i>	5	9.68 ± 2.05	7.28 ± 2.56	55.04 ± 28.42
Phyllanthaceae	<i>Hymemocardia acida</i>	8	10.93 ± 0.76	4.81 ± 0.54	29.49 ± 3.47
Malvaceae	<i>Mansonia altissima</i>	14	9.01 ± 0.55	3.47 ± 0.26	16.34 ± 2.21
Urticaceae	<i>Musanga cercropioides</i>	3	5.20 ± 1.36	3.53 ± 0.55	16.41 ± 1.91

Family	Species	Frequency	Height	Canopy	DBH
Malvales	<i>Nesogordonia papaverifera</i>	10	6.84 ± 0.75	5.55 ± 0.72	15.50 ± 2.43
Fabaceae	<i>Pterocarpus erinaceus</i>	4	8.80 ± 1.00	4.20 ± 0.82	13.21 ± 1.18
Malvaceae	<i>Pterygota bequaertii</i>	5	7.68 ± 0.55	2.63 ± 0.41	15.12 ± 2.13
Malvaceae	<i>Pterygota macrocarpa</i>	30	8.06 ± 0.33	5.04 ± 1.31	16.77 ± 1.27
Euphorbiaceae	<i>Ricinodendron heudelotii</i>	55	8.95 ± 0.29	4.69 ± 0.30	22.14 ± 1.43
Malvaceae	<i>Steculia rhinopetala</i>	13	11.47 ± 0.98	2.93 ± 0.40	20.12 ± 2.39
Combretaceae	<i>Terminalia superba</i>	3	11.87 ± .245	8.90 ± 3.91	31.00 ± 8.39
Malvaceae	<i>Triplochiton scleroxylon</i>	5	10.64 ± 2.14	4.26 ± 0.58	26.07 ± 4.79

Values signify Mean ± Standard error at 95% Confidence limit; DBH signifies Diameter at Breast Height.

3.2 Height and canopy disparities in undisturbed sites

The phytosociological characteristics of woody species within the undisturbed areas of Ise Forest Reserve are presented in Table 2. *Terminalia superba* had the tallest mean height (14.30 ± 0.50 m), while *Funtumia elastica* recorded the shortest mean height (3.10 ± 0.00 m). *Diospyros lotus* displayed the highest mean canopy cover (18.60 ± 0.00 m) and the largest DBH (138.13 ± 0.00 cm). In contrast, *Pterygota bequaertii* had the lowest canopy cover (1.60 ± 0.00 m), and *Funtumia elastica* had the smallest DBH, measuring (10.03 ± 0.16 cm). In terms of occurrence frequency, *Ricinodendron heudelotii* led with (45), while *Diospyros lotus*, *Musanga cercropioides*, *Pterygota bequaertii*, and *Milicia excelsa* each appeared only 1) time.

Table 2

Phytosociological characteristics of woody species within the undisturbed areas of Ise Forest Reserve

Family	Species	Frequency	Height	Canopy	DBH
Fabaceae	<i>Albizia zygia</i>	16	7.39 ± 0.73	5.19 ± 0.75	19.60 ± 2.06
Apocynaceae	<i>Alstonia congensis</i>	2	11.70 ± 2.10	7.85 ± 1.35	24.38 ± 9.36
Sapindaceae	<i>Bligia sapida</i>	2	8.60 ± 0.40	3.00 ± 0.00	13.52 ± 0.16
Malvaceae	<i>Ceibal pentandra</i>	3	6.63 ± 1.98	4.20 ± 0.75	16.13 ± 1.49
Cannabaceae	<i>Celtis mildbraedii</i>	25	14.42 ± 5.09	4.84 ± 0.53	19.88 ± 2.18
Cannabaceae	<i>Celtis zenkeri</i>	2	10.20 ± 2.00	3.50 ± 2.70	22.50 ± 18.40
Sapotaceae	<i>Chrysophyllum albidum</i>	6	9.58 ± 1.37	4.10 ± 1.58	21.70 ± 5.26
Boraginaceae	<i>Cordia millenii</i>	3	10.50 ± 2.23	7.93 ± 3.05	27.58 ± 5.52
Ebenaceae	<i>Diospyros lotus</i>	1	12.20 ± 0.00	18.60 ± 0.00	138.13 ± 0.00
Meliaceae	<i>Entandrofragma cylindricum</i>	3	8.60 ± 0.92	4.20 ± 1.50	28.33 ± 2.67
Rutaceae	<i>Fagara zanthoxyloidea</i>	6	9.55 ± 1.36	3.07 ± 0.77	22.37 ± 5.49
Rutaceae	<i>Fagura spp</i>	37	8.96 ± 0.47	4.44 ± 0.26	20.52 ± 1.22
Moraceae	<i>Ficus exasperata</i>	11	7.09 ± 0.50	4.21 ± 0.66	22.97 ± 5.78
Apocynaceae	<i>Funtumia elastica</i>	2	3.10 ± 0.00	2.05 ± 0.25	10.03 ± 0.16
Ulmaceae	<i>Holoptelea grandis</i>	4	10.33 ± 2.04	5.98 ± 2.39	54.67 ± 28.54
Phyllanthaceae	<i>Hymemocardia acida</i>	7	11.00 ± 0.87	4.84 ± 11.97	30.56 ± 3.81
Malvaceae	<i>Mansonia altissima</i>	12	9.04 ± 0.63	3.72 ± 0.20	16.88 ± 2.52
Malvaceae	<i>Milicia excelsia</i>	1	9.40 ± 0.00	9.00 ± 0.00	29.29 ± 0.00

Family	Species	Frequency	Height	Canopy	DBH
Urticaceae	<i>Musanga cercropioides</i>	1	7.80 ± 0.00	4.60 ± 0.00	18.30 ± 0.00
Malvales	<i>Nesogordonia papaverifera</i>	8	6.85 ± 0.95	51.63 ± 7.79	16.43 ± 2.48
Fabaceae	<i>Pterocarpus erinaceus</i>	4	8.80 ± 1.00	4.20 ± 0.82	113.21 ± 1.18
Malvaceae	<i>Pterygota bequaertii</i>	1	9.10 ± 0.00	1.60 ± 0.00	23.33 ± 0.00
Malvaceae	<i>Pterygota macrocarpa</i>	20	8.14 ± 0.44	5.88 ± 1.95	17.28 ± 1.53
Euphorbiaceae	<i>Ricinodendron heudelotii</i>	45	9.19 ± 0.33	4.84 ± 0.34	22.33 ± 1.72
Malvaceae	<i>Steculia rhinopetala</i>	12	11.79 ± 1.00	3.08 ± 0.36	20.82 ± 2.48
Combretaceae	<i>Terminalia superba</i>	2	14.30 ± 0.50	12.75 ± 1.15	39.30 ± 2.07
Malvaceae	<i>Triplochiton scleroxylon</i>	5	10.64 ± 2.14	4.26 ± 0.58	26.07 ± 4.80

Values signify Mean ± Standard error at 95% Confidence limit; DBH signifies Diameter at Breast Height.

3.3 Unique structural traits in select undisturbed species

Phytosociological characteristics of woody species within the undisturbed areas of Ise Forest Reserve are presented in Table 3. *Hymenocardia acida* reached the highest mean height (10.40 ± 0.00 m), while *Musanga cercropioides* recorded the shortest mean height (3.90 ± 0.70 m). *Holoptelea grandis* had the most extensive canopy cover (10.20 ± 0.00 m) and the highest DBH (26.93 ± 0.00 cm). *Funtumia elastica* recorded the smallest canopy cover (1.07 ± 0.13 m) and the lowest DBH (8.83 ± 3.80 cm). In terms of occurrence, *Celtis mildbraedii* was the most frequent (12), while *Sterculia rhinopetala*, *Terminalia superba*, *Holoptelea grandis*, *Hymenocardia acida*, and *Alstonia congensis* each appeared only 1) time.

Table 3
Phytosociological characteristics of woody species within the disturbed areas of Ise Forest Reserve

Family	Species	Frequency	Height	Canopy	DBH
Fabaceae	<i>Albizia zygia</i>	11	9.25 ± 1.00	2.69 ± 0.36	19.02 ± 1.41
Apocynaceae	<i>Alstonia congensis</i>	1	4.80 ± 0.00	3.80 ± 0.00	11.87 ± 00
Cannabaceae	<i>Celtis nibreda</i>	12	7.18 ± 0.62	3.91 ± 0.60	16.48 ± 2.70
Cannabaceae	<i>Celtis zenkeri</i>	3	10.27 ± 0.29	2.90 ± 0.15	17.49 ± 7.39
Boraginaceae	<i>Cordia millenii</i>	3	7.83 ± 1.32	3.93 ± 1.66	21.04 ± 3.40
Rutaceae	<i>Fagura spp</i>	6	5.95 ± 0.57	2.48 ± 0.34	15.92 ± 1.79
Moraceae	<i>Fiscus exasperata</i>	2	7.20 ± 2.60	3.50 ± 0.70	11.39 ± 10.38
Apocynaceae	<i>Funtumia elastica</i>	3	5.30 ± 0.61	1.07 ± 0.13	8.83 ± 3.80
Ulmaceae	<i>Holoptelea grandis</i>	1	8.60 ± 0.00	10.20 ± 0.00	26.93 ± 0.00
Phyllanthaceae	<i>Hymemocardia acida</i>	1	10.40 ± 0.00	4.60 ± 000	21.99 ± 0.00
Malvaceae	<i>Mansonia altissima</i>	2	6.93 ± 1.95	2.33 ± 0.52	12.92 ± 1.78
Urticaceae	<i>Musanga cercropioides</i>	2	3.90 ± 0.70	3.00 ± 0.20	15.45 ± 2.88
Malvales	<i>Nesogordonia papaverifera</i>	2	6.80 ± 0.40	6.70 ± 0.90	11.76 ± 8.77
Malvaceae	<i>Pterygota bequaertii</i>	4	7.33 ± 0.55	2.89 ± 0.41	13.07 ± 0.77
Malvaceae	<i>Pterygota macrocarpa</i>	10	7.91 ± 0.47	3.36 ± 0.50	15.76 ± 2.35
Euphorbiaceae	<i>Ricinodendron heudelotii</i>	10	7.91 ± 0.42	4.01 ± 0.58	21.30 ± 1.63
Malvaceae	<i>Steculia rhinopetala</i>	1	7.60 ± 0.00	1.20 ± 0.00	11.62 ± 0.00
Combretaceae	<i>Terminalia superba</i>	1	7.00 ± 0.00	1.20 ± 0.00	14.39 ± 0.00

Values signify Mean ± Standard error at 95% Confidence limit; DBH signifies Diameter at Breast Height.

3.4 Structural and diversity superiority in undisturbed areas

Two hundred and forty-one woody tree stands representing twenty-seven species and nineteen families were documented in the undisturbed areas, compared to seventy-five stands from eighteen species and fourteen families in the disturbed areas. The undisturbed section recorded a higher mean height (9.55 ± 0.56 m), mean canopy cover (4.79 ± 0.23 m), and DBH (21.92 ± 0.96 cm). In contrast, the disturbed area exhibited lower values, with a mean height (7.64 ± 0.26 m), canopy cover (3.35 ± 0.22 m), and DBH (16.77 ± 0.88 cm). Statistical analysis indicated significant differences ($p > 0.05$) between the undisturbed and disturbed areas for height ($t = -3.34$, $p = 0.00$), canopy cover ($t = -1.84$, $p = 0.03$), and DBH ($t = -0.29$, $p = 0.01$) (Table 4). The undisturbed area exhibits a higher Shannon-Wiener index (2.73), Simpson concentration index (0.91), and Margalef richness index (4.74), exceeding those of the disturbed area (2.53, 0.89, and 3.94, respectively).

Table 4

Independent T-test and phytosociological characteristics of tree growth in disturbed and undisturbed areas of Ise Forest Reserve.

Variables	Whole landscape	Undisturbed	Disturbed	t Value	Significant level
Mean height(m)	8.71 ± 0.15	9.55 ± 0.56	7.64 ± 0.26	-3.34	0.00*
Mean canopy cover (m)	4.26 ± 0.58	4.79 ± 0.23	3.35 ± 0.22	-2.27	0.03*
Mean DBH (cm)	26.07 ± 4.80	21.92 ± 0.96	16.77 ± 0.88	-0.27	0.01*
Dominant height (m)	17.40	17.40	13.6		
Dominant canopy cover (m)	18.60	18.60	10.20		
Dominant DBH (cm)	140.04	140.04	35.90		
Area (Km ²)	56.7	33.3	23.4		
Number of individuals/km ²	316	241	75		
No of species	27	27	18		
No of family	19	19	14		
Dominance	0.09	0.09	0.10		
Simpson	0.91	0.90	0.89		
Shannon	2.76	2.73	2.53		
Evenness	0.58	0.57	0.69		
Margalef	4.51	4.74	3.97		
Fisher Alpha	7.06	7.79	7.51		
* implies significant difference (p < 0.05), ns implies non- significant difference (p > 0.05)					

3.5 Rapid forest degradation from 2016 to 2023

From 2016 to 2023, significant changes occurred in the land use/land cover of the Ise Forest Reserve (Fig. 2, Table 5). In the undisturbed area, the secondary forest, which dominated in 2016 at 31.40 km² (97.65%), declined sharply to 14.10 km² (43.85%) by 2023, representing a net loss of 17.31 km² (-53.80%). Conversely, degraded vegetation increased remarkably from 0.14 km² (0.44%) in 2016 to 17.06 km² (53.04%) in 2023, gaining 16.92 km² (+ 52.61%). Farmland showed a modest rise from 0.62 km² (1.91%) to 1.00 km² (3.11%), with a net gain of 0.38 km² (+ 1.20%). In the disturbed area, secondary forest, initially the largest class at 10.84 km² (84.54%) in 2016, decreased drastically to 2.39 km² (18.65%) by 2023, losing 8.45 km² (-65.89%). Degraded vegetation increased substantially from 0.54 km²

(4.22%) in 2016 to 7.24 km² (56.48%) in 2023, marking a gain of 6.70 km² (+ 52.26%). Farmland increased from 1.44 km² (11.25%) to 3.19 km² (24.87%) through an expansion of 1.75 km² (+ 13.62%).

Table 5

Land use /land cover classes for the undisturbed and disturbed areas of Ise Forest Reserve (Area in kilometers)

Class	2016		2023			
	Area	% Proportion	Area	% Proportion	Δ Area	Δ %proportion
Undisturbed area						
Secondary forest	31.40	97.65	14.10	43.85	-17.31	-53.80
Degraded vegetation	0.14	0.44	17.06	53.04	16.92	52.61
Farmland	0.62	1.91	1.00	3.11	0.38	1.20
Total	32.16					
Disturbed area						
Secondary forest	10.84	84.54	2.39	18.65	-8.45	-65.89
Degraded vegetation	0.54	4.22	7.24	56.48	6.70	52.26
Farmland	1.44	11.25	3.19	24.87	1.75	13.62
Total	12.82					

Δ signifies land use/land cover change.

3.6 Dominant conversion from forest to degraded land

The land cover change analysis for the Ise Forest Reserve shows significant differences between undisturbed and disturbed areas (Fig. 3, Table 6). In the undisturbed area, the largest unchanged category was Secondary Forest to Secondary Forest, spanning 14.09 km² (43.88%), while in the disturbed area, it covered 2.37 km² (18.56%). Secondary Forest degradation to Degraded Vegetation dominated both areas, accounting for 16.42 km² (51.16%) in the undisturbed area and 6.12 km² (48.01%) in the disturbed area. Conversion from Secondary Forest to Farmland was minimal in the undisturbed area (0.85 km², 2.63%) but higher in the disturbed area (2.29 km², 17.98%). Restoration from Degraded Vegetation to Secondary Forest was nearly absent, with only 0.00 km² (0.01%) in both areas. Farmland remained unchanged at 0.13 km² (0.42%) in the undisturbed area and 0.64 km² (4.99%) in the disturbed area, while minor changes included Farmland to Degraded Vegetation (0.47 km², 1.48%; 0.78 km², 6.12%).

Table 6
Change detection for the undisturbed and disturbed areas of Ise Forest Reserve

Change detection	Undisturbed area			Disturbed area		
	Area (km ²)	% proportion	Remarks	Area (km ²)	% proportion	Remarks
Secondary forest - Secondary Forest	14.09	43.88	No change	2.37	18.56	No change
Secondary forest - Degraded vegetation	16.42	51.16	Degradation	6.12	48.01	Degradation
Secondary forest - Farmland	0.85	2.63	Degradation	2.29	17.98	Degradation
Degraded vegetation - Secondary Forest	0.00	0.01	Restoration	0.00	0.01	Restoration
Degraded vegetation - Degraded vegetation	0.12	0.38	No change	0.29	2.28	No change
Degraded vegetation - Farmland	0.01	0.04	No change	0.25	1.93	No change
Farmland-Secondary Forest	0.00	0.00	Restoration	0.02	0.12	Restoration
Farmland - Degraded vegetation	0.47	1.48	No change	0.78	6.12	No change
Farmland - Farmland	0.13	0.42	No change	0.64	4.99	No change

3.7 Disturbed areas show higher degradation and lower recovery

The degradation and restoration dynamics in the undisturbed and disturbed areas of the Ise Forest Reserve show variation across land-use/land-cover classes (Table 7). The secondary forest experienced a reduction in both undisturbed (-0.11) and disturbed (-0.21) areas, with a restoration rate of 10.00%, the highest yet, but also the most significant adverse change in the disturbed area (-0.21). Degraded vegetation recorded increases in undisturbed (0.68) and disturbed (0.37) areas, with the undisturbed area showing the most significant positive change (0.68). In contrast, farmland expansion was least prominent in undisturbed areas (0.07), whereas disturbed areas showed a slight increase (0.11).

Table 7
Degradation/restoration changes of the undisturbed and disturbed areas of Ise Forest Reserve.

Land use/land cover class	Undisturbed	Disturbed	% Rate of restoration
Secondary forest	-0.11	-0.21	10.00
Degraded vegetation	0.68	0.37	
Farmland	0.07	0.11	

4 Discussion

The phytosociological analysis of woody species in the Ise Forest Reserve revealed differences in vegetation structure and composition between undisturbed and disturbed areas, indicating the effects of human activities on the forest ecosystem [40]. The undisturbed areas had more tree stands, species, and families than the disturbed areas, indicating how anthropogenic activities affect forest biodiversity. This agreed with the findings of [41], who noted that species richness and density decreased in the disturbed forest habitats in Nigeria. Such patterns demonstrate the importance of natural forests in maintaining ecological diversity and stability.

Regarding structure, the undisturbed areas had better characteristics, such as higher mean tree height, canopy cover, and diameter at breast height (DBH), than their counterparts in the disturbed areas [40]. These features indicate that undisturbed forests, free of human pressure, can support more mature and larger trees, thereby increasing ecosystem functions and services. On the other hand, the disturbed areas had lower structural attributes, indicating that habitat degradation is ongoing. Similar trends were reported by [42] in Taraba State, where logging severely deteriorated forest properties. Shielding undisturbed forests is essential for their ecological functions and habitat quality.

Species occurrence patterns also showed the effects of disturbances on diversity. The resilient species include *Ricinodendron heudelotii*, which had high frequency in undisturbed and disturbed areas, according to [40]. However, economically important species, such as *Milicia excelsa*, were rare in disturbed areas due to overexploitation. [43] noted that the overexploitation of financially valuable species reduces biodiversity in forest landscapes. These findings showed that disturbances select particular species, exerting pressure on the overall species composition and, therefore, on the stability of the ecosystem.

The differences in species richness and structural integrity between the undisturbed and disturbed areas conformed to the global patterns in tropical forest conservation [40]. Higher biodiversity and structural resilience in undisturbed forests supported the need for focused conservation actions for these habitats. Therefore, it is essential to implement measures to prevent further degradation and restore disturbed areas, ensuring the sustainable use of forest resources [41]. The findings also supported previous studies, such as those by [44], which noted that secondary succession species are necessary for the

resilience of disturbed ecosystems. Nevertheless, this resilience is exceptionally low in the heavily degraded Ise Forest Reserve.

The independent t-test results showed a statistically significant difference in the tree growth characteristics between the disturbed and undisturbed areas of the Ise Forest Reserve. Tree height, canopy cover, and diameter at breast height were significantly higher in the undisturbed areas. These findings support previous studies showing that anthropogenic activities hurt forest structure and tree growth. For example, [45] showed that undisturbed forests in the Ago-Owu Forest Reserve in Southwestern Nigeria had higher structural diversity and species richness than disturbed forests affected by logging and agriculture. Biodiversity further underscores ecological disparities, with undisturbed areas having higher species richness and diversity. This pattern aligned with the findings of [46], who reported higher biodiversity and ecosystem stability in minimally disturbed Ghanaian tropical forests. Similarly, [47] linked the lower species evenness and diversity in the disturbed forests to habitat fragmentation and resource competition.

The slightly higher Simpson concentration index indicated that the undisturbed areas have a more stable species composition. This was consistent with results from Ghanaian forest reserves, where undisturbed sites showed greater ecological stability and species composition than disturbed sites [46]. [47] also discussed minimizing disturbances to ensure forest ecosystems sustain their structure and function. These results showed the need to implement proper conservation measures, such as the Ise Forest Reserve, to combat pressures and protect the forest reserves' ecological integrity. Sustainable management practices, such as controlled logging and community conservation programs, have successfully improved forest health and biodiversity [46]. It is essential to conserve undisturbed forests to maintain ecological services and preserve regional biodiversity, as [45] suggests.

Over 2016–2023, the LULC patterns of the Ise Forest Reserve indicated that the landscape is undergoing significant ecological changes because of increasing anthropogenic pressure. The undisturbed areas showed decreased secondary forest and increased degraded vegetation, suggesting unsustainable activities such as illegal logging and shifting cultivation, as in other Nigerian forest reserves [48]. A slight expansion of agricultural land also demonstrated that agricultural pressure is a significant factor in the conversion of natural habitats [49]. These changes were even more extreme in the disturbed areas, with significant declines in secondary forests and substantial expansions of agricultural lands and degraded vegetation. Similar processes have been observed in the Akure Forest Reserve, where forest cover is converted into other land cover types [50].

These trends were consistent with those in Nigerian forest ecosystems, where population and agricultural pressures, and the lack of policy implementation for conservation, contribute to forest degradation [51]. The significant increase in degraded vegetation and farmland in both disturbed and undisturbed areas clearly demonstrated the need for targeted restoration and sustainable land management actions. Measures such as agroforestry, community involvement, and remote-sensing-based monitoring may help reduce these losses [49]. It is therefore essential to strengthen enforcement

mechanisms and develop adaptive approaches to protect Nigeria's forest resources and reduce current pressures on forest degradation. Thus, these findings suggested a need to take the initiative to address the socio-ecological pressures on forest ecosystems.

The change-detection analysis of the Ise Forest Reserve showed that land-cover change differs between undisturbed and disturbed zones, reflecting varying levels of human pressure. The undisturbed area was characterized by the persistence of secondary forest, indicating better ecological health. On the other hand, the disturbed zones exhibited elevated levels of degradation and conversion of secondary forests into agricultural land use, indicating higher anthropogenic pressure. These findings aligned with earlier studies on tropical forest reserves, which have reported higher rates of degradation and agricultural pressure at disturbed sites [52]. Both zones experienced widespread secondary forest degradation to degraded vegetation, but the disturbed zones were more affected, thus making these ecosystems more vulnerable to stressors. [53] observed that human activities, such as logging and farming, contribute to forest degradation in Nigerian reserves, thereby calling for urgent action.

The low conversion rate of secondary forest to farmland in undisturbed areas may be attributed to more conservative conservation practices and limited accessibility, in contrast to the disturbed zones, where farmland persistence and transition to degraded vegetation are observed. [53] attributed these trends to weak enforcement mechanisms that allow rampant agricultural encroachment into Nigerian reserves. The lack of restoration of degraded vegetation to secondary forest in both areas indicates that natural regeneration is inadequate, a situation that is a cause for concern and has been highlighted by [54], who argued that targeted restoration of the degraded habitats is necessary. Moreover, the results agreed with those of [55], who suggested that community engagement in reforestation may improve environmental conditions in tropical reserves and thus contribute to sustainable management of land resources and biodiversity conservation.

Thus, the dynamics of degradation and restoration in the Ise Forest Reserve differed, reflecting the complexity of processes in undisturbed and disturbed areas of the forest. Some regions have shown high restoration rates across land-use/land-cover categories, particularly in secondary forests. However, this positive development was offset by counter-trends in the disturbed areas, where pressures such as logging and encroachment remain rampant. These findings agreed with studies showing that forest regeneration in disturbed zones is slower because natural regrowth is hindered by intense land-use pressures [56]. Furthermore, degraded vegetation was observed in both undisturbed and disturbed areas, indicating a general deterioration of the ecosystems. The greater increase in the undisturbed zones may be due to edge effects or minor disturbances, which are consistent with studies showing that poor buffer zones and non-enforcement of regulations expose protected areas to degradation [57].

Farmland showed slight increases in undisturbed and disturbed areas due to subsistence agricultural encroachment, a widespread problem in Nigerian forest reserves [57]. Socioeconomic pressures may also drive the conversion of marginal lands for agricultural production, thereby driving these changes. Although the rates are low, they point to the ongoing conflict between conservation and people's

livelihoods. These findings supported earlier works that have discussed agricultural encroachment as a continuous threat to conservation efforts [57]. These tendencies revealed the need for practical management actions, including enhancing enforcement and buffer zone management to guarantee the sustainable protection and rehabilitation of forest ecosystems within the reserve.

5 Conclusions

This study investigated how natural regeneration interacts with human-made disturbances to affect forest recovery patterns in Ise Forest Reserve, Nigeria. Phytosociological analysis showed that undisturbed forests had superior structure and composition compared to disturbed forests, including more species, higher percent cover, and larger diameter at breast height. These differences showed that intact forests are vital to ecological stability and biodiversity. *Ricinodendron heudelotii* was the dominant species that showed resilience across zones, whereas the economically valuable species *Milicia excelsa* was almost absent from the disturbed areas due to over-exploitation. The statistical analysis showed significant differences in tree growth parameters, biodiversity indices, and habitat quality between the two zones. These results, therefore, revealed the effects of human activities on forest ecosystems and the need to adopt conservation strategies.

Land cover and land use analysis between 2016 and 2023 revealed significant ecological changes driven by logging, agricultural expansion, and weak enforcement of conservation measures. The undisturbed zones revealed significant secondary forest degradation, increased degraded vegetation and almost no farmland expansion. The disturbed zones showed high forest loss, high farmland persistence and low natural regeneration. These trends depict the general issues in Nigerian forest ecosystems worsened by population stress and weak policy implementation. Although some restoration actions have been observed in certain areas, they are insufficient to offset the high rate of degradation. Organized reforestation, agroforestry, and increased enforcement are critical to reducing current losses and promoting sustainable forest management. The study therefore revealed the necessity of adaptive conservation management to protect the ecological capital and species diversity of the Ise Forest Reserve and to confront socio-economic pressures.

Abbreviations

The following abbreviations are used in this manuscript:

DBH	Diameter at Breast Height
MEA	Millennium Ecosystem Assessment
FAO	Food and Agriculture Organization (of the United Nations)
NDVI	Normalized Difference Vegetation Index

EVI	Enhanced Vegetation Index
UN	United Nations
USDA	United States Department of Agriculture
GPS	Global Positioning System
ETM	Enhanced Thematic Mapper
TIRS	Thermal Infrared Sensor
OLI	Operational Land Imager
USGS	United States Geological Survey
PAST	Paleontological Statistics
GCPs	Ground Control Points
LULC	Land-Use/Land-Cover
GIS	Geographic Information System

Declarations

Consent for publication

Not applicable

Ethical approval and consent to participate

Not applicable. The study does not involve any human participants, secondary data, animals, plants or plant parts.

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The authors declare no conflicts of interest.

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Author Contribution

Study conception, OEO and EAO; data collection, OEO; methodology, OEO and EAO; computation, OEO and KOR; writing, OEO, EAO and ELA; review, OEO and ELA; editing, OEO and ELA; formal analysis, OEO and EAO.

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Data Availability

Requests for the data used in this research should be made to the corresponding author.

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Figures

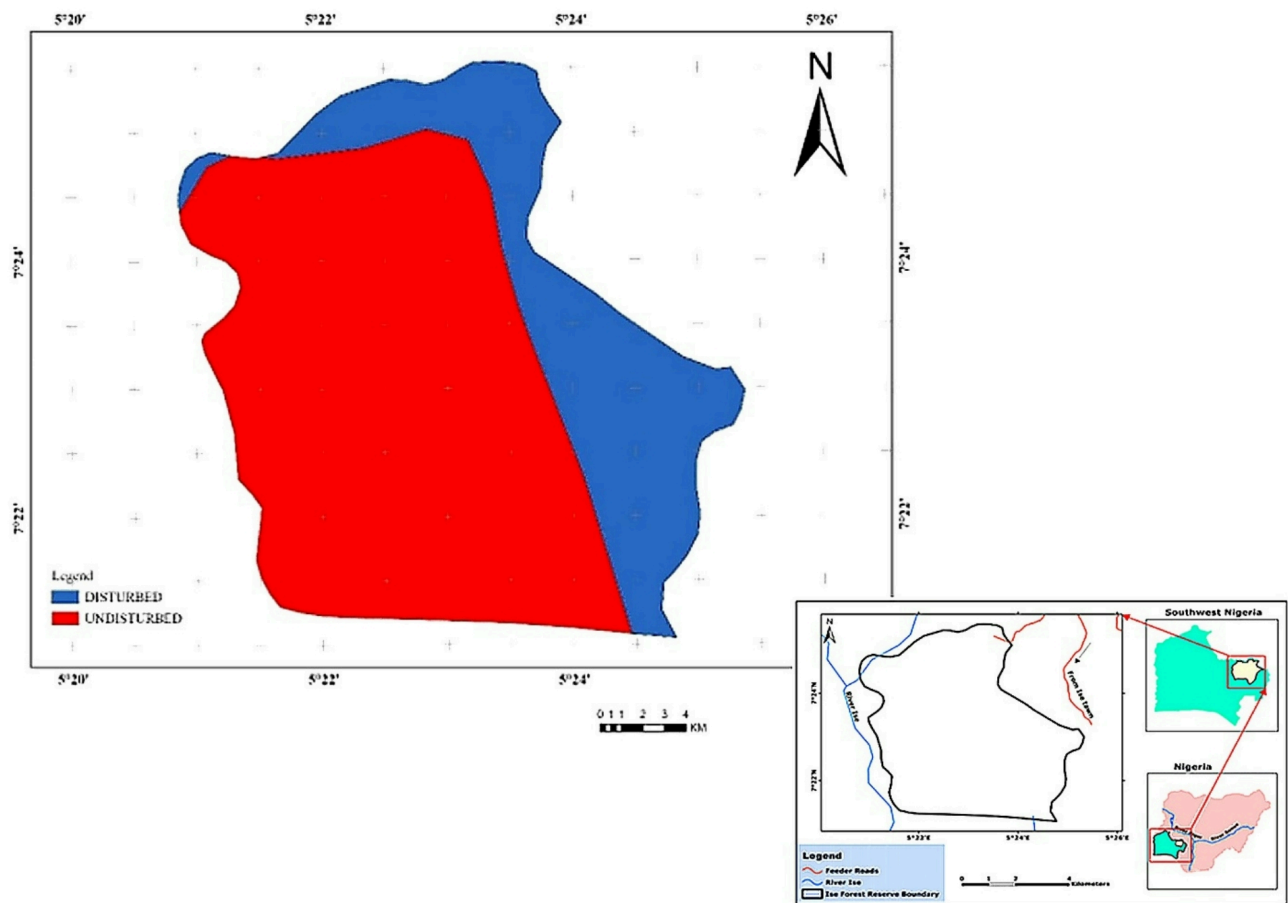


Figure 1

Disturbed and undisturbed areas of Ise Forest Reserve in Ekiti State, Nigeria

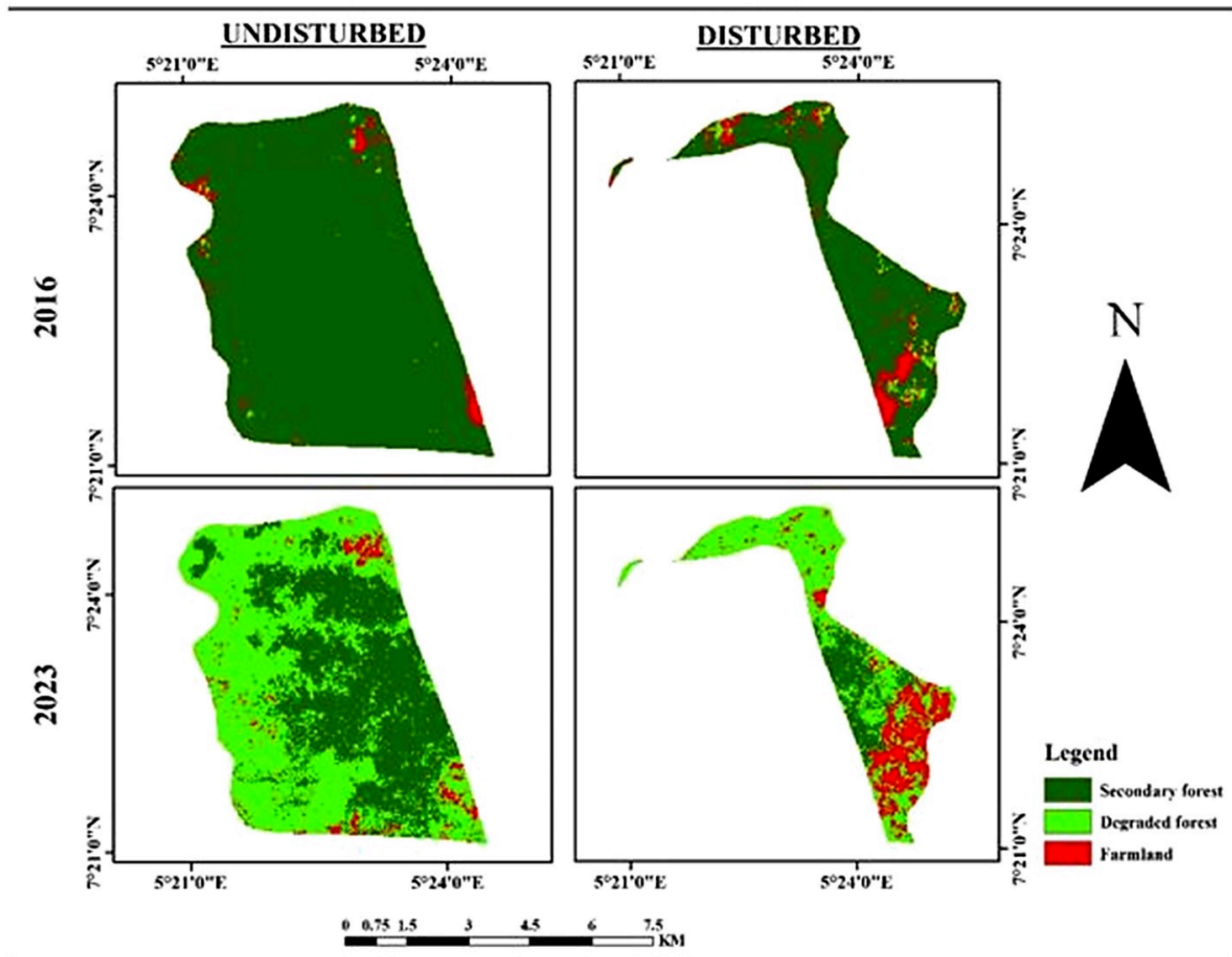


Figure 2

Land use/land cover of the disturbed and undisturbed area of Ise Forest Reserve, Nigeria, in 2016 and 2023.

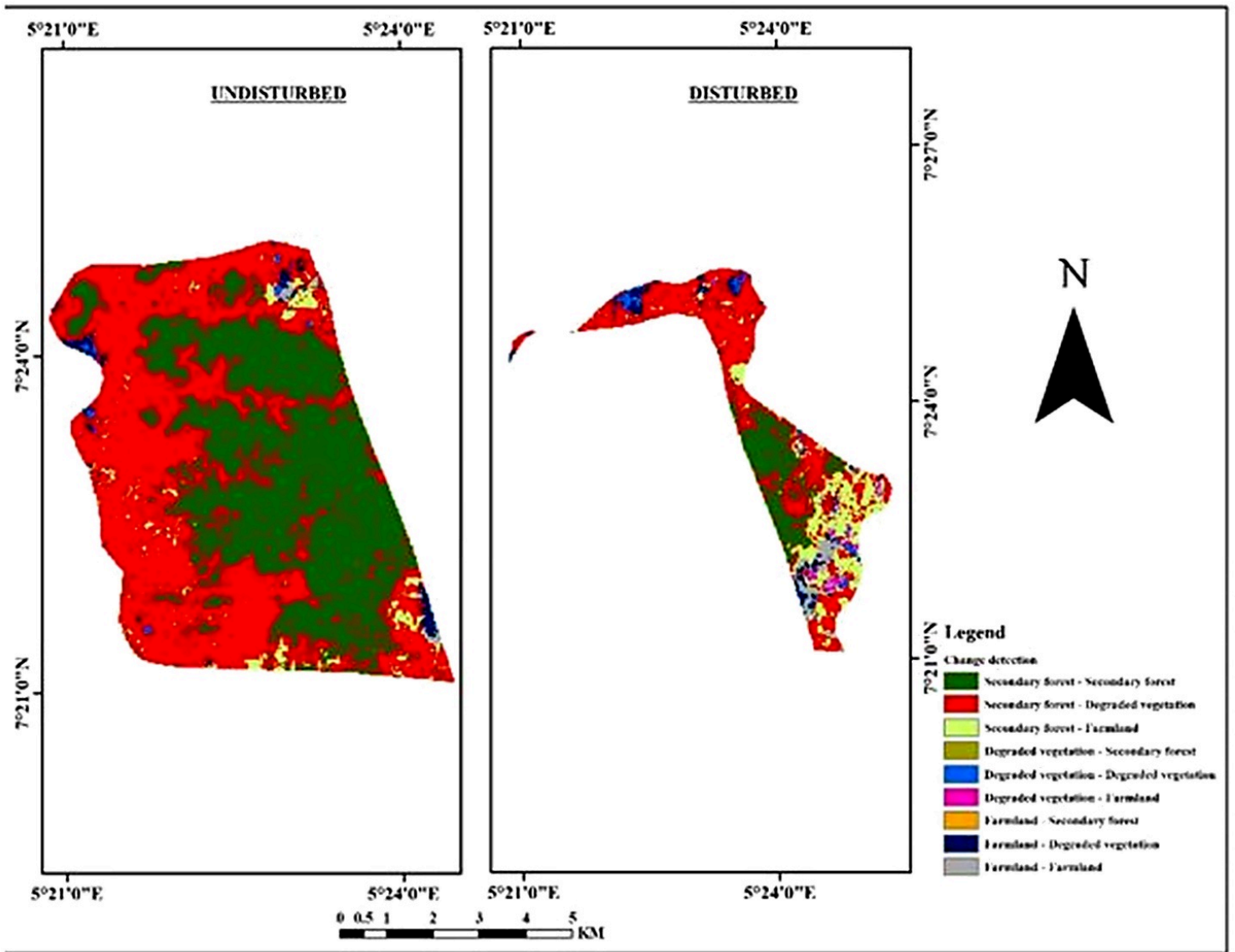


Figure 3

Transition matrix of the land use/land cover of the disturbed and undisturbed area of Ise Forest Reserve, Nigeria.