Landscape and Ecological Engineering (2018) 14:135–146
https://doi.org/10.1007/s11355-017-0340-z

ORIGINAL PAPER

Fourteen years of anthropization dynamics in the *Uapaca bojeri* Baill. forest of Madagascar

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Received: 1 December 2016 / Revised: 25 October 2017 / Accepted: 28 October 2017 / Published online: 29 January 2018

Abstract
Anthropization of forest landscapes is a major threat to ecosystems and biodiversity. To gather comprehensive information on anthropization dynamics in forest landscapes, fine-scale surveys of deforestation are required, coupled with detailed analysis of both spatial transformation processes and forest patch geometry. We conducted such a comprehensive study in a monospecific *Uapaca bojeri* (Baill.) forest of Madagascar, between 1999 and 2013. A diachronic set of four maps was produced and deforestation rates were calculated. Spatial transformation processes were described using Bogaert et al. (2004) typology. Forest patch geometry was monitored using largest patch index, mean patch size, and squared mean patch size to describe patch size dynamics, mean shape index and area weighted mean shape index to describe patch compactness, and fractal dimension analysis to describe patch outline complexity. For fractal dimension analysis, an innovative segmented regression model (Muggeo 2008) was used to separately quantify fractal dimensions for multiple ranges of patch sizes. Our results showed a growing anthropization of the *U. bojeri* forest landscape in the area, through a strong yet decelerating deforestation (from − 59.5% year^{-1} between 1999 and 2005 to − 2.84% year^{-1} between 2009 and 2013), clear forest fragmentation, and a subtle yet growing-in-scale simplification of patch geometry for small forest patches. Deforestation was artisanal in nature and, in 2013, large patches were withdrawing to less accessible topographic features. Our results forecast a medium-term loss of resilience of the *U. bojeri* forest in the area, if no direct forest conservation measures are taken.

Keywords Fragmentation · Deforestation · Fractal dimension · Segmented regression · Tropics · Endemic species

Introduction

Human activities have, since the beginning of civilization, fundamentally altered Earth's landscapes (Urban et al. 1987) in terms of composition and configuration. Today, there is a general agreement to describe the Earth as a human-dominated planet (Vitousek et al. 1997) as more than 75% of the planet's ice-free landscapes are now showing evidence of human influence (Ellis and Ramankutty 2008; Lewis and Maslin 2015). No longer pristine, landscapes are now biocultural landscapes, generated by both natural processes and human disturbances (Bridgewater and Arico 2002; Bogaert et al. 2014).

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Anthropization, the process of change from pristine toward human-disturbed landscapes, is, under a certain threshold of human pressure, a gradual process (Scheffer et al. 2001; Hirota et al. 2011). Anthropization can take many forms, depending on the landscapes affected and the human activity involved (Vranken 2015). Several methodological frameworks have been developed to monitor anthropization in various landscapes (August et al. 2002; Urban and Wallin 2002; Bogaert et al. 2011). Although a consensus on a unified methodological framework to monitor anthropization has yet to be reached, it is generally accepted that the conversion from natural land cover toward non-natural land cover, the fragmentation of natural land cover, and the simplification of patch geometry are effects of anthropization and good proxies to assess the dynamics of anthropization.

In the tropics, deforestation, the massive conversion of forest lands into non-forest land covers, is one of the most important impacts of anthropization, and a major threat on forest ecosystems and biodiversity (Food and Agriculture Organization of the United Nations (FAO) 2011, 2014; Malhi et al. 2014; Achard et al. 2014). In the Afrotropics, Madagascar, one of the priority areas for global biodiversity conservation (Myers et al. 2000; Mittermeier et al. 2011), has become a textbook example of deforestation and its impact on natural landscapes (Green and Sussman 1990; Agarwal et al. 2005). It has been estimated that 85–90% of Madagascar's rainforest has been converted into other land covers, either by logging, fires, or slash-and-burn agriculture (Myers et al. 2000; McConnell 2002; Kull 2004; Kull et al. 2005). Between 2000 and 2010, deforestation was still ongoing, with a rate of 0.4% year^{-1} for the entire country, a rate four times higher than the world's annual rate (Food and Agriculture Organization of the United Nations (FAO) 2011).

At the regional scale, the Itasy region in the highlands of Madagascar underwent an even more extreme land cover change. Between 2000 and 2005, its forest cover, composed mostly of the endemic monospecific *Uapaca bojeri* (Baill.) forests, was deforested at a rate of 7.41% year^{-1} (Rajoelison et al. 2009), i.e., over 18 times faster than the average rate for the entire island.

The aforementioned results only provide an initial idea on the anthropization dynamics in the Itasy region through natural land cover conversion rates. In order to gather comprehensive information on anthropization dynamics, local studies encompassing finer-scale survey of deforestation (Villard and Metzger 2014; Tropek et al. 2014) coupled with detailed analysis of fragmentation dynamics and natural patch geometry dynamics are required (Bogaert et al. 2011).

In this paper we aim to conduct such a local study of the anthropization in the Arivonimamo II rural township, a study site representative of the Itasy forest landscapes. Using four remotely sensed images distributed over the 1999–2013 time period, we specifically aimed to (1) assess the dynamics of deforestation, (2) describe the spatial transformation process sequence of the forest in order to expose any fragmentation mechanisms, and (3) evaluate the dynamics of forest patch geometry within the area to uncover simplifications in patch geometry. To fulfill the third objective, we conducted a fractal dimensions analysis using an innovative segmented regression model (Muggeo 2008) to separately compute fractal dimensions for multiple ranges of patch sizes.

Methods

Study area

The study was conducted in the Itasy region, 50 km west of Antananarivo, in central Madagascar (Fig. 1). The Itasy region is composed of three districts: Soavinandriana, Miarinarivo, and Arivonimamo. The study area is located in the Arivonimamo II rural township, between Miarinarivo and Arivonimamo districts and corresponds to a 648 km^2 rectangle (24 km × 27 km) centered on 19°0′3.1896″S, 47°6′55.7532″E. Local topography is irregular and rugged, varying between hills (up to 1568 m above sea level; Danielson and Gesch 2011), vast plains, volcanic cones, and narrow valleys (Klein 2002). The climate is tropical tempered by altitude (Peel et al. 2007) and is characterized by two distinct seasons: a dry and cool season from April to October, and a hot and rainy season from November to March.

Arivonimamo's forest consists mainly of monospecific *U. bojeri* forests. The *U. bojeri* tree is a sclerophyllous species of small stature, endemic to Madagascar highlands. The *U. bojeri* forest is characterized by an upper strata (10–20 m high) of *U. bojeri* trees with low branching, and a lower strata of shrubs and suffrutescent plants (Kull et al. 2005; Rakotondrasoa et al. 2012, 2013b). The *U. bojeri* forest is an important bio-cultural environment (Bridgewater and Arico 2002; Bogaert et al. 2014), fulfilling a role in both conservation and the livelihood of local populations. The *U. bojeri* forest provides refuge for multiple small mammals and is the preferred habitat of many species of wild silk moths and edible worms, for which *U. bojeri* leaves constitute the main fodder (Gade 1985; Barsics et al. 2013; Razafimanantsoa et al. 2013). Although aboveground biomass density is relatively low (20 t ha^{-1}) in the *U. bojeri* forest (Rakotondrasoa et al. 2012), the various resources, including both woody and non-woody products, play an important role in the informal economy, contributing up to 7% of total local economy (Kull et al. 2005; Rakotondrasoa et al. 2012).

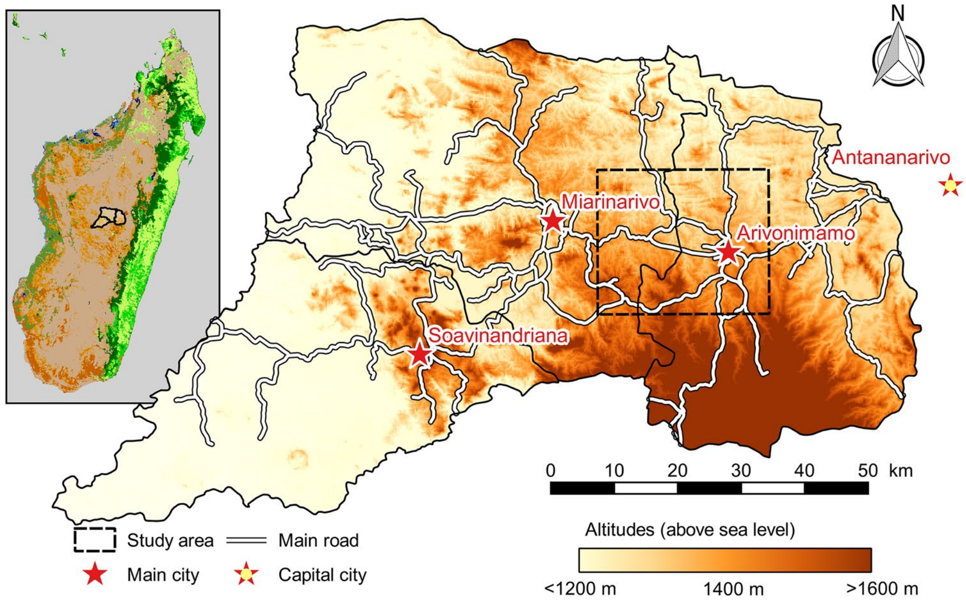


Fig. 1 Location of the study area within the Itasy region. The study area is located in the Arivonimamo II rural township, between Miarinarivo and Arivonimamo districts, and corresponds to a 648 km^2 rectangle (24 km × 27 km) centered on 19°0′3.1896″S, 47°6′55.7532″E. The map is overlaid on a base map showing district boundaries, cities, roads, and elevation according to Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch 2011). Inset: location of the Itasy region within Madagascar overlaid on a base map of forest cover according to Mayaux et al. (2003) Maps produced with QGIS (QGIS Development Team 2015a)

Remotely sensed data and classification

For this study, we gathered three Landsat 7 Enhanced Thematic Mapper+ (ETM+) images, dated December 20th 1999, November 18th 2005, and November 13th 2009, and one Landsat 8 Operational Land Imager (OLI) image, dated September 29th 2013. Spatial resolution was 30 m for all images. Both the 2005 and 2009 images were affected by the Landsat 7 ETM+ scan line corrector failure, missing some pixels on the sides of the image after cropping. These losses were, however, considered negligible, as the study area was located in the center of the tile (the percentage of pixels lost to the sensor failure in the study area was 1.5% in 2005 and 0.5% in 2009). The images were geo-referenced (Laborde, EPSG 29702) and atmospheric corrections were performed using the DARK Subtract tool from ENVI 4.3. Only green (band 2), red (band 3), and near-infrared (band 4) bands were used for classification. Ten-class unsupervised classification was performed on each image using ENVI's ISODATA module (Iterative Self-Organizing Data Analysis Technics). The generated classes within each image were merged through visual interpretation into two classes: "Forest" and "Other land". In this paper all forests were considered as *U. Bojeri* forests, as it is by far the most dominant forest type in the area (Rajoelison et al. 2009). Finally, all patches presenting an area smaller than 1 ha (11 pixels) were removed from the maps to avoid bias in shape metric calculations (O'Neill et al. 1999).

The quality of the classification was controlled through field validation using 143 ground truth points collected in May 2009. For the three other maps (2003, 2005, and 2013), a total of 140 ground truth points were selected on each image through visual interpretation. Map accuracy assessments were performed using the kappa index (Foody 2002). For each image, kappa accuracy values remained fairly high (84% in 1999, 89% in 2005, 83% in 2009, and 77% in 2013). We thus had a sufficiently high degree of confidence in our classifications to proceed with our analysis.

Deforestation dynamics

To assess the dynamics of deforestation over the 1999–2013 period, total forest area was measured for each year, in conjunction with corresponding annual change rates between each date. To illustrate the change in forest cover between each date, a map of the forest cover at the beginning and end of each period was produced.

Spatial transformation processes

To describe the spatial transformation process sequence of the forest over the 1999–2013 period, Bogaert et al. (2004) typology was used, and patch size dynamics were evaluated using largest patch index (LPI) (McGarigal and Marks 1995), arithmetic mean patch size (MPS), and squared mean patch size (SMPS) (Bollback 2006). Each metric was calculated for each image, in conjunction with corresponding annual change rates between each date.

Bogaert et al. (2004) typology enables an unequivocal description of the spatial transformation process of a given land cover class over a given period of time. It is based on the sign of the variation of three metrics of the land cover class: total area, total perimeter, and total number of patches (Table 1).

Table 1 Spatial transformation process (STP) typology Adapted from Bogaert et al. (2004)

STP	Definition	Direction of the variation of		
		Total area	Total perimeter	Total number of patches
Aggregation	To bring or gather together into a whole	− or 0	/	−
Attrition	Disappearance of patches	−	/	−
Creation	The formation of new patches	+	/	+
Deformation	The changes of patch shape, without patch size change	0	− or +	0
Dissection	The carving up or subdividing of an area or patch using equal-width lines; sectioning of an area or patch	− ($t_{obs} > 0.75$)	/	+
Enlargement	The increase of patch size	+	/	0
Fragmentation	The breaking up of extensive landscape features into disjoint, isolated, or semi-isolated patches	− ($t_{obs} \leq 0.75$)	/	+
Perforation	The process of making holes in an area or patch	−	+	0
Shift	Patch translocation	0	0	0
Shrinkage	The decrease or reduction in size of patches, without "attrition"	−	− or 0	0

All spatial transformation processes are assigned an unequivocal definition based on the variation of three metrics of the selected land cover class, during the selected time period: total area, total perimeter, and total number of patches. To distinguish between fragmentation and dissection, t_{obs} ($t_{obs} = a_1/a_0$) is calculated and compared to a threshold value t (set as 0.75 in this study)

a_0 total area of the land cover class at the beginning of the period, a_1 total area of the land cover class at the end of the period, + the metric increases, − the metrics decreases, 0 the metric stays stable, / no characteristic effect of the spatial transformation process on the metric

To distinguish between fragmentation and dissection processes, an area ratio is calculated and compared to a threshold value (t):

$$t_{obs} = \frac{a_1}{a_0} \quad (1)$$

where a_0 is the total area of the land cover class at the beginning of the time period, and a_1 is the total area of the land cover class at the end of the time period. When $t_{obs} > t$, the transformation is identified as dissection; if $t_{obs} \leq t$, the transformation is identified as fragmentation.

In our study, total area, total perimeter, and total number of patches of the forest were calculated for each year, in conjunction with corresponding annual change rates between each date. The t value was set as 0.75.

LPI is the percentage of the total forest area represented by the area of the largest forest patch in the landscape, and is computed as follows:

$$\mathrm{LPI} = \frac{a_{LP}}{a_{tot}} \times 100(\%) \quad (2)$$

where a_{LP} is the area of the largest forest patch, and a_{tot} is the total forest area in the landscape.

MPS and SMPS are measurements of the average patch size: the higher the index is, the larger the average patch size is. They are computed as follows:

$$\mathrm{MPS} = \frac{\sum_{i=1}^{i=N} a_i}{N} \quad (3)$$

$$\mathrm{SMPS} = \sqrt{\frac{\sum_{i=1}^{i=N} a_i^2}{N}} \quad (4)$$

where N is the total number of forest patches in the landscape and a_i is the area of ith patch. While MPS attributes the same weight to each patch (Eq. 3), SMPS attributes a greater weight to large patches (Eq. 4). For a diachronic analysis of landscapes, a greater variation of SMPS (compared to MPS) indicates a change focused on large patches, and a smaller variation of SMPS indicates a change focused on small patches.

Patch geometry

To evaluate the dynamics of forest patch geometry within the area over the 1999–2013 time period, the compactness of the patch was quantified using mean shape index (MSI) and area weighted mean shape index (AWMSI) (Saura and Martinez-Millan 2001) and the complexity of the outline of the patch was quantified using fractal dimensions.

MSI and AWMSI are measurements of the compactness of the patch: the higher the index value is, the less compact the patch is. The metrics were calculated for each year, in conjunction with the corresponding annual change rates over each time period as follows:

$$\mathrm{MSI} = \frac{\sum_{i=1}^{i=N} \frac{p_i}{4\sqrt{a_i}}}{N} \quad (5)$$

$$\mathrm{AWMSI} = \frac{\sum_{i=1}^{i=N} \frac{p_i}{4\sqrt{a_i}} a_i}{\sum_{i=1}^{i=N} a_i} = \frac{\sum_{i=1}^{i=N} p_i \sqrt{a_i}}{4\sum_{i=1}^{i=N} a_i} \tag{6}$$

where p_i is the outline of the ith patch. As for MPS and SMPS, MSI attributes the same weight to each patch (Eq. 5), while AWMSI attributes a higher weight to large patches (Eq. 6). For a diachronic analysis of landscapes, a greater variation of AWMSI (compared to MSI) indicates a change focused on large patches, and a smaller variation of AWMSI indicates a change focused on small patches.

Fractal dimension (D) is a measurement of the complexity of the outlines of the patches. D varies between two theoretical values: when $D \approx 1$, the outlines of the patch are simple and regular; whereas when $D \approx 2$, the outlines of the patch are complex and irregular (Halley et al. 2004). In our study, fractal dimension was computed using the perimeter-area method, as follows.

Before performing the analysis, patches in contact with the border of the study area are removed from the dataset to avoid taking into account artificial straight outlines generated by the cropping of the image to the study area (O'Neill et al. 1999).

The perimeter-area method is based on the following relationships between the perimeter and the area of the patches:

$$p_i = k + a_i^{\frac{D_i}{2}} \tag{7}$$

$$\Leftrightarrow \log(p_i) = \log(k) + \frac{D_i}{2}\log(a_i) \tag{8}$$

where D_i is the fractal dimension of the ith patch and k is a constant. If D_i can be considered constant for all patches, $D_i \approx D$, and D can thus be calculated through the linear regression of $\log(p_i)$ against $\log(a_i)$; then D is equal to twice the slope of the regression (Halley et al. 2004).

Empirical studies shows that D_i is not constant for all patches within the same given landscape, but often takes two distinct values: a low value for small patches (D_{SP}), whose outlines are more likely to have been (re)shaped by short-scale anthropogenic disturbances, and a high value for large patches (D_{LP}), whose outlines are more likely to have been (re)shaped by large-scale natural patterns and processes (see Krummel et al. (1987) in the USA, Meltzer & Hastings (1992) in Zimbabwe, and Imre and Bogaert (2004) in Belgium). Within these two ranges, however, D_{SP} and D_{LP} can be considered constant. Separate regression for small and large patches is thus recommended (Meltzer and Hastings 1992).

In our study, we used a segmented regression model (Muggeo 2008) to perform the separated regression for small and large patches and to compute the threshold (in area) between these two ranges of areas (ψ). The computation of the segmented regression model is an iterative process and was thus provided with an initial estimate of ψ, equal to 5 (i.e. 10^5 = 100,000 m^2 (or 10 ha) in non-logarithmic scale).

To test the added value of a segmented regression in comparison to a simple linear regression, the Davies test was performed (Davies 1987; Muggeo 2008). The segmented regression was considered justified when the Davies test was significant. In this case, D_{SP}, D_{LP}, and ψ values were computed, and ψ was converted into metric units, using a reverse-log transformation (10^{ψ}).

Results

Deforestation dynamics

Between 1999 and 2013, more than half of the remaining Arivonimamo forest was deforested. However, deforestation slowed down over time. Between 2009 and 2013, the annual deforestation rate was more than two times slower than the rate observed between 1999 and 2005 (Table 2, Fig. 2).

Spatial transformation processes

In 1999, Arivonimamo forest was almost unfragmented: the landscape exhibited large continuous patches (MPS = 23.46 ha, Table 2) and the largest patch represented almost a quarter of the total forested area (LPI = 24.03%, Table 2).

Over the 1999–2005 period, Arivonimamo forest underwent a fragmentation process (total number of patches increased, total area decreased, $t_{\mathrm{obs}} < t$, Tables 1 and 2). This fragmentation process was supported by the sharp decrease of the percentage of the total forest area represented by the largest forest patch in the landscape (i.e., LPI). Over the 2005–2009 period, Arivonimamo forest underwent an attrition process (total area decreased, total number of patches decreased, total perimeter decreased, Tables 1 and 2). Finally, over the 2009–2013 period, the Arivonimamo forest underwent a shrinkage process (total number of patches remained almost stable, total area decreased, total perimeter decreased (although mildly), Tables 1 and 2).

Over the whole study, an underlying shrinkage process occurred as the mean patch size and the squared mean patch size decreased. However, the mean patch size and the squared mean patch size rate of decrease slowed down over time, following the same trend as deforestation rate. This reduction of the mean patch size predominantly affected large patches (the annual rate of decrease of SMPS was steeper than the annual rate of decrease of MPS for all periods, and LPI decreased during the 1999–2005 and 2009–2013 periods, Table 2).

Table 2 Forest landscape dynamics in Arivonimamo II rural township over the 1999–2013 period: set of selected metrics

Metric	Absolute value				Annual change rate (% year^{-1})			Total change (%)
	1999	2005	2009	2013	1999–2005	2005–2009	2009–2013	1999–2013
Total area (ha)	29882	17162	13653	12104	− 7.09	− 5.11	− 2.84	− 59.50
Total number of patches	1274	2023	1850	1843	9.80	− 2.14	− 0.09	44.66
Total perimeter (km)	4494	4055	3529	3439	− 1.63	− 3.24	− 0.64	− 23.48
LPI (%)	24.03	9.19	9.27	8.77	− 10.29	0.23	− 1.35	− 63.51
MPS (ha)	23.46	8.48	7.38	6.57	− 10.64	− 3.25	− 2.75	− 72.00
SMPS (ha)	230.65	45.37	35.32	30.38	− 13.39	− 5.54	− 3.50	− 86.83
MSI	20.13	18.48	18.31	18.83	− 1.36	− 0.24	0.72	− 6.42
AWMSI	71.71	36.56	35.60	37.82	− 8.17	− 0.66	1.56	− 47.27
	Spatial transformation process				Fragmentation	Attrition	Shrinkage	

The set includes total area, total number of patches, total perimeter

The metrics were computed for each year, and annual change rates between each date were calculated. Total change over the whole study period and spatial transformation process (following Bogaert et al. (2004) typology) between each date are also given

LPI largest patch index, *MPS* mean patch size, *SMPS* squared mean patch size, *MSI* mean shape index, *AWMSI* area weighted mean shape index

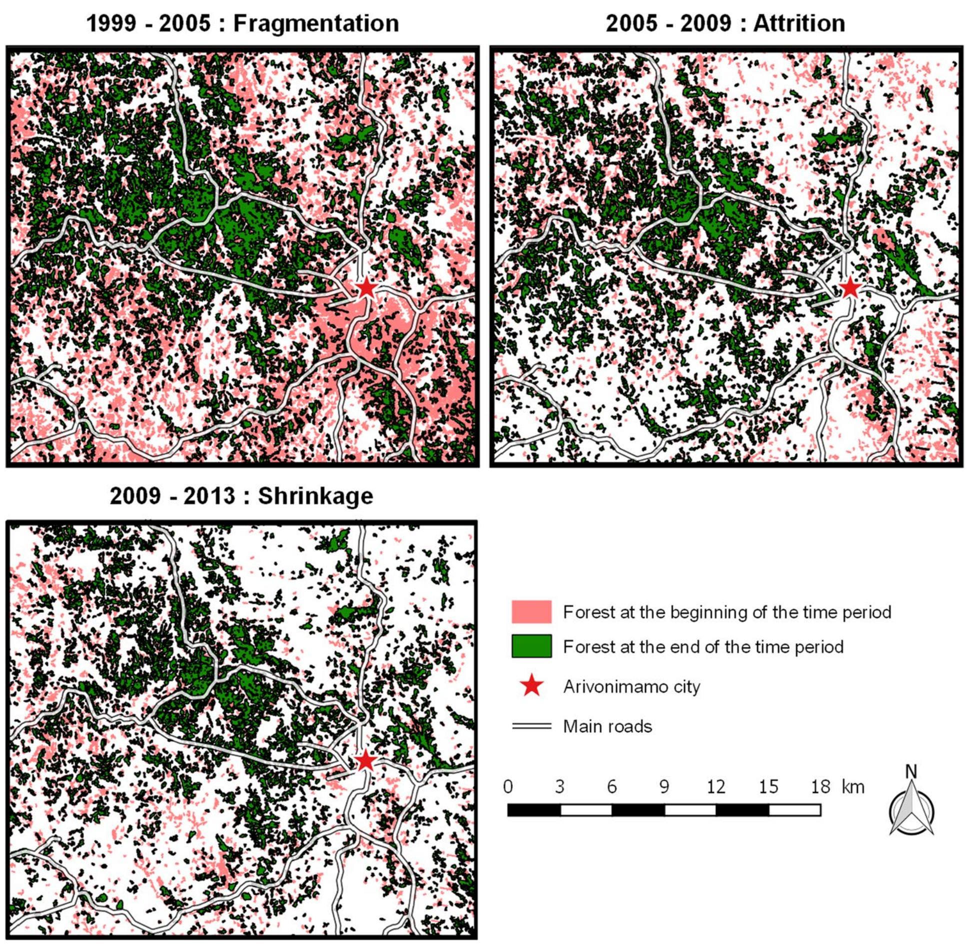


Fig. 2 Forest dynamics in Arivonimamo II rural township over the 1999–2013 period. The images used are dated December 20th 1999, December 18th 2005, November 13th 2009, and September 29th 2013. 1999, 2005, and 2009 maps were produced using unsupervised classification of bands 2, 3, and 4 of the ETM+ sensor, on Landsat 7, and 2013 map was produced using unsupervised classification of bands 2, 3, and 4 of OLI sensor, on Landsat 8 Maps produced with QGIS (QGIS Development Team 2015a)

Patch geometry

Segmented regression was justified for each year of the study (Davies tests upper bound p values: 4.27×10^{-10} in 1999; 1.41×10^{-3} in 2005; 1.08×10^{-8} in 2009; 6.34×10^{-6} in 2013). Over the whole study, the complexity of the outline of small patches (i.e., D_{SP}) did not change considerably, and the complexity of the outline of large patches (i.e., D_{LP}), although fluctuating over the study, remained higher than the (almost constant) complexity of the outline of small patches (Fig. 3).

Between 1999 and 2005, the fragmentation process had three effects on the patch geometry. First, the complexity of the outline of large patches decreased, indicating some regularity in the logging patterns in large patches. Secondly the threshold between small and large patches ranges (i.e., ψ) decreased sharply, suggesting that intermediate-sized patches with complex outlines were generated. Because the ongoing spatial transformation process was fragmentation, it is likely that the intermediate-sized patches were fragments of large patches which retained some of the complexity of the outlines of their parent patches. Thirdly the generated fragments (especially large ones) were more compact than their parent patches (MSI and AWMSI decreased between 1999 and 2005, MSI < AWMSI in 2005, Fig. 3). All these results indicate that large spread-out patches with complex outline were broken into smaller, more compact patches during the fragmentation process. These smaller patches, however, presented fairly complex outlines.

Between 2005 and 2013, these three trends were inverted. First the threshold between small and large patches ranges increased, suggesting that the outlines of larger and larger fragments were reshaped into more simple shapes. Secondly the complexity of the outline of large patches increased. Thirdly, the compaction of the patches stopped and then decreased, as patches (especially large ones) gradually assumed more spread-out shapes (MSI increased between 2005 and 2013, AWMSI stabilize between 2005 and 2009 then increased between 2005 and 2013, MSI < AWMSI during both time periods, Fig. 3). These last two results suggest that, after the fragmentation process (1999–2005), the remaining (large) patches gradually shrunk anisotropically to more spread-out shapes presenting more complex outlines.

Discussion

Deforestation dynamics

Between 1999 and 2013, the Arivonimamo II rural township area underwent a strong but decelerating deforestation (Table 2), which suggests an important anthropization process of the landscape. The non-stationarity (Urban and Wallin 2002) of deforestation rates was likely due to the increased scarcity of readily accessible forest land, forcing the local population either to use (young) fallow land to set up their slash-and-burn crops or logging plots, or to turn to slower, more troublesome forest exploitation on less accessible land. This pattern is self-feeding as remaining forest lands are increasingly difficult to access, further decelerating deforestation rates. This pattern was observed in Madagascar (Green and Sussman 1990) and in several other country in the tropics (see Nagendra et al. in Honduras 2003; Getahun et al. in Ethiopia 2013; and Ferretti-Gallon and Busch for a cross-tropics review 2014). Though quickly decelerating, the intensity of deforestation in the area remains extremely concerning, with a rate still seven times above the rate observed at the country level between 2000 and 2010 (Food and Agriculture Organization of the United Nations (FAO) 2011).

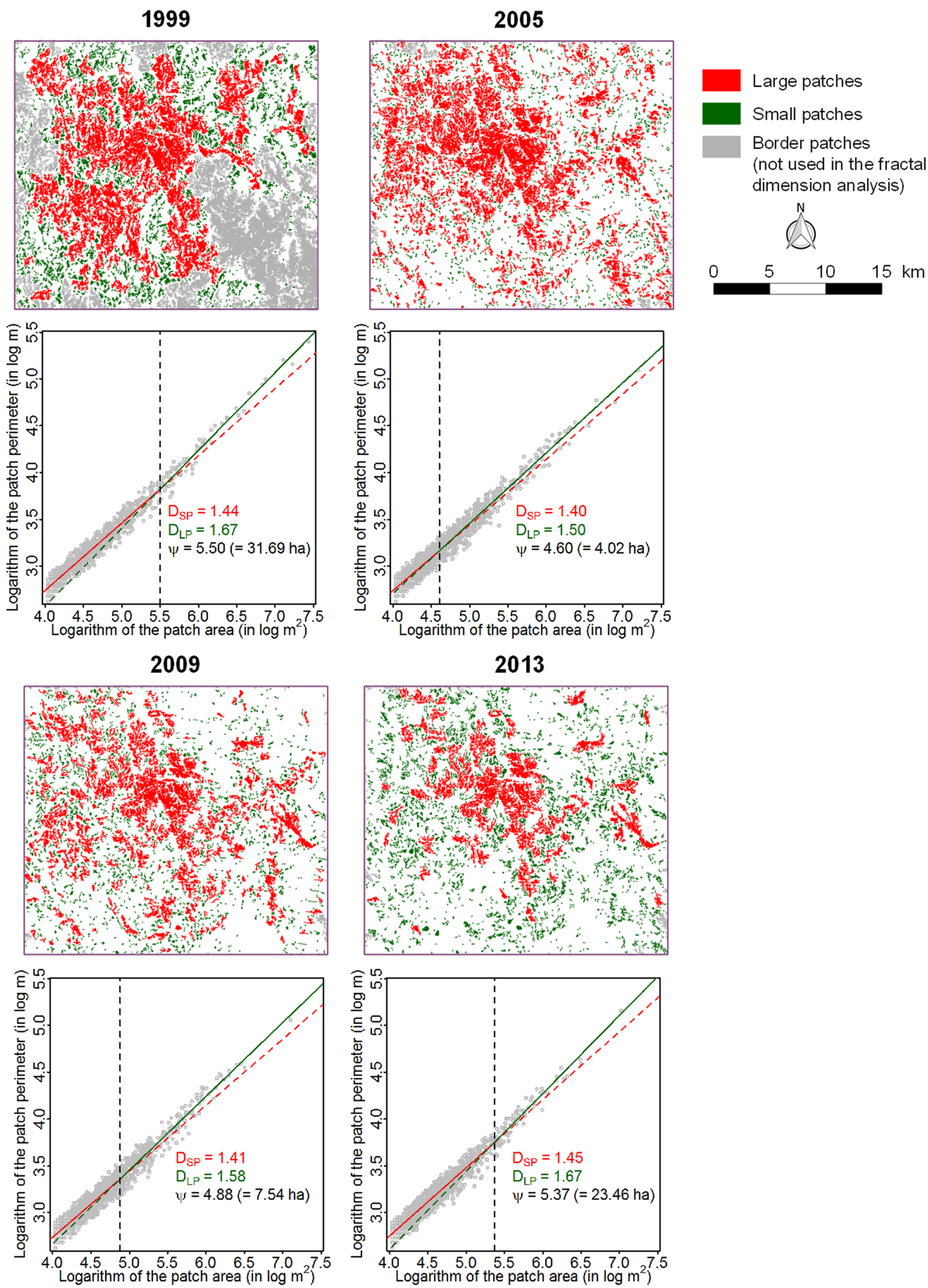
During this deforestation period, several community-based forest management projects (Hutton et al. 2005) were undertaken to limit deforestation in Arivonimamo II rural township, within the legal framework of Madagascar's "GéLoSé" management transfer law (Ratsimbarison and Ramanarivosoa 2006). As for most of the community-based natural resources management projects, these projects were based on the assumption that local populations are best placed and possess the best knowledge to manage their neighboring natural environment and its resources (Pollini et al. 2014). These projects may thus have contributed to the deceleration of the deforestation in the area (Table 2).

However, these "GeLoSé" projects were highly criticized all over Madagascar, for their lack of proper funding, the absence of enforcement of the project decisions, and the inadequate integration of local populations, through the hijack of the management board by local elites (Pollini et al. 2014; Rasolofoson et al. 2015; Waeber et al. 2016). In some cases, the new regulation was even exploited to establish new slash-and-burn crops (Pollini et al. 2014). It is, however, unclear whether Arivonimamo II rural township "GéLoSé" projects faced these shortcomings.

Spatial transformation processes

Over the 1999–2013 period, Arivonimamo II rural township forest underwent a spatial transformation sequence following a fragmentation/attrition/shrinkage sequence, in conjunction with an underlying shrinkage process focused on large patches (Tables 1 and 2). These processes further support the previously suggested anthropization process of the landscape.

The spatial transformation sequence slightly differed from the theoretical fragmentation/shrinkage/attrition anthropization sequence described by Forman (1995). This early attrition episode may be explained by the Malagasy customary rights on forest management. Indeed, to be recognized as the rightful owners of a woodlot by customary laws, a household must first carve the desired fragment out of the forest massif (Urech et al. 2015): fragmentation is therefore a prerequisite before exploitation and clearing. This custom would explain the focus of the underlying shrinkage process on large patches (Table 2), as the ownership of smaller patches is likely to be claimed already. This result thus reinforces the hypothesis of Rakotondrasoa et al. (2013a), suggesting that


1999
2005
2009
2013
Large patches
Small patches
Border patches
(not used in the fractal
dimension analysis)
N
0 5 10 15 km
Logarithm of the patch perimeter (in log m)
Logarithm of the patch area (in log m²)
D_SP = 1.44
D_LP = 1.67
ψ = 5.50 (= 31.69 ha)
D_SP = 1.40
D_LP = 1.50
ψ = 4.60 (= 4.02 ha)
D_SP = 1.41
D_LP = 1.58
ψ = 4.88 (= 7.54 ha)
D_SP = 1.45
D_LP = 1.67
ψ = 5.37 (= 23.46 ha)

◂**Fig. 3** Fractal dimension assessment. We analyzed the relationship between the logarithm of the patch area (in log m^2) and the logarithm of the patch perimeter (in log m) to assess the fractal dimensions of the outline of the patches. The analysis was carried out using a fragmented regression model to assess the fractal dimensions of the outline of small patches and large patches separately (Muggeo 2008). The breakpoint between the ranges of small and large patches was assessed for each year. ψ breakpoint value, i.e., log-area threshold between the ranges of small and large patches, in log (m^2) and in ha. D_{SP} the fractal dimension of the outline of small patches (patches smaller or equal to ψ), D_{LP} fractal dimension of the outline of large patches (patches larger than ψ) Maps produced with QGIS (QGIS Development Team 2015a), graph produced with R (R Development Core Team 2015b)

deforestation in the area is artisanal and due to smallholders' activities.

Patch geometry

Over the 1999–2013 period, the analysis of the dynamics of patch geometry offered further insights into the on-going anthropization process in Arivonimamo II rural township (Fig. 3).

Over the whole study period the complexity of the outlines of small patches remained lower than the complexity of the outlines of the large patches (Fig. 3), supporting the hypothesis that the outlines of small patches are more susceptible to small-scale anthropogenic disturbances (Krummel et al. 1987; Meltzer and Hastings 1992; Imre and Bogaert 2004).

The complexity of the outlines of small patches did not change considerably over the study period, presenting a constant minimum level of complexity for the area (Fig. 3). This constant minimum level of complexity is likely to correspond to the (low) technical level of artisanal deforestation practices, which may limit the capacity of local populations to reshape the complex outline of natural patches past a certain maximum level of regularity.

Comparatively to other studies (Krummel et al. 1987; Bamba et al. 2010), the level of complexity of the outlines of the patches in the area remained quite complex, as fractal dimension values (for both small and large patches) remained relatively high. However, Bamba et al. (2010) suggested an inverse correlation between fractal dimension levels and population density in the Democratic Republic of Congo. Thus, if this inverse correlation holds in Madagascar, the fairly low density of human population in the study area (38.19 inhabitants per km^2 in 2012, Rakotondrasoa 2012) may explain the relatively high level of complexity in the outlines of the patches in the area.

During the 1999–2005 period, large spread-out patches with complex outlines were fragmented following fairly regular logging patterns, and the generated fragments were more compact and presented simpler outlines than their parent patches (Table 2, Fig. 3). However, this simplification was not complete as the generated fragments did not reach the minimum level of complexity in the area. This dynamic is again likely to be explained by Malagasy customary rights on forest management, as presented in the previous section (Urech et al. 2015). Fragmentation of a forest patch is likely to be the primary objective of a new household, without any regard to the general shape of the newly generate fragment, except perhaps its compactness for convenience of use. The outlines of the generated fragments would thus retain some of the complexity of the outline of their parent patches.

During the 2005–2013 attrition/shrinkage periods, the outlines of larger and larger fragments were gradually simplified (Table 2, Fig. 3), highlighting the increase in scale (but not intensity) of the anthropization process on patches shapes in the area. This subtle effect of anthropization on the landscape may be the result of the structuring effect of the "GeLoSé" projects in the area, encouraging the local population to work together as a collectivity, thus impacting larger and larger fragments.

During the same 2005–2013 attrition/shrinkage periods, large patches shrunk anisotropically into more complex spread-out geometries, with complex outlines (Fig. 3). This new dynamic can be attributed to topography: as large accessible forest patches are logged, the remaining forest patches gradually shrink to steeper and less accessible topographic features, such as ridges and hill crests, where deforestation is more troublesome work (Ferretti-Gallon and Busch 2014). The shape of the remaining large forest patches therefore changed to match the spread-out complex outlines of these topographic features. This result thus nuances the links between anthropogenic pressure and shape complexity (Krummel et al. 1987; Meltzer and Hastings 1992; Imre and Bogaert 2004), as it demonstrates that a given landscape undergoing anthropogenic pressure can present an increase in the fractal dimension of its patches if a strong fractal spatial driver (such as topography) forces the dynamics of patch outline toward more complex and irregular structures.

Conclusion

This study presented an illustration of the effects, at the landscape level, of smallholder's slash-and-burn activities on the configuration and extent of tropical forested landscapes. Between 1999 and 2013 the forested landscape of Arivonimamo II rural township underwent a growing anthropization period, through a strong yet decelerating deforestation, a clear forest fragmentation, and a more subtle yet growing-in-scale simplification of patch geometry for small forest patches. Patch geometry analysis confirmed the artisanal nature of the deforestation as suggested by Rakotondrasoa (2012). By the end of the study period, large patches were withdrawing to less accessible topographic features, reducing the rate of deforestation while assuming more complex geometries.

This study displayed the subtle influence of anthropization on the complexity of patch geometry and develops an innovative method to detect and quantify the scale and extent of the variation of patch geometry, using fragmented regression to estimate fractal dimensions. This method could therefore be used in other tropical rural and peri-urban areas, where the effects of anthropization on patch geometry are yet to be quantified and monitored (Vranken 2015).

Because deforestation and fragmentation are mainly driven by local populations, efforts must be made to reinforce the "GéLoSé" projects in the area, not only to raise better collective concern regarding deforestation and fragmentation but also to present the local population with new methods of livelihood, in order to decrease their impact on the forested environment. These methods may include sedimentary agricultural technique such as crop rotation; production of non-agricultural high-value goods, such as wild silk (Coulon et al. 2013); and production of non-charcoal-based energy, or, if proven impossible in the present infrastructural situation, a controlled charcoal production based on wood from plantations of low-impact and fast-growing species (Rakotondrasoa et al. 2013c).

To reverse the actual trend of fragmentation and deforestation and to achieve creation and enlargement of the forest patches (Table 1), direct forest conservation measures, such as a stronger enforcement of the ban on tapia logging, and reforestation through the creation of tapia tree nurseries and shrub plantations, have to be taken.

These projects would, however, require funding, as well as external monitoring (to avoid foul play, see "deforestation dynamics" in "Discussion") and governmental stability to ensure the continuity of the endeavor. But above all, these projects would require active participation and enforcement by the local population. This is probably the most important and most challenging issue to overcome in the area, as land claiming and clearing are an important part of Malagasy traditions and a prerequisite to create new family units (Keller 2008). Thus, in order to initiate this change in mentalities and traditions, the new methods of livelihood presented above should be introduced to local populations as attractive and efficient alternatives to traditional methods, through complete and socially adapted workshops and effective pilot projects.

Be that as it may, in 2013, the landscape in Arivonimamo II rural township was heavily deforested and fragmented, forecasting a medium-term loss of resilience of *U. bojeri* forest in the area, if none of these direct and locally enforced forest conservation measures are taken.

Acknowledgements The authors thank the GeVaBo project and its funding body, the Belgian University Commission for Development (CUD). The experiments used in this paper comply with the current laws of the country in which they were performed.

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