



Investigating forest fragmentation through earth observation datasets and metric analysis in the tropical rainforest area

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Abstract

Extensive mining operations, deforestation, jhumming, and soil erosion coupled with population stress in the study area have put an adverse effect on its forest resources. This study investigates the transition in forest cover classes and its fragmentation in the Jaiñtia Hills District of Meghalaya (India). Satellite data (multispectral images from Landsat 5 and 8) for 1995, 2001, 2007, and 2015 were classified using the supervised classification method. Landscape metrics from the classified images were calculated using FRAGSTATS. The overall accuracy of classification was found to be 87.50% (1995), 87.50% (2001), 85.00% (2007) and 91.67% (2015), respectively. The results revealed an increase in dense forest with an increase in the patch number from 1995 to 2007. Additionally, a decrease in non-forest cover with an increase in the number of patches from 2001 to 2015 was observed which further suggests fragmentation. It has been reported that 8.13% of the dense forest increased and 19.47% of non-forested areas decreased during the study period. Overall, this study highlights the changes in the distribution of forest area which could aid policy makers to adopt appropriate forest conservation strategies.

Keywords Forest cover · FRAGSTATS · Forest fragmentation · Class metrics · Deforestation · Soil erosion · Jaiñtia Hills (India)

1 Introduction

Fragmentation can be defined as a division of the landscape into smaller isolated patches which decrease the natural habitat in a landscape. Loggers, commercial cultivators, settlement planners, infrastructure developers, and expansion in the population are some of the destructive trends maximizing forest fragmentation at an alarming rate [1]. These aforementioned factors severely expose the

forested area leading to vulnerability of wildlife species as well as disturbing the entire forest ecosystem.

Mining operations can also contribute to forest fragmentation which is apparent in many regions of India including the state of Meghalaya. Meghalaya possesses huge reserves of various minerals including coal, limestone, kaolin, clay, granite, glass-sand, uranium, etc. Over-exploitation of such resources, e.g. extensive coal mining [2] has led to a drastic change in the land use/land cover (LULC) of the state.

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The district of Jaiñtia Hills is among the most adversely affected area of the state of Meghalaya in regard to forest fragmentation resulting from coal mining. Extraction of coal is carried out by the primitive method known as rat hole mining. Major coal-bearing areas in this district are Sutnga, Shkentalang, Sohkympkor, Lakadong, Ladrymbai, Bapung, Khliehriat, Musiang Lamare, Iooksi, and Jaraiñ [3].

Use of technology along with appropriate policies is need of the hour for assessing, inventorying, and restricting over-exploitation of minerals towards conserving the forest ecosystem. In the last two decades, integration of remote sensing (RS) data with geographic information systems (GIS) made noteworthy contributions towards the assessment of spatial–temporal patterns and processes of forest ecosystems in criteria-based decision-making and selection of the optimal alternative [4, 5]. Numerous researchers have developed metrics to measure multiple aspects of landscape patterns [6–12]. FRAGSTATS 4.2.1 has emerged as one of the most promising tools for performing spatial analysis to compute the disturbance index [12].

Considering the aforementioned issues with regard to forest fragmentation particularly in the district of Jaiñtia Hills, this study aims to analyse the spatial and temporal pattern of forest fragmentation during the past two decades using FRAGSTATS model along with RS and GIS techniques.

2 Materials and methods

2.1 Study area

The study area (district of Jaiñtia Hills) consists of the eastern part of Meghalaya with a geographic area of 3819 km². It is situated between east longitude 91.59° and 92.45° and between north latitude 25.3° and 25.45° (Fig. 1). It covers around 17% of the total area of Meghalaya State. The elevation of the district ranges between 1050 m and 1350 m. Jaiñtia Hills has a comparably flatter topography with a mild gradient. The district has a forest area of 1540.6 km², i.e. about 40% of the total geographic area [13].

Study area is enclosed on the north and east by the state of Assam, on the south by Bangladesh, and on the west by the East Khasi Hills District of Meghalaya. Jaiñtia Hills District is divided into five blocks consisting of Amlarem, Thadlaskeiñ, Laskeiñ, Khliehriat, and Saipung [14]. Amlarem is the smallest block in the district with a population of 43,844, whereas Thadlaskeiñ is the biggest block with a population of 137,939 [15]. Myntdu is one of the major water bodies of the study area (Appendix 1). The drainage pattern of the study area is sub-parallel to parallel. It is being controlled by joints and faults as indicated

by the straight courses of the rivers and streams with deep gorges.

2.2 Data used and methodology

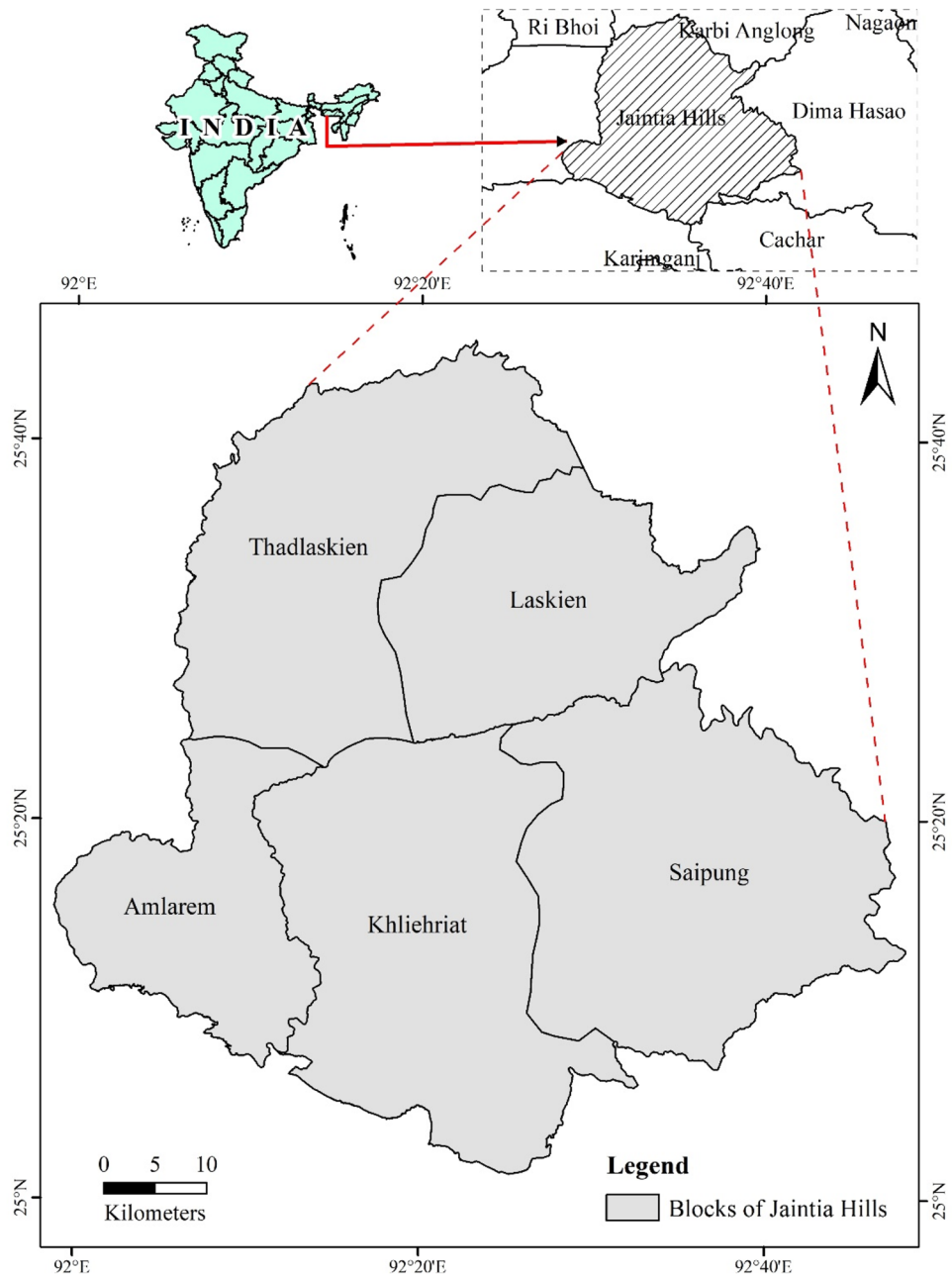
Satellite images from Landsat 5 and 8 for the period 1995–2015 were used towards spatio-temporal analysis of Jaiñtia Hills District, Meghalaya. The study area is covered by path 136 and row 42/43 of Landsat images. Details of the satellite images utilized in the present study are provided in Appendix 2. The Landsat images utilized in the present study were acquired for the month of March to minimize the significant exposure of the sun angle on the northern slope. Top of atmospheric (ToA) calibration was performed to obtain the reflectance values on a scale of 0 to 1. Many studies have used remote sensing data based on classification algorithms for the extraction of forest land cover information [16, 17]. Satellite images were classified using the supervised classification method with a maximum likelihood algorithm [18–21]. Major land cover classes of the study area were categorized into dense forest, open forest, scrub forest, and non-forest (the wastelands, built-up, croplands, and water bodies were clubbed in the non-forest category). After that, post-classification techniques were used which help in removing noises and improve the quality of the classified image. It was achieved by sieve, clump, elimination, and majority filter tools which has enhanced the output image quality before comparing two different time period images. A description of various land cover classes is provided in Appendix 3.

Change analysis was performed to assess changes in the past decade of 1995–2015. A colour coded scheme was adopted to delineate positive change with green colour (non-forest to forest change) as well as negative change with red colour (forest to non-forest change). A change matrix for different land cover classes was calculated. The positive and negative changes were also identified at block-level in the study area. Lastly, the data were processed using FRAGSTATS 4.2.1 software to analyse the spatial metrics and comprehend the fragmentation of various land covers. The methodology followed in the present study is summarized in Fig. 2.

2.3 Computation of landscape metrics

Landscape ecology is the interaction between various elements of a landscape, and how these patterns/interactions change over time [22–25]. Landscape metrics explores site variability and the effects of fragmentation. Several studies have shown that landscape metrics have the potential for analysing the spatial arrangement of LULC and monitoring the spatio-temporal changes [26–32]. However, a selection of appropriate key approaches must be done in

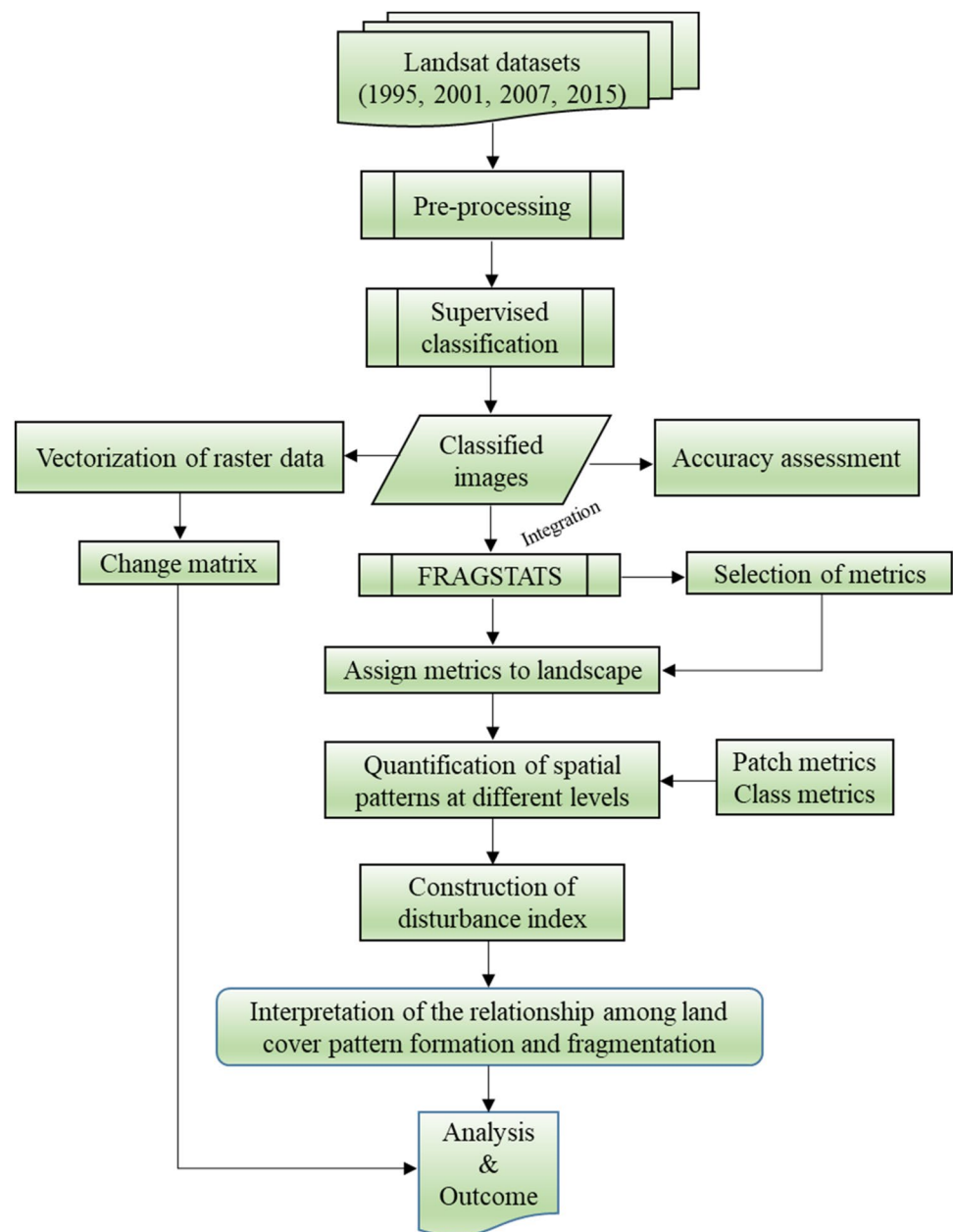
Fig. 1 Study area map: Jaiñtia Hills, Meghalaya (India)



order to avoid redundant information of the landscape metrics [26, 33–37]. A set of key metrics that can be used to characterize landscape structure includes Class Area (CA), Percentage of Landscape (PLAND), Number of Patches (NP), Patch Density (PD), Largest Patch Index (LPI), Total Edge (TE), Edge Density (ED), Largest Shape index (LSI), Inter-juxtaposition Index (IJI) and MESH. Quantification of landscape habitat connectivity can be done on various spatial levels based on patch, class, and landscape [38] (Appendix 4). In this study, the analysis of fragmentation was focused at the class level. To analyse the process of fragmentation, the LULC raster maps were subjected to

FRAGSTATS 4.2.1 [39, 40]. Ten parameters underclass metrics that included CA, PLAND, NP, PD, LPI, TE, ED, LSI, IJI, and MESH were selected using 8-neighbouring rule [36, 41–44] (Appendix 5). This gives the required flexibility to assess the landscape pattern and landscape connectivity [45]. PLAND, NP, PD, LPI, TE, and ED delineate amply the extent of fragmentation [26, 35, 46]. NP indicates the rate of loss denoting the information about the area, shape, or distribution of the fragments. The density of patches is computed using PD metrics, ultimately indicating the level of fragmentation. IJI is used for identifying the intermixing of different patch types irregularly.

Fig. 2 Flowchart of methodology



3 Results and discussion

3.1 Accuracy assessment

Accuracy assessment of land cover maps (1995, 2001, 2007, and 2015) was performed to obtain user accuracy, producer accuracy, overall classification accuracy, and kappa statistics using equalized random sampling strategy [47]. Additionally, 50 ground control points were utilized for comparing the accuracy of land cover maps. The overall classification accuracy was found to be 87.50, 87.50, 85.00, and 91.67% for 1995, 2001, 2007, and 2015, respectively (Table 1).

Table 1 Accuracy assessment of supervised classification method

Year-wise analysis	Classification accuracy (%)	Kappa (K [^])
1995	87.50	0.8333
2001	87.50	0.8333
2007	85.00	0.7887
2015	91.67	0.8889

3.2 Spatial extent of forest cover classes (1995–2015)

Forest cover change throughout the study period is presented in Table 2 and Fig. 3, respectively. Based on

temporal forest change analysis for the period 1995–2001, an increase in dense forest cover has been observed which is about 13.18% (764.98 to 1269.64 km²). Similarly, during the period 2001–2007, about 1.5% (1269.64 to 1327.23 km²) dense forest has increased. However, for the year 2007–2015, dense forest cover declined considerably to 250.63 km² (1327.23 to 1076.60 km²) which is 6.55%. The maximum area (34.64%) for dense forest was observed in the year 2007. However, in the past 20 years, approximately 19.45% of the area lost its forest cover (Fig. 3). Approximately 9.79% (928.27 to 553.21 km²) of the open forest has decreased for the period 1995–2001. Moreover, a decrease of approximately 6.18% (553.21 to 790.16 km²) has been observed for the period 2001 to 2007. However, an increase of 14.75% (790.16 to 1355.20 km²) in the open forest was observed during 2007–2015.

Scrub forest indicated an overall decrease in its area during 1995–2007 with a slightly abrupt increase (0.48%) between 2007 and 2015 covering an area of 18.52 km² (9.09 to 27.61 km²). The non-forest area exhibited a decreasing trend from 1995 with an area of 2118.06 km² (55.28%) to 1989.44 km² (51.93%) in 2001 followed by a spontaneous decline of 1704.68 km² (44.49%) in 2007 and 1372.18 km² (35.81%) in the year 2015 (Table 2).

Table 2 summarizes the changes in forest cover. Increase in dense forest apparent between 1995 and 2007 can be attributed to the intensification of commercial plantations

such as Areca nut (*Areca catechu*), bamboo (*Bambusa sp.*), banana (*Musa paradisiaca*), black pepper (*Piper nigrum*), and canes (*Calamus sp.*) cultivated with *Acquilaria* [48]. Betel leaf is an important cash crop in Meghalaya with high demands across local, national and international markets which are planted in lower altitude, i.e. low-lying area of Khliehriat block near Bangladesh border. Secondly, it may be due to plantation via afforestation programmes under the social forestry division. Three forest divisions of Khasi, Jaiñtia, and Garo Hills were under programmes such as social forestry where the forest department carried out plantation in more than 1645 km² area [49]. Although [50] reported a decrease in a dense forest in the study area, the result obtained for this area is same as statistics produced by the Forest Survey of India (FSI) where forest area increased from 1995 to 2007 with a slight decrease in forest cover from 2007 to 2015 [51]. In general, during 1990–2000, India's forest cover increased at the rate of 0.22% per year and 0.46% during 2000–2010. As reported by the India State of Forest Report (ISFR), India's forest cover has increased by 2000 km² [52]. Increase in forest area was also observed between 2015 and 2017 in parts of the southern states of Karnataka, Kerala, and Andhra Pradesh due to plantation activities [53]. It was reported that from the year 2007 onwards larger scale of limestone mining, and production activity was started by the cement factories in Jaiñtia Hills [54]. This could be among the

Table 2 Temporal land cover change analysis for different years of Jaiñtia Hills in terms of area (km²)

Land cover classes	1995		2001		2007		2015	
	Area	Area	Area	Area	Area	Area	Area	Area
	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)
Scrub forest	20.35	0.53	18.86	0.49	9.09	0.24	27.61	0.72
Open forest	928.27	24.23	553.21	14.44	790.16	20.62	1355.20	35.37
Dense	764.98	19.96	1269.64	33.14	1327.23	34.64	1076.60	28.09
Non-forest	2118.06	55.28	1989.44	51.93	1704.68	44.49	1372.18	35.81
Total	3831.66	100	3831.16	100	3831.16	100	3831.59	100

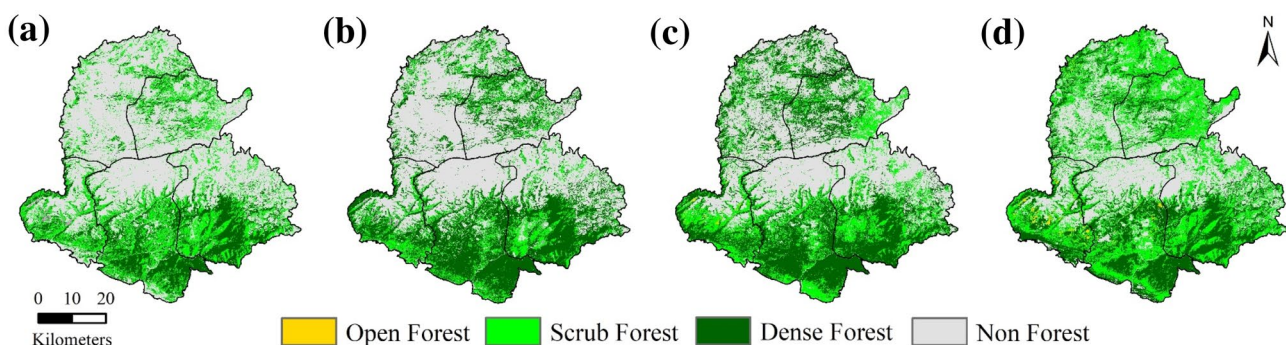


Fig. 3 Classified imageries for the years (a) 1995, (b) 2001, (c) 2007, and (d) 2015 using a supervised classification method

probable reasons for the decrease in dense forest cover from 2007 to 2015. Such activities create canopy gaps resulting in the spread of invasive exotic species which adversely affects faunal species of the area. Mining activities leave significant ecological, economic and social footprints much beyond the physical boundaries of mines by disrupting continuous forest patches [55, 56].

3.3 Matrix of land cover change

The square transition matrix gives insights into the degree of change of classes when the two images acquired in different years are directly compared to assess increase and decrease in classes. In this study, a change matrix table was generated by the intersection of two datasets viz., 1995–2001, 2001–2007, 2007–2015, and 1995–2015, respectively. The results were summarized using tables and figures that aided in the comparison and interpretation of the results for the area and its block.

3.3.1 LULC changes (1995–2001)

Land cover change matrix using the classified data for the years 1995 and 2001 is presented in Table 3. It is apparent that the total area (764.98 km²) of dense forest during 1995–2001 has been converted to open forest (52.54 km²), scrub forest (0.24 km²), and non-forest area (36.31 km²) ultimately reducing the dense forest area to 675.90 km². In case of open forest, a large portion of its area got converted into dense forest (428.84 km²), followed by non-forest (136.64 km²) and scrub forest (9.13 km²). This conversion reduced the open forest area from 928.27 to 428.84 km². A reduction in scrub forest area from 20.35 to 6.99 km² was also apparent where 8.70 km² of its area got converted into open forest, 2.56 km² to non-forest and 2.10 km² to dense forest, contribution of 162.94 km² from non-forest and 2.10 km² of scrub forest which got converted to the dense forest adding up its area to 1269.77 km². The diagonal axis of the land cover change matrix represents no changing area. The change category (non-forest to forest and forest to non-forest) is presented in Fig. 4.

3.3.2 LULC changes (2001–2007)

The land cover change matrix was analysed using the classified thematic output for the years 2001 and 2007. It is apparent that out of the total dense forest area of 1269.64, 935.44 km² (73.68%) of the dense forest was intact (Table 4). A large area of 271.34 km² (21.37%) has been converted to open forest, 0.27 km² to scrub forest, and 62.59 km² (4.9%) to non-forest. During this period, it was also observed that 210.36 km² of non-forest area followed by 178.08 km² of open forest area and 3.35 km² area of scrub forest area converted to the dense forest area. Therefore, the total dense forest area gained during 2001–2007 was 57.59 km², an increase from 1269.64 to 1327.23 km². The area under the open forest category increased to 790.16 km² (20.62%). Scrub forest area reduced to 9.09 km² (0.24%) and non-forest reduced to 1704.69 km² (44.49%). The change category (non-forest to forest and forest to non-forest) is presented in Fig. 5.

3.3.3 LULC changes (2007–2015)

The land cover change matrix was analysed using the classified thematic output for the period 2007–2015. It is apparent that out of the total dense forest area of 1327.68, 779.88 km² (73.68%) of the dense forest was undisturbed (Table 5). However, its large area expanding to 468.62 km² (35.29 %) got converted to open forest, 4.51 km² to scrub forest, and 74.67 km² (4.9%) to non-forest, respectively. During this period, it was also observed that about 64.45 km² of non-forest, 231.97 km² of open forest, and 0.30 km² area of scrub forest got converted to dense forest area (Fig. 6). Overall, a decrease of 251.09 km² area was apparent in dense forest during 2007–2015. Area under open forest and scrub forest categories increased from 790.61 to 1355.20 km² and 9.08 to 27.61 km², respectively. However, a decrease from 1704.23 to 1372.18 km² in the non-forest area was apparent during this period (Fig. 7)

Table 3 Change matrix on land cover class between the year 1995 and 2001

Land cover categories	1995 ----->				
	Non-forest	Dense forest	Open forest	Scrub forest	Total
2001 ----->					
Non-forest	1813.75	162.94	138.89	2.48	2118.06
Dense forest	36.31	675.90	52.54	0.24	764.98
Open forest	136.64	428.84	353.66	9.13	928.27
Scrub forest	2.56	2.10	8.70	6.99	20.35
Total	1989.26	1269.77	553.78	18.84	3831.66

Fig. 4 Change in forest class map for the year 1995 to 2001

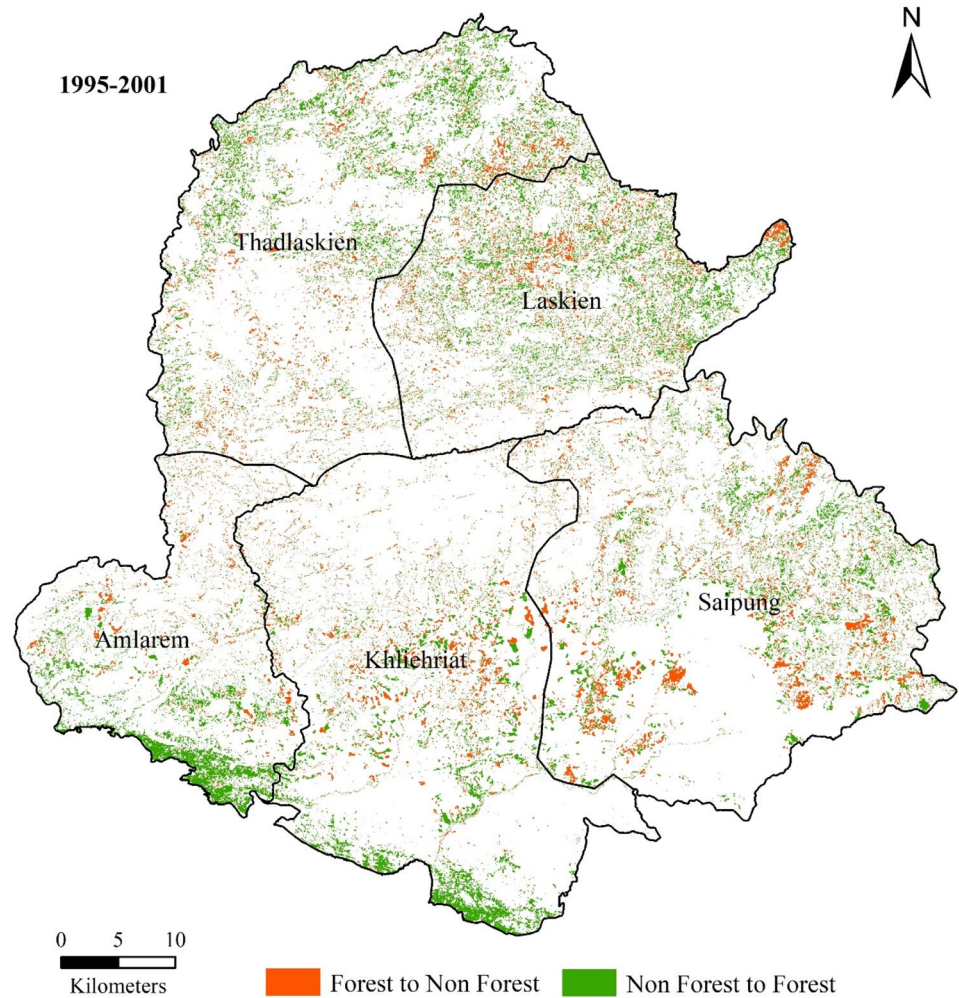


Table 4 Change matrix on land cover class between the year 2001 and 2007

Land cover categories	2001 ----->				
	Non-forest	Dense forest	Open forest	Scrub forest	Total
2007 ----->					
Non-forest	1583.46	210.36	191.42	4.20	1989.45
Dense forest	62.59	935.44	271.34	0.27	1269.64
Open forest	57.91	178.08	316.00	1.24	553.21
Scrub forest	0.73	3.35	11.40	3.38	18.86
Total	1704.69	1327.23	790.16	9.09	3831.16

3.3.4 LULC changes (1995–2015)

It is apparent that during 1995–2015, 2118.36 km² area of the non-forest area reduced to 1372.97 km² and got converted to various other classes including dense forest, open forest and scrub forest. During the same period the dense forest increased from 764.91 km² to 1076.19 km². Maximum contribution in the increase in dense forest area in this period came from open forest that contributed

301.90 km². The scrub forest had an area of 20.35 km² which got increased to 27.61 km² during this period. The non-forest area conversion into open forest area apparent during this period can be attributed to plantation in the wastelands and scrublands which ultimately contributed to an increase in the open forest area (Table 6).

Fig. 5 Change in forest class map between 2001 and 2007

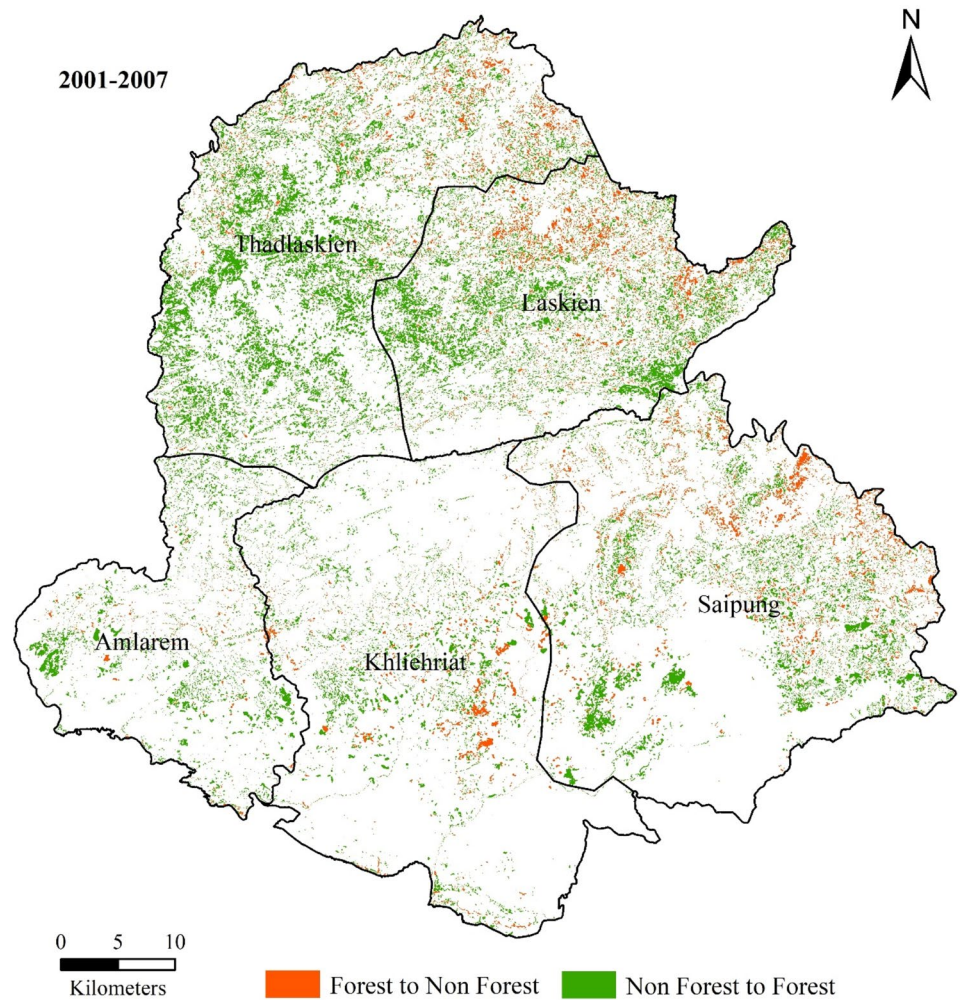


Table 5 Change matrix on land cover between the year 2007 and 2015

Land cover categories	2007 ----->				
	Non-forest	Dense forest	Open forest	Scrub forest	Total
2015 ----->					
Non-forest	1203.90	64.45	432.50	3.39	1704.23
Dense forest	74.67	779.88	468.62	4.51	1327.68
Open forest	90.95	231.97	452.31	15.37	790.61
Scrub forest	2.66	0.30	1.78	4.34	9.08
Total	1372.18	1076.59	1355.20	27.61	3831.60

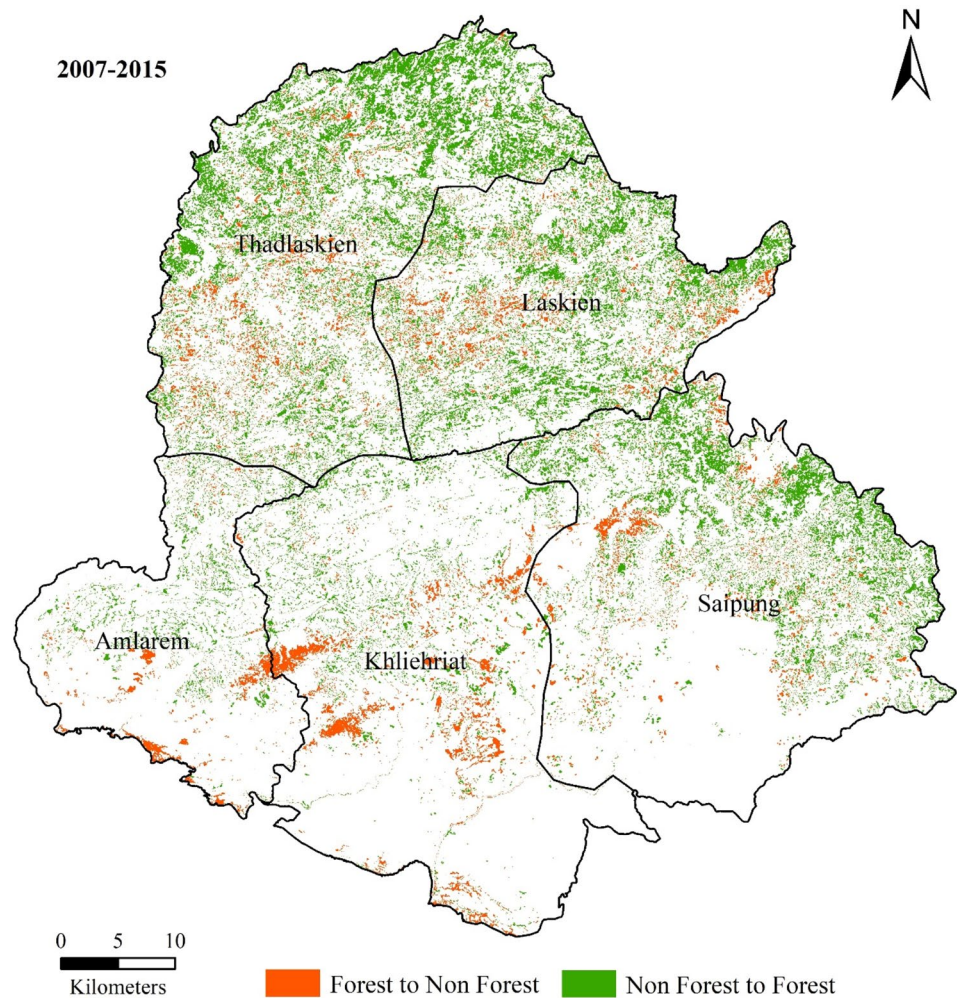
3.3.5 Change area—block-wise

The block-wise changes in area are summarized in Table 7. Change from forest to non-forest area was considered as a negative change and non-forest to forest area as a positive change (Fig. 8). The blocks considered in the present study include Amlarem, Khliehriat, Laskeiñ, Thadlaskeiñ, and Saipung with an area of 398, 1280, 390.4, 896.6, and 846 km², respectively. The highest positive change during the periods of 1995–2001 (72.83 km²) and 2001–2007 (171.52 km²)

was observed in Thadlaskeiñ block whereas the highest negative changes during the same period were observed in the Saipung block (56.01 and 42.08 km², respectively). During 2007–2015, the highest positive and negative changes were observed in Thadlaskeiñ (212.01 km²) and Khliehriat (44.79 km²), respectively.

A positive change was apparent in Thadlaskeiñ block with an increased area of 72.83, 171.52, and 212.81 km² during the period 1995–2001, 2001–2007, and 2007–2015, respectively. This could be due to agro-horticulture

Fig. 6 Change in forest class map for the year 2007 to 2015



plantation adopted at Saphoh and Larnai village in Thadlaskien block between 2011 and 2016 [57]. Additionally, a similar trend of positive change during the study period was also apparent in Laskein block which can be attributed to horticultural plantations such as oranges around the Raliang area. It is widely adopted by the farmers in the Jaiñtia Hills of Meghalaya, where hill slopes are quite steep with low soil depth. Overall, the highest negative change for the period 1995–2015 was apparent in Khliehriat block can be attributed to the large scale of limestone mining and production activity for cement factories in Jaiñtia Hills.

3.3.6 Quantification of the spatial pattern of forest fragmentation

It has been observed that from 1995 to 2007 the number of patches (NP) and patch density (PD) has increased in the dense forest category. The number of patches was observed to be 12600, 17032, and 17950, and patch density was observed to be 1.87, 2.53, and 2.67, respectively, for the

years 1995, 2001, and 2007. This indicates the division of habitats segregated by a matrix of man-made transformed land cover in the past 12 years. After a gap of almost a decade, the number of patches in 2015 decreased to 13940 which signifies an improvement. As per the table, it was observed PLAND was found to be complementary with the class area (CA) which both showed an increase from 1995 to 2007 and a decrease from 2007 to 2015. LPI increased from 1995 to 2007 at a rate of 2.44, 11.58, and 12.97% in 1995, 2001, and 2007, respectively, and a big decrease of 4.45% in 2015. To understand the fragmentation better, the edge density (ED) is another variable to assess. In this case, ED revealed an increase of 20.66 m/ha and 31.15 m/ha, 31.94 m/ha in 1995, 2001 and 2007, respectively. However, 2015 observed a decrease up to 25.66 m/ha. This denotes that with more high-value ED there is fragmentation in the spatial extent [58]. Landscape shape index (LSI) is also one of the indices that quantify the complexity of the landscape which measures the total edge that adjusts for the landscape [59]. LSI also indicated the same trend

Fig. 7 Change in forest class map for the year 1995 to 2015

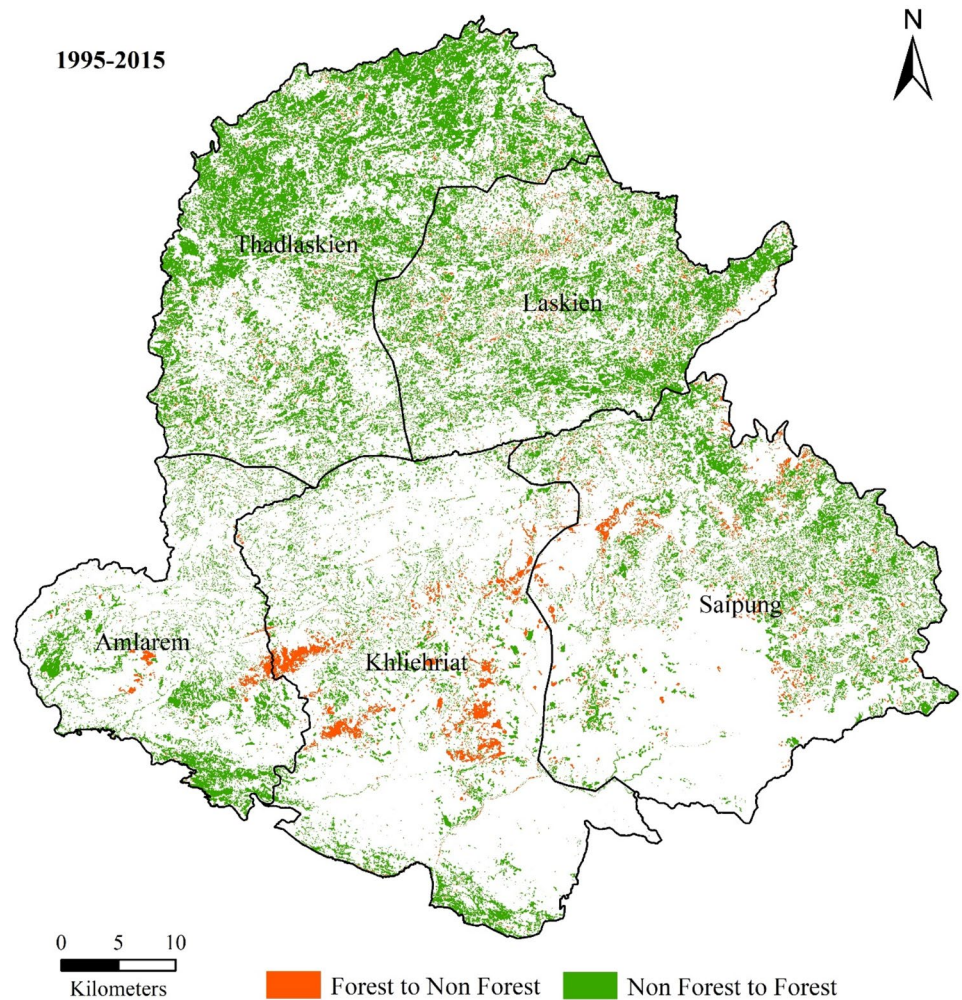


Table 6 Change matrix on land cover between the year 1995 and 2015

Land cover categories	1995 ----->				Total
	Non-forest	Dense forest	Open forest	Scrub forest	
2015 ----->					
Non-forest	1277.74	192.46	641.36	6.80	2118.36
Dense forest	23.96	578.85	159.12	2.98	764.91
Open forest	69.44	301.90	544.74	12.12	928.20
Scrub forest	1.83	2.98	9.83	5.72	20.35
Total	1372.97	1076.19	1355.05	27.61	3831.82

increased then decrease, i.e. 125.58, 146.97, 147.42 for the years 1995, 2001, and 2007, respectively, and decreased to 131.47 in 2015. IJI is based on how often the cells along the perimeter of each patch type are adjacent to other patch types. The category of IJI increased from 1995 to 2001, then decreased 2001 onwards and lasted till 2015 IJI. The IJI value of dense forest categories shows a uniform configuration of dense forest (Table 8). However, a decrease in IJI (2001 to 2015) denotes that the dense forest

area is less uniform [60]. MESH measures the proportional area of each patch based on the total landscape including background. It was observed that MESH value for dense forest has increased from 1995 to 2001. It covered an area of 703.67 ha in 1995 and 9049.58 ha in 2001, whereas later in 2007 it decreases to 8384.25 ha then it reduced to 1791.19 ha in 2015. The number of patches and patch density for the open forest category increase, then with time it reduced. The number of patches was 19968, 20360,

Table 7 Analysis of change area according to the block boundary

1995–2001		2001–2007		2007–2015		1995–2015	
Block	Area (km ²)	Block	Area (km ²)	Block	Area (km ²)	Block	Area (km ²)
Amlarem	62.73	Amlarem	42.24	Amlarem	45.15	Amlarem	84.66
Negative	14.90	Negative	5.05	Negative	21.71	Negative	7.48
Positive	47.83	Positive	37.18	Positive	23.44	Positive	77.18
Khliehriat	95.09	Khliehriat	63.55	Khliehriat	87.50	Khliehriat	140.53
Negative	34.00	Negative	18.04	Negative	44.79	Negative	40.75
Positive	61.09	Positive	45.50	Positive	42.71	Positive	99.77
Laskeiñ	108.58	Laskeiñ	136.45	Laskeiñ	217.23	Laskeiñ	302.04
Negative	39.22	Negative	33.39	Negative	34.52	Negative	13.75
Positive	69.35	Positive	103.06	Positive	182.71	Positive	288.28
Saipung	118.45	Saipung	119.52	Saipung	226.83	Saipung	342.09
Negative	56.01	Negative	42.08	Negative	32.40	Negative	28.52
Positive	62.44	Positive	77.43	Positive	194.43	Positive	313.57
Thadlaskeiñ	108.85	Thadlaskeiñ	196.94	Thadlaskeiñ	255.18	Thadlaskeiñ	411.84
Negative	36.02	Negative	25.42	Negative	43.17	Negative	8.03
Positive	72.83	Positive	171.52	Positive	212.01	Positive	403.81
Total	493.70	Total	558.69	Total	831.88	Total	1281.16

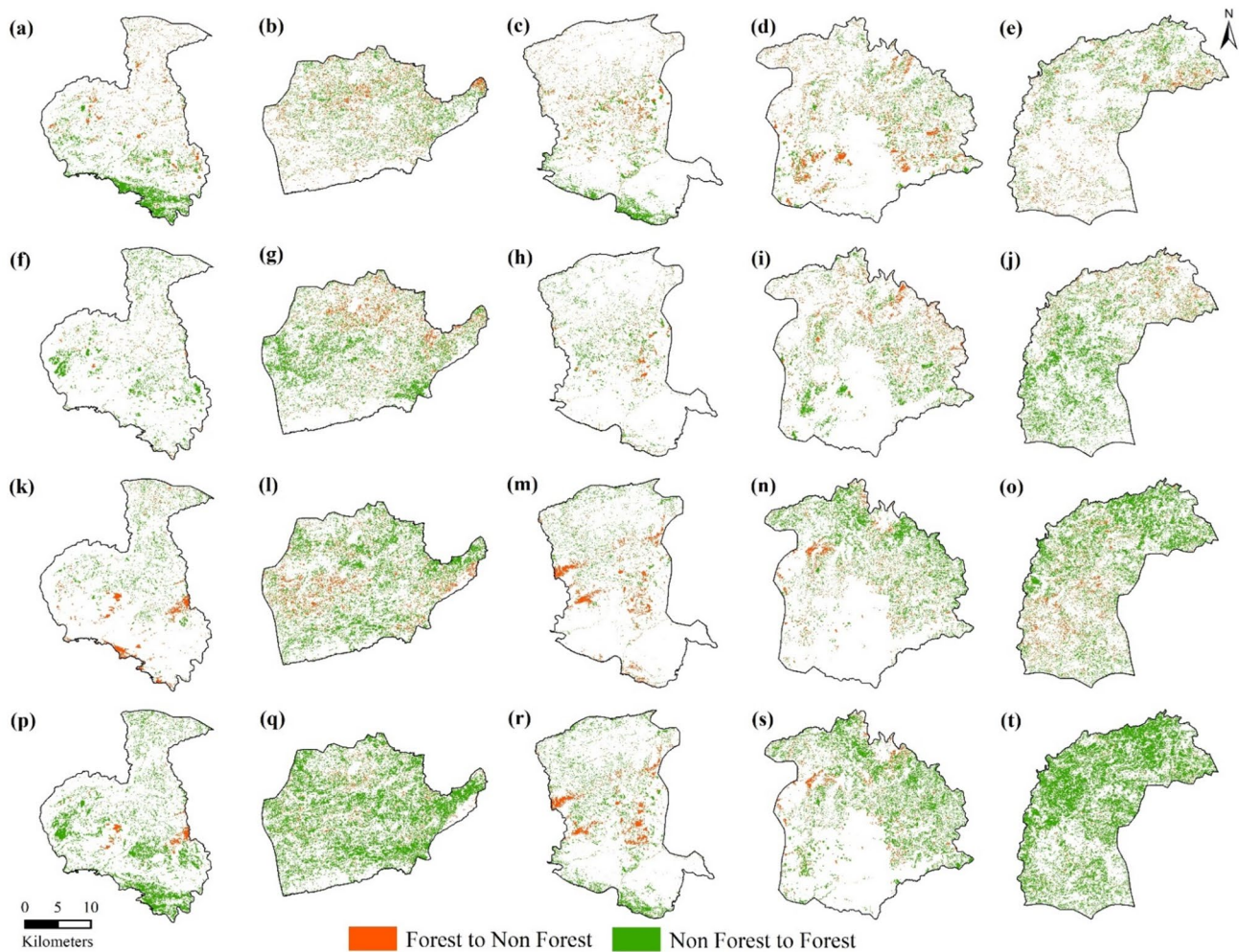


Fig. 8 Change category maps of (a) Amlarem (b) Laskeiñ (c) Khliehriat (d) Saipung (e) Thadlaskeiñ for 1995–2001: (f) Amlarem (g) Laskeiñ (h) Khliehriat (i) Saipung (j) Thadlaskeiñ for 2001 to

2007: (k) Amlarem (l) Laskeiñ (m) Khliehriat (n) Saipung (o) Thadlaskeiñ for 2007 to 2015: (p) Amlarem (q) Laskeiñ (r) Khliehriat (s) Saipung (t) Thadlaskeiñ for 1995 to 2015

Table 8 Overview of fragmentation in spatial extent of land cover (1995, 2001, 2007, and 2015)

Sl. No.	LULC CLASS	CA	PLAND (%)	NP	PD	LPI (%)	TE(m)	ED (m/ha)	LSI	IJI	MESH (ha)
1995											
1	Scrub forest	2034.72	0.30	1455	0.22	0.02	730620	1.09	40.46	55.05	0.07
2	Open forest	92827.17	13.80	19968	2.97	0.89	23859060	35.47	170.69	57.72	172.25
3	Dense forest	76497.75	11.37	12600	1.87	2.44	13893780	20.66	125.58	43.26	703.67
4	Non-forest	211806.38	31.46	6928	1.03	27.25	16347270	24.30	88.83	45.94	49985.27
2001											
1	Scrub forest	1885.95	0.28	1318	0.20	0.014	675540	1.0043	38.82	42.66	0.042
2	Open forest	55321.38	8.22	20360	3.03	0.49	16443420	38.45	174.67	55.96	43.09
3	Dense forest	126963.9	18.88	17032	2.53	11.58	20951580	31.15	146.97	54.39	9049.58
4	Non-forest	198944.28	29.58	5787	0.86	25.55	14660460	21.80	82.16	51.62	43930.47
2007											
1	Scrub forest	908.82	0.14	1042	0.15	0.012	408360	0.61	33.86	50.66	0.02
2	Open forest	79015.86	11.75	19875	2.95	1.09	19230540	34.47	171.03	54.23	172.47
3	Dense forest	132722.55	19.73	17950	2.67	12.97	21484560	31.94	147.42	51.65	8384.25
4	Non-forest	170468.28	25.34	6384	0.95	18.56	15861600	23.58	96.03	56.31	23322.70
2015											
1	Scrub forest	2761.47	0.41	1543	0.23	0.03	892740	1.33	42.39	59.76	0.128
2	Open forest	135520.38	20.15	18980	2.82	4.55	28510980	31.39	165.56	57.52	1685.98
3	Dense forest	107659.53	16.01	13940	2.07	4.45	17259540	25.66	131.47	43.50	1791.19
4	Non-forest	137217.89	20.37	9912	1.47	14.48	17674260	26.28	119.36	40.78	14117.82

CA Class area, PLAND Percentage of landscape, NP No. of patches, PD Patch density, LPI Largest patch index, TE Total edge, ED Edge density, LSI Largest shape index, IJI Inter-juxtaposition index, MESH

and 19875 for the years 1995, 2001, and 2007 respective and later reduced to 18980 in 2015. The patch density was found to be 2.97, 3.03, 2.95, and 2.82 for the years 1995, 2001, 2007, and 2015, respectively. This behavioural pattern of NP showed an increase over a period of time and a decrease from 20360 to 18980 during 2001–2015 could be due to patch amalgamation. PLAND decreases from the year 1995 to 2001 whereas increases from 2007 to 2015. From 1995 to 2001 LPI for open forest decreased from 0.89 to 0.49% and later it increased from 0.49 to 4.55% during 2001–2015. This depicts an increase due to aggregation of patch type. Edge density increased from 1995 to 2001 and then decreased between 2007 and 2015 possibly due to anthropogenic activities. The decline in NP and ED of open forest could be a diversion of dense forest and non-forest to open forest category. The LSI for the open forest reported an increase from 170.69 to 174.67 during 1995–2001 and a decrease from 174.67 to 165.56 for the period 2001–2015. The increase in LSI indicates open forests had undergone a disaggregation of the patches. Over time, LSI decreased implying an increase in open forest addressing an aggregation of patches under a dominating class which is the open forest category. IJI value seemed to be decreasing from 1995 to 2001 indicating a non-uniform spatial distribution and an increase from 1995 to 2001 denotes uniform spatial distribution. When IJI approaches zero, it indicates

the uneven distribution of patches whereas a value of hundred indicates that all the patch types are equally adjacent with other patch types [61, 62]. Based on MESH index, a decrease in 1995 to 2001 from 172.25 to 43.09 ha was apparent along with a significant increase between 2001 and 2015 from 43.09 to 1685.98 ha. While the number of patches (NP) of scrub forest decreased from 1995 to 2007, an increase in 2015 was apparent. A similar pattern has been followed by patch density (PD).

It has been observed that number of patches (NP) decreased from 6928 to 5717 between 1995 and 2001; however, an increase from 6384 to 9912 was apparent between 2007 and 2015. It has also been observed that after a gap of 14 years (2001 to 2015) non-forest indicated an increase in the number of patches with an increase in edge density as 21.8, 23.58, and 26.28 m/ha, respectively. A higher patch number indicates more edges which shows a greater extent of fragmentation. The number of patches of wasteland, built-up land, croplands, and water bodies has expanded during the studied period. It has been reported that non-forest such as built-up and croplands are the reason for forest degradation [63, 64]. LSI increased from 82.16 to 119.36 for the year 2001 to 2015 which shows segregation of aggregated patches. MESH value decreased continuously from 49985.27 to 14117.82 over the studied period. LPI of non-forest for all the years

revealed a decreasing trend, i.e. 27.25, 25.55, 18.56, and 14.48%, respectively.

The dense forest and non-forest category are reported to have experienced major disturbances which led to fragmentation. Assessment of forest canopy density and forest fragmentation has been adopted by various studies for analysing the status of forest conditions [65, 66]. Despite of apparent fragmentation, the increase in forest cover can be attributed to regeneration, afforestation, or secondary forest succession [67, 68]. The study area is rich in mineral resources, high population of rural and tribal communities which has a high dependence on forest resources for their livelihood, enterprise, and subsistence [69]. Such dependency on forest resources could ultimately lead to more fragmentation in the study area.

It was reported from 1994 to 2014 that the community forests and the reserved forest were more exploited as compared to state forests [70]. India State Forest Report 2015, outline that the forest cover of India has increased by 5081 km² with 21.34% for moderate dense (21.34%) whereas 2510 km² of the very dense forest has been lost [52]. An increase in forest fragmentation is due to anthropogenic activities [71, 72], it is due to the cultivation of paddy, minor fuelwood, and shifting cultivation for turmeric cultivation [73]. The area reported 40% of rice is cultivated in jhum sites [74] which is detrimental to forests, soil, and biodiversity [75-76]. Moreover, the mining activities are high in the area which ultimately affects the common herbal remedies used by the Jaiñtia tribe community namely *Litsea khasiana*, *Aegle marmelos*, *Averrhoa carambola*, *Gaultheria fragrantissima*, *Gmelia arborea*, *Nepenthes khasiana*, *Oroxylum indicum*, *Rhododendron arboreum*, *Swertia chirayita*, *Ficus benghalensis*, *Taxus baccata*, *Mimosa pudica*, *Eupatorium cannabinum*, *Potentilla fulgens* and *Rubus ellipticus* [77].

4 Conclusion

The study reported that dense forest and open forest increased by 8.13% and 11.14%, respectively, however, 19.47% of non-forests has decreased during the study period. Specifically, dense forest areas have become more degraded due to anthropogenic activities in this area. Landscape fragmentation has a great impact on the ecological system, e.g. when natural forests areas are confined into smaller size this ultimately disconnects the ecological corridors and results in loss of biodiversity. An increase in the dense forest is apparent from the temporal land cover change analysis; however, a significant amount of fragmentation has also been observed. Similarly, over the years

fragmentation was also observed in the non-forest category accounting for 19.45% of its spatial extent. This region of interest implies that it has been experiencing land cover changes with more activity resulting in fragmentation. The landscape of Jaiñtia Hills is under pressure due to the local population which is highly dependent on agriculture, coal, and cement industry. The study suggests to curb the intensification of forest cover lost in the study area. The conclusion drawn from this study is that the pattern of forest cover change and forest fragmentation is unpredictable which may be due to the complexity of the landscape structure. Hence, it is crucial to understand the pattern of land cover dynamics and its fragmentation to sustain biological diversity. The outcome will help in redefining ecological zones to maintain the overall spatial composition and configuration of the habitat.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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Appendix 1

See Table 9.

Table 9 Administrative blocks of Jaiñtia Hills, Meghalaya, India

Name of the blocks	Area(km ²)	Headquarter	District of Jaiñtia Hills
Khliehriat	1280	Khliehriat	East Jaiñtia Hills
Saipung	846		
Amlarem	398	Jowai	West Jaiñtia Hills
Thadlaskein	896.6		
Laskein	390.4		

Appendix 2

See Table 10.

Table 10 Description of satellite data used for the present study

Satellite/Sensor	Date of image acquisition	Path/Row	Bands used	Spatial Resolution (m)
Landsat 5/TM	19 March 1995	136/42	B1, B2, B3, B4	30
		136/43		
	19 March 2001	136/42	B1, B2, B3, B4	
	20 March 2007	136/42	B1, B2, B3, B4	
		136/43		
Landsat 8/OLI	10 March 2015	136/42	B1, B2, B3, B4, B5	
		136/43		

Appendix 3

See Table 11.

Table 11 Description of land use/land cover class

Land use/land cover classes	Description of the classes
Dense forest	Tree species with canopy over more than 40%
Open forest	Tree species with canopy over more than 10% and less than 40%
Scrub forest	Degraded forest land with canopy less than 10%
Non-forest	Wasteland, built-up, cropland, water bodies

Appendix 4

See Table 12.

Table 12 Types of metrics level

Metrics level	Description
Patch level metrics	Size, shape, and distance to neighbouring patches of an individual patch area quantified at the patch level
Class level metrics	Use these values for all the patches in the same LULC type to give a value for the entire class in the landscape.
Landscape metrics	Provide unique values without reference to individual patches or classes as they aggregate the properties for all the patches in the landscape

Appendix 5

See Table 13.

Table 13 List of landscape metrics used

Metrics	Description	Units
Class area	Tells about how much landscape is comprised of a particular patch type	ha
Percentage of landscape	PLAND equals the percentage of the landscape comprised of the corresponding patch type.	%
Number of patches	NP equals the number of patches of the corresponding patch type (class).	No unit
Patch density	Ratio of number of patches and the area	per unit per ha
Largest patch index	LPI equals the percentage of the landscape comprised by the largest patch	ha
Total edge	TE equals the sum of the lengths (m) of all edge segments involving the corresponding the patch type.	m
Edge density	ED equals the sum of the lengths (m) of all edge segments involving the corresponding patch type, divided by the total landscape area (m ²), multiplied by 10,000 (to convert to hectares).	m/ha
Landscape shape index	Complexity of the landscape that measures the total edge that adjusts for the landscape.	No unit
Interspersion juxtaposition index	IJI is based on patch adjacency. It is the arrangement of patches on the basis of composition and configuration in the landscape.	No unit
Effective mesh size	MESH measures the proportional area of each patch based on total landscape including background.	ha

References

- www.intechopen.com
- Das Gupta S (1999) Studies on vegetal and microbiological processes in coal mining affected areas. Ph.D. Thesis. North_Eastern Hill University, Shillong. India.
- www.megdmg.gov.in
- Nandy S, Kushwaha SPS, Dadhwal VK (2011) Forest degradation assessment in the upper catchment of the river Tons using remote sensing and GIS. *Ecol Indic* 11:509–513. <https://doi.org/10.1016/j.ecolind.2010.07.006>
- Ramachandra TV, Krishnadas G, Setturu B, Kumar U (2012) Regional bioenergy planning for sustainability in Himachal Pradesh, India. *J Energy Environ Carbon Credits* 2:13–49
- O'Neill RV, Krummel JR, Gardner RH et al (1988) Indices of landscape pattern. *Landscape Ecol* 1:153–162. <https://doi.org/10.1007/BF00162741>
- Turner MG (1990) Spatial and temporal analysis of landscape patterns. *Landscape Ecol* 4:21–30. <https://doi.org/10.1007/BF02573948>
- Li H, Reynolds JF (1993) A new contagion index to quantify spatial patterns of landscapes. *Landscape Ecol* 8:155–162. <https://doi.org/10.1007/BF00125347>
- McGarigal K, Marks BJ (1995) FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Rep. PNW-GTR-351. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 122 pp. 351.
- Gustafson EJ (1998) Quantifying landscape spatial pattern: what is the state of the art? *Ecosystems* 1:143–156. <https://doi.org/10.1007/s100219900011>
- He HS, DeZonia BE, Mladenoff DJ (2000) An aggregation index (AI) to quantify spatial patterns of landscapes. *Landscape Ecol* 15:591–601. <https://doi.org/10.1023/A:1008102521322>
- McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATSv3: spatial pattern analysis program for categorical maps.
- www.cgwb.gov.in/District_Profile/Meghalaya/Jaintia.
- <http://shodhganga.inflibnet.ac.in/bitstream/>
- Census of India (2011) Blocks in Jaintia hills district, Meghalaya.
- Mickelson JG, Civco D, Silander J (1998) Delineating forest canopy species in the Northeastern United States using multi-temporal TM imagery. *Photogramm Eng Remote Sens* 64:891–904
- Franklin J, Logan TL, Woodcock CE, Strahler AH (1986) Coniferous forest classification and inventory using Landsat and digital terrain data. *IEEE T Geosci Remote Sens* 24:139–149. <https://doi.org/10.1109/TGRS.1986.289543>
- Lee JK, Park RA, Mausell PW (1992) Application of geoprocessing and simulation modeling to estimate impacts of sea level rise on the northeast coast of Florida. *Photogramm Eng Remote Sens* 58:1579–1586
- Clark ML, Roberts DA, Clark DB (2005) Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. *Remote Sens Environ* 96:375–398. <https://doi.org/10.1016/j.rse.2005.03.009>
- Butera MK (1983) Remote sensing of wetlands. *IEEE T Geosci Remote Sens* 21:383–392. <https://doi.org/10.1109/TGRS.1983.350471>
- Yi GC, Risley D, Koneff M, Davis C (1994) Development of Ohio's GIS-based wetlands inventory. *J Soil Water Conserv* 49:23–28
- Turner MG (2005) Landscape ecology: what is the state of the science? *Ann Rev EcolEvolSyst* 36:319–344
- Turner MG, Gardner RH, O'Neill RV (2001) *Landscape ecology in theory and practice* Springer. pp. 406.
- Turner MG (1989) Landscape ecology: the effect of pattern on process. *Annu Rev Ecol Syst* 20:171–197. <https://doi.org/10.1146/annurev.es.20.110189.001131>
- Urban DL, O'Neill RV, Shugart HH (1987) Landscape Ecology: A hierarchical perspective can help scientists understand spatial

- patterns. *Bioscience* 37:119–127. <https://doi.org/10.2307/1310366>
26. Riitters KH, O'Neill RV, Hunsaker CT, Wickham JD, Yankee DH, Timmins SP, Jones KB, Jackson BL (1995) A factor analysis of landscape pattern and structure metrics. *Landscape Ecol* 10:23–39. <https://doi.org/10.1007/BF00158551>
 27. Herzog F, Lausch A (2001) Supplementing land-use statistics with landscape metrics: some methodological considerations. *Environ Monit Assess* 72:37–50. <https://doi.org/10.1023/A:1011949704308>
 28. Zheng D, Wallin DO, Hao Z (1997) Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. *Landsc Ecol* 12:241–254. <https://doi.org/10.1023/A:1007963324520>
 29. Wei L, Luo Y, Wang M, Su S, Pi J, Li G (2020) Essential fragmentation metrics for agricultural policies: Linking landscape pattern, ecosystem service and land use management in urbanizing China. *Agric Syst* 182:102833
 30. Gabriel EMA, Denis DM, Nath S, Paul A, Kumar M (2019) Quantifying LULC change and landscape fragmentation in Prayagraj district, India using geospatial techniques. *Pharma Innov* 8(5):670–675
 31. Mahato LL, Kumar M, Kumar J, Nath S, Lal D (2021) Forest changes and fragmentation analysis of Hazaribagh district of Jharkhand, India using Geospatial technology. *Pharma Innov J SP-10(1)*:222–227
 32. Singh SK, Laari PB, Mustak SK, Srivastava PK, Szabó S (2018) Modelling of land use land cover change using earth observation data-sets of Tons River Basin, Madhya Pradesh. *India. Geocarto Int* 33(11):1202–1222
 33. Cushman SA, McGarigal K, Neel MC (2008) Parsimony in landscape metrics: strength, universality, and consistency. *Ecol Indic* 8:691–703. <https://doi.org/10.1016/j.ecolind.2007.12.002>
 34. Linke J, Franklin SE (2006) Interpretation of landscape structure gradients based on satellite image classification of land cover. *Can J Remote Sens* 32:367–379. <https://doi.org/10.5589/m06-031>
 35. Griffith JA, Martinko EA, Price KP (2000) Landscape structure analysis of Kansas at three scales. *Landsc Urban Plan* 52:45–61. [https://doi.org/10.1016/S0169-2046\(00\)00112-2](https://doi.org/10.1016/S0169-2046(00)00112-2)
 36. Hargis CD, Bissonette JA, David JL (1998) The behavior of landscape metrics commonly used in the study of habitat fragmentation. *Landscape Ecol* 13:167–186. <https://doi.org/10.1023/A:1007965018633>
 37. Cain DH, Riitters K, Orvis K (1997) A multi-scale analysis of landscape statistics. *Landscape Ecol* 12:199–212. <https://doi.org/10.1023/A:1007938619068>
 38. Lamine S, Petropoulos GP, Singh SK, Szabó S, Bachari NEI, Srivastava PK, Suman S (2018) Quantifying land use/land cover spatio-temporal landscape pattern dynamics from Hyperion using SVMs classifier and FRAGSTATS. *Geocarto Int* 33:862–878. <https://doi.org/10.1080/10106049.2017.1307460>
 39. Van Strien MJ, Slager CTJ, de Vries B, Grêt-Regamey A (2016) An improved neutral landscape model for recreating real landscapes and generating landscape series for spatial ecological simulations. *Ecol Evol* 6:3808–3821. <https://doi.org/10.1002/ece3.2145>
 40. Prastacos P, Lagarias A (2016) An analysis of the form of urban areas in Europe using spatial metrics. *AGILE*.
 41. Schumaker NH (1996) Using landscape indices to predict habitat connectivity. *Ecol* 77(4):1210–1225
 42. Neel MC, McGarigal K, Cushman SA (2004) Behavior of class-level landscape metrics across gradients of class aggregation and area. *Landscape Ecol* 19(4):435–455
 43. Cardille J, Turner M, Clayton M, Gergel S, Price S (2005) META-LAND: characterizing spatial patterns and statistical context of landscape metrics. *AIBS Bulletin* 55(11):983–988
 44. Linke J, McDermid GJ, Pape AD, McLane AJ, Laskin DN, Hall-Beyer M, Franklin SE (2009) The influence of patch-delineation mismatches on multi-temporal landscape pattern analysis. *Landscape Ecol* 24(2):157–170
 45. www.umass.edu
 46. Singh SK, Srivastava PK, Szabó S, Petropoulos GP, Gupta M, Islam T (2017) Landscape transform and spatial metrics for mapping spatiotemporal land cover dynamics using Earth Observation data-sets. *Geocarto Int* 32(2):113–127. <https://doi.org/10.1080/10106049.2015.1130084>
 47. Jensen JR (1996) *Introductory digital image processing* prentice-hall. Englewood Cliffs, NJ.
 48. MECOFED (2011) Jaintia Hills District.
 49. www.indiastat.com
 50. Sarma K (2005) Impact of coal mining on vegetation: a case study in Jaintia Hills district of Meghalaya, India. M.Sc. Thesis. Faculty of Geo-Information Science and Earth Observation (ITC), Netherlands. pp. 1–85.
 51. www.fsi.nic.in
 52. India State of Forest Report (ISFR) (2015) Forest Survey of India, Ministry of Environment Forest & Climate Change, Government of India.
 53. www.livemint.com
 54. www.downtoearth.org.in
 55. Ramachandra TV, Bharath S, Bharath A (2014) Spatio-temporal dynamics along the terrain gradient of diverse landscape. *J Environ Eng Landscape Manage* 22:50–63. <https://doi.org/10.3846/16486897.2013.808639>
 56. Schmidt H, Glaesser C (1998) Multitemporal analysis of satellite data and their use in the monitoring of the environmental impacts of open cast lignite mining areas in Eastern Germany. *Int J Remote Sens* 19:2245–2260. <https://doi.org/10.1080/01431698214695>
 57. www.megsoil.gov.in
 58. Laurance WF, Nascimento HE, Laurance SG, Andrade A, Ewers RM, Harms KE, Luizao RC, Ribeiro JE (2007) Habitat fragmentation, variable edge effects, and the landscape-divergence hypothesis. *PLoS One* 2:1–8. <https://doi.org/10.1371/journal.pone.0001017>
 59. Mansour M, Hochschild V, Schultz A, NkuoKuma J (2016) Fragmentation rate and landscape structure of the Tillabry landscape (Sahel region) with reference to desertification. *J Geogr Reg Plann* 9:77–86. <https://doi.org/10.5897/jgrp2015.0538>
 60. Herzog F, Lausch A (2001) Supplementing land-use statistics with landscape metrics: some methodological considerations. *Environ Monit Assess* 72:37–50. <https://doi.org/10.1023/A:1011949704308>
 61. McGarigal K, Marks BJ (1994) *Spatial pattern analysis program for quantifying landscape structure*. Dolores (CO): PO Box, 606, pp. 67.
 62. Kumar M, Denis DM, Singh SK, Szabó S, Suryavanshi S (2018) Landscape metrics for assessment of land cover change and fragmentation of a heterogeneous watershed. *Remote Sens Appl Soc Environ* 10:224–233. <https://doi.org/10.1016/j.rsase.2018.04.002>
 63. Southworth J, Munroe D, Nagendra H (2004) Land cover change and landscape fragmentation—comparing the utility of continuous and discrete analyses for a western Honduras region. *Agr Ecosyst Environ* 101:185–205. <https://doi.org/10.1016/j.agee.2003.09.011>
 64. Lepers E, Lambin EF, Janetos AC, DeFries R, Archard F, Ramankutty N, Scholes RJ (2005) A synthesis of information on rapid land-cover change for the period 1981–2000. *Bioscience* 55:115–124.

- [https://doi.org/10.1641/0006-3568\(2005\)055\[0115:ASOIOR\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0115:ASOIOR]2.0.CO;2)
65. Mon MS, Kajisa T, Mizoue N, Yoshida S (2010) Monitoring deforestation and forest degradation in the Bago Mountain Area, Myanmar using FCD Mapper. *J For Plan* 15:63–72. https://doi.org/10.20659/jfp.15.2_63
 66. Biradar CM, Saran S, Raju PLN, Roy PS (2005) Forest canopy density stratification: How relevant is biophysical spectral response modelling approach? *Geocarto Int* 20:15–21. <https://doi.org/10.1080/10106040508542332>
 67. Aerts R, Honnay O (2011) Forest restoration, biodiversity and ecosystem functioning. *BMC Ecol* 11:29. <https://doi.org/10.1186/1472-6785-11-29>
 68. Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD, Cook WM et al (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci Adv* 1:1–9. <https://doi.org/10.1126/sciadv.1500052>
 69. Tynsong H, Tiwari BK, Dkhar M (2012) Contribution of NTFPs to cash income of the War Khasi community of southern Meghalaya, North-East India. *For Stud China* 14:47–54. <https://doi.org/10.1007/s11632-012-0104-7>
 70. Goswami R, Mariappan M, Singh TS, Ganesh T (2016) Conservation effectiveness across state and community forests: the case of Jaintia Hills, Meghalaya, India. *Curr Sci* 111:380–387. <https://doi.org/10.18520/cs/v111/i2/380-387>
 71. Malhi Y, Gardner TA, Goldsmith GR, Silman MR, Zelazowski P (2014) Tropical forests in the Anthropocene. *Annu Rev Environ Resour* 39:125–159. <https://doi.org/10.1146/annurev-environ-030713-155141>
 72. Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Mac Nally R, Thomson JR, de Barros Ferraz SF, Louzada J, Oliveira VHF, Parry L et al (2016) Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* 535:144–147. <https://doi.org/10.1038/nature18326>
 73. Jeeva SRDN, Laloo RC, Mishra BP (2006) Traditional agricultural practices in Meghalaya, North East India. *Indian J Tradit Knowl* 5:7–18
 74. www.westjaintiahills.gov.in
 75. Malik B (2003) The “problem” of shifting cultivation in the Garo Hills of North-East India, 1860–1970. *Conserv Soc* 1:287–315
 76. Shimrah T, Sarma K, Varga OG, Szilard S, Singh SK (2019) Quantitative assessment of landscape transformation using earth observation datasets in Shirui Hill of Manipur, India. *Remote Sens Appl Soc Environ* 15:100237. <https://doi.org/10.1016/j.rsase.2019.100237>
 77. Kayang H (2007) Tribal knowledge on wild edible plants of Meghalaya. Northeast India. *Indian J Tradit Knowl* 6(1):177–181

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