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The extent of edge effects in fragmented landscapes: Insights from satellite measurements of tree cover

Mateus Dantas de Paula[a,*], Jürgen Groeneveld[a], Andreas Huth[a,b,c]

[a] Helmoltz Center for Environmental Research UFZ Leipzig, Department of Ecological Modelling, Permoserstr. 15, 04318 Leipzig, Germany
[b] Institute of Environmental Systems Research, University of Osnabrück, Barbarastraße 12, 49076 Osnabrück, Germany
[c] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany

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ABSTRACT

Due to deforestation, intact tropical forest areas are increasingly transformed into a mixture of remaining forest patches and human modified areas. These forest fragments suffer from edge effects, which cause changes in ecological and ecosystem processes, undermining habitat quality and the offer of ecosystem services. Even though detailed and long term studies were developed on the topic of edge effects at local scale, understanding edge effect characteristics in fragmented forests on larger scales and finding indicators for its impact is crucial for predicting habitat loss and developing management options. Here we evaluate the spatial and temporal dimensions of edge effects in large areas using remote sensing. First we executed a neighborhood pixel analysis in 11 LANDSAT Tree Cover (LTC) scenes (180×185 km each, 8 in the tropics and 3 in temperate forested areas) using tree cover as an indicator of habitat quality and in relation to edge distance. Second, we executed a temporal analysis of LTC in a smaller area in the Brazilian Amazon forest where one larger forest fragment (25,890 ha) became completely fragmented in 5 years. Our results show that for all 11 scenes pixel neighborhood variation of LTC is much higher in the vicinity of forest edges, becoming lower towards the forest interior. This analysis suggests a maximum distance for edge effects and can indicate the location of unaffected core areas. However, LTC patterns in relation to fragment edge distance vary according to the analyzed region, and maximum edge distance may differ according to local conditions. Our temporal analysis illustrates the change in tree cover patterns after 5 years of fragmentation, becoming on average lower close to the edge (between 50 and 100 m). Although it is still unclear which are the main causes of LTC edge variability within and between regions, LANDSAT Tree Cover could be used as an accessible and efficient discriminator of edge and interior forest habitats in fragmented landscapes, and become invaluable for deriving qualitative spatial and temporal information of ecological and ecosystem processes.

1. Introduction

In tropical fragmented forests, a rich amount of research has focused on the ecological process changes that occur in the edges of forest fragments (Haddad et al., 2015; Ibáñez et al., 2014; Laurance et al., 2011, 2006; Wade et al., 2003). Due to microclimatic changes such as higher light incidence, reduced humidity and higher temperatures (Camargo and Kapos, 1995), the forest structure in edges is remarkably different from interior forest (Oliveira et al., 2008). Edge tree communities are more similar to early successional stages, with larger abundance of pioneer species, and low recruitment of large-seeded shade tolerant groups (Tabarelli and Lopes, 2008). Trees in these areas suffer from increased mortality, especially in the emergent stratum (Oliveira et al., 2008), resulting in lower aboveground carbon stocks in edges (Dantas de Paula et al., 2011). The continuing degradation of edges in recently fragmented forests presents a challenge for the control of carbon emissions (Chaplin-Kramer et al., 2015; Pütz et al., 2014). Even though global forest emissions have decreased by over 25% between the period 2001–2010 and 2011–2015 due to decline in deforestation rates, emissions due to forest degradation have more than doubled, and now represent one-quarter of total forest emissions (FAO, 2015), persisting especially in poor tropical countries (Sloan and Sayer, 2015). This means strategies to monitor forest degradation will become more relevant as deforestation rates decrease.

The spatial scale in which edge effects occurs vary from 10 m, in case of reduced density of fungus fruiting bodies, to more than 1000 m in the case of changes in plant phenology, increased fire

* Corresponding author.
E-mail address: mateus.dantas@ufz.de (M. Dantas de Paula).

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frequency and weed invasion, although most changes happen up to the 200 m distance range (Broadbent et al., 2008; Laurance et al., 2002). The temporal scale has also been observed, and the transition from an interior into an edge community at least 5 years (Laurance et al., 2002), although simulations suggests changes in stem number and biomass content can take up to 100 years (Dantas de Paula et al., 2015). The temporal dimension of fragmentation is important to note, because changes can take several years to manifest (Ibáñez et al., 2014). Therefore, three "debts" of recently fragmented forests have been identified (Haddad et al., 2015): the "extinction debt", where loss of forest species takes more than 10 years to reach 50% of previous pristine areas; the "immigration lag", where fewer species arrive in remote areas; and "ecosystem function debt", described as delayed changes in nutrient cycling and to plant and consumer biomass.

However, these debts still predict that edges will become degraded in relation to core areas. Therefore, specific observations have been reported for several biotic and abiotic variables—for example, edges have up to 36% less biomass than interior forests (Laurance, 1997). In spite of this, when samples, not average values are considered, some forest edge areas measurements show great variation and retain in some cases core area conditions (Ibáñez et al., 2014; Pinto et al., 2010), as can be seen with aboveground carbon content in Fig. 1.

Recent advances in remote sensing have been particularly useful for conservation biology, providing access to large amounts of data in short time, and permitting researchers to work in large scale with detail (Kerr and Ostrovsky, 2003). A particularly interesting dataset is the LANDSAT Tree Cover, a global 30 m resolution rescaling of the MODIS (Moderate Resolution Imaging Spectroradiometer) vegetation continuous fields (VCF) product (Sexton et al., 2013). The original MODIS VCF, with 250 m resolution, is a classification of annual global tree cover (each pixel having a value of 0–100%), and now is in its 5th version with yearly data from 2000 to 2010. It was developed in order to substitute conventional methods of categorical land classifications, which suffer from the imposition of arbitrary thresholds between classes (DeFries et al., 1995). The resulting tree cover pixel values, represent light penetration to the ground, as opposed to simple "crown" cover (Townshend et al., 2011). Several global and regional studies exist evaluating vegetation patterns of the MODIS VCF product (Hansen et al., 2005; Montesano et al., 2009; Ranson et al., 2011), its advantages and limitations (Hansen et al., 2005), and applicability in monitoring using ground validation data (Hansen et al., 2008a,b). Higher errors for MODIS VCF estimation of tree cover can be expected for values of tree cover lower than 20% (Jeganathan et al., 2009) The 30 m LANDSAT VCF dataset is a further improvement of the original MODIS product, and was created using 2000–2005 LANDSAT images and MODIS' own Cropland Layer in order to increase the accuracy of agricultural areas. Also, validation with high resolution LIDAR data was used, having a post-calibration RMSE of 9.4% compared to 13.5% in MODIS VCF estimates. (Sexton et al., 2013).

Tree cover is considered to be an important forest descriptor—it is has been used for calculations of absorbed photosynthetically active radiation (FPAR), albedo, canopy conductance, roughness, photosynthesis and transpiration, net primary production, and carbon and nutrient dynamics (DeFries et al., 1995). Furthermore, tree cover affects patterns of animal diversity (Harvey et al., 2006), large predator habitat preference (Conde et al., 2010), bird foraging dynamics (Trainor et al., 2013), and soil water balance (Joffre and Rambal, 1993). Also, tree cover influences human property value (Sander et al., 2010), and may help to indicate areas rich in the offer of environmental services (Huang et al., 2009). Finally, in regard to fragmented forests, tree cover has been identified as one of the most significant variables driving the microclimatic patterns of forest edges (Pinto et al., 2010).

One of additional goals of having large-scale information on the environment in fragmented forests is identification of areas for conservation (Groves et al., 2002; Poiani et al., 2000; Sanderson et al., 2002). Since the main focus for conservation biology is the preservation of endangered species, their occurrence, or of indicator species that signal preserved habitats, is the main pointer that an area should be protected. In the absence of those (or if indicator species are large area ranging carnivores), forest fragment size is used as criteria (Poiani et al., 2001), being larger fragments preferred. This makes sense because larger fragments have larger interior to edge ratios (less prone to edge effects) (Metzger and Décamps, 1997), can meet more species requirements in terms of area and heterogeneity(Martensen et al., 2012) and have more area isolated from human disturbances (Tabarelli et al., 2004; Veríssimo et al., 1995). However, several studies have pointed out the importance of very small (<100 ha) fragments in large-scale conservation schemes, due to their role in the increase of connectivity, use as stepping stones, and simply because in many cases a very large part of the remaining forest area is contained in the small fragment category (Hernandez-Ruedas et al., 2014; Ribeiro et al., 2009). Most approaches to conservation areas identification however, are limited due to the fact that no information on habitat quality within forest patches is included. In those cases fragment delimitations can include secondary and degraded forests, or patches occurring in poor soil types which are of suboptimal conservation value (Ribeiro et al., 2009).

In this work, we aim to observe how tree cover fraction changes in relation to forest edge distance, a measurement that is crucial to understand the ability of fragmented landscapes to retain biodiversity and ecosystem services. We use as an indicator of forest conditions LANDSAT Tree Cover (LTC) (Sexton et al., 2013), which although is indirect, can provide much more data and in a larger scale than field measurements of biotic variables. For this we analyzed 11 LTC images from different fragmented forest regions around the world in order to answer the question: How does LTC vary in relation to edge distance? It is crucial to use for this analysis the highest resolution sensors available, since edge effects are known to occur in the 100 m range (Laurance et al., 2002), and many sensors used for large scale studies have 300, 500 or 1000 m resolution (Chaplin-Kramer et al., 2015; Loveland et al., 2010; Pérez-Hoyos et al., 2012; Saatchi et al., 2011). Also, since many studies on edge effects (e.g. carbon loss in fragments) define a fixed distance for forest edges e.g. (Pütz et al., 2014), it is important to investigate the distance threshold beyond which edge effects do not affect our measured variable.

2. Materials and methods

2.1. Analysis of edge effects on LANDSAT Tree Cover

We selected 11 complete LANDSAT Tree Cover (LTC) scenes (each 170×185 km, with 30 m resolution) from several fragmented forests around the world (Fig. 2) using the Global Land Cover Facility (http://glcf.umd.edu/data/) website, for the year 2000. The 11 scenes are home to 3 different forest types: Closed broadleaved deciduous forest, Closed to open broadleaved evergreen or semi-deciduous forest, Closed to open mixed broadleaved and needleleaved forest, as categorized by the GLOBCOVER 2009 v2.3 map (http://due.esrin.esa.int/page_globcover.php). We calculated statistical information for each fragmented landscape and present them in Table 1. This illustrates the diverse conditions of our selected scenes (Forest extent varying from 1.86% in scene 7 (Northeastern Brazil) to 56.89% in scene 11, Northern Brazil 2). As an example, in Fig. 3 LTC values for two sites in Brazil are shown. In each selected scene, we defined forest fragments, using a >30%

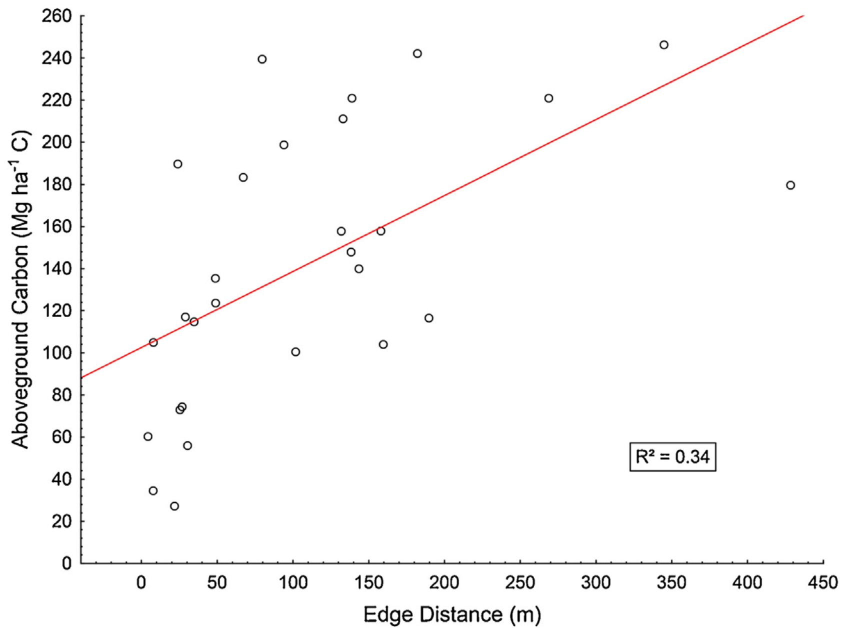

Fig. 1. Above ground carbon tree content from 0.1 ha (upscaled to 1 ha) samples measured in the Northeastern Atlantic Forest of Brazil (adapted from (Dantas de Paula et al., 2011)) in relation to sample edge distance.

Table 1
Landscape statistics for the selected LANDSAT scenes. Areas are in square kilometers (km^2). SD: standard deviation; VAR: variance; NE—Northeast, SE—South East, N—North. Forest types were defined using the 2009 GLOBCOVER map. (A) Closed broadleaved deciduous forest; (B) closed to open broadleaved evergreen or semi-deciduous forest; (C) closed to open mixed broadleaved and needleleaved forest.

Scene No. Location	1 USA	2 Australia	3 Cambodia	4 Madagascar	5 Poland	6 Germany	7 NE Brazil	8 SE Brazil 1	9 N Brazil 1	10 SE Brazil 2	11 N Brazil 2
LANDSAT Scene Id.	p021r030	p089r079	p125r052	p159r069	p190r024	p194r023	p214r065	p221r075	p223r064	p223r076	p224r067
Forest Type	A	B	B	B	C	C	B	B	B	B	B
Land	32,085.04	16,477.43	30,167.23	11,967.91	33,246.92	32,254.04	18,626.09	32,725.96	32,037.44	32,563.95	32,820.26
Forest	6,768.00	4,506.81	7,341.42	1,168.58	4,834.22	7,063.02	347.79	716.17	9,554.90	1,192.28	18,670.19
Forest Extent (%)	21.09%	27.35%	24.34%	9.76%	14.54%	21.90%	1.87%	2.19%	29.82%	3.66%	56.89%
Largest Fragment	145.87	695.45	2,360.51	302.12	399.43	794.93	18.24	28.07	458.85	182.08	9,260.07
Non-Land	1,306.16	16,913.77	3,493.70	21,640.70	395.62	1,209.13	14,303.44	769.08	828.32	949.95	27.61
Average Fragment Size	0.77	2.17	3.32	1.80	1.73	2.01	0.69	0.55	2.06	0.98	10.75
Fragment Size VAR	14.83	809.34	3,053.04	181.16	98.02	262.34	2.73	2.43	173.99	52.11	67,335.21

LTC threshold criterion. Other thresholds (20%, 50% and 70%) were also tested for one of the scenes, and are available in the appendix (Figure A1). In order to evaluate the gradient of tree cover in the images, we executed a focal neighborhood analysis calculating the mean and standard deviation of tree cover around each pixel, generating output maps of local mean and SD. These maps were then correlated with edge distance maps, where each pixel represents the distance to nearest edge. Since pixels on the border of a forest fragment can be potentially an average of forest-non forest areas, we consider only pixels with an edge distance larger than 60 m (two pixel distance from edge). We tested different window sizes for the neighborhood analysis (Figure A2), from 2 to 200 pixels and concluded that a window size of 4 × 4 (1.44 ha, with approx. 60 m radius) is adequate since we want to try and capture the tree cover variation within the 100 m mark. This distance value is interesting because many processes are known to be affected at distances up to 100 m (Laurance et al., 2002).

In order to better visualize the distance where the neighborhood standard deviation in edges stabilize (i.e. the distance where edge effects stop occurring, and the interior forest begins) we executed a local regression and plotted a LOESS (locally weighed scatterplot smoothing) curve through the data. We decided here not to develop a model yet explaining the reduction in tree cover variation in relation to edge distance, because of the potential complexity of the explanatory variables (land use history, forest type, topography, soils, etc.) and limitations of LTC.

2.2. *Temporal analysis*

Finally, we selected one large fragment from the deforestation arc in Brazil, near the city of Araguaia, State of Pará, which is intact in the year 2000 scene, but becomes fragmented in the year 2005 scene. This area allows us the opportunity of observing possible tree cover changes over the period of 5 years or less caused by edge effects and their extent. This analysis was done in the same manner as the previous one, using a 4 pixel window neighborhood analysis to calculate mean LTC. The edge distance map for 2005 (when the landscape became fragmented) was used for both images in order to evaluate edge influence before and after fragmentation.

3. Results

The temporal analysis from the fragmentation images of Araguaia, in Northern Brazil (Fig. 4) show the relevance of LANDSAT Tree Cover for fragmentation studies. According to the forest change data for the area from (Hansen et al., 2013), the main fragment has been systematically cut between 2000 and 2005, resulting in forest remnants with different edge ages. The scatter-

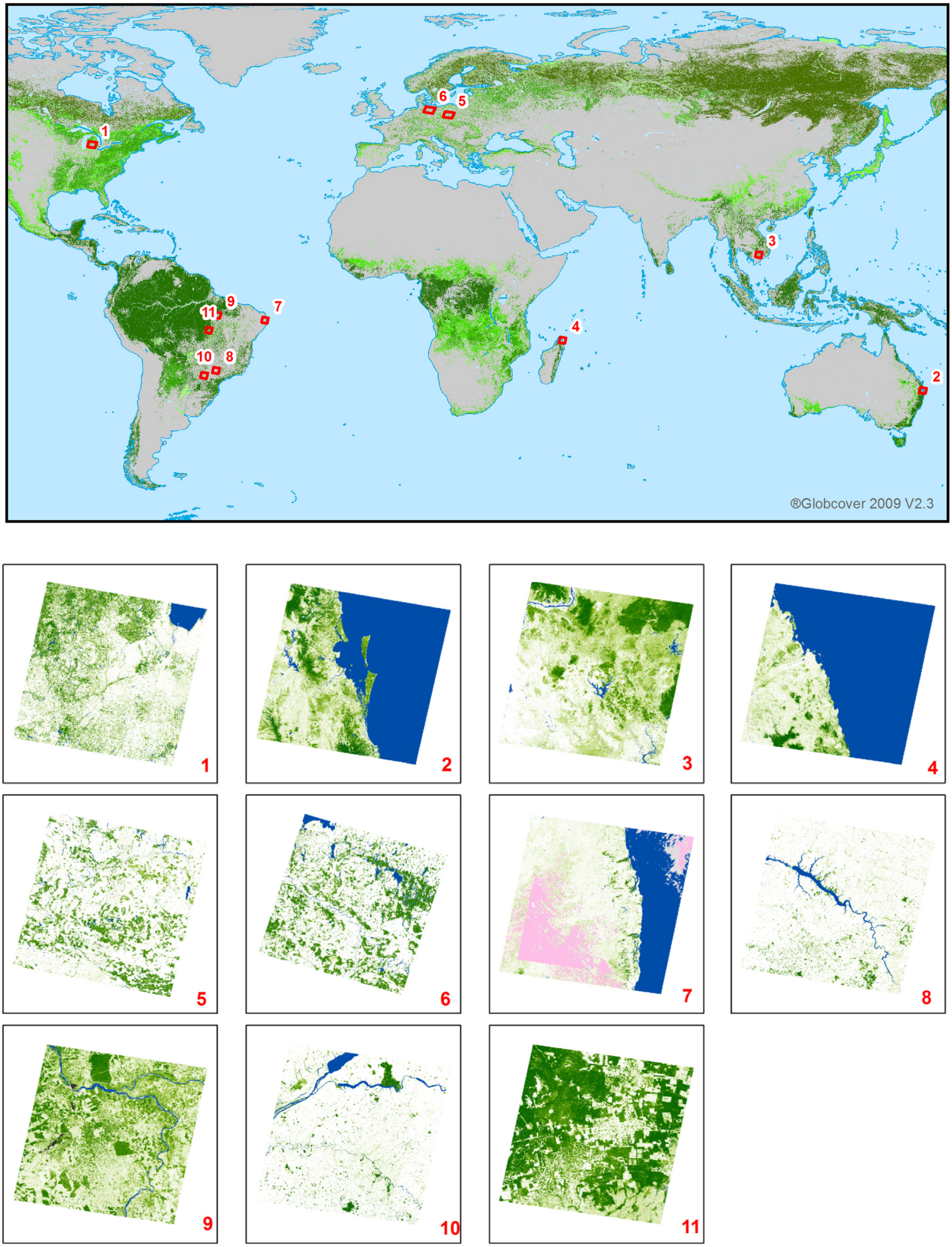

Fig. 2. Selected LANDSAT Tree Cover scenes for image analysis. (1) Northern United States; (2) Eastern Australia; (3) Central Cambodia; (4) Northern Madagascar; (5) Central Poland; (6) Central Germany; (7) Northeastern Brazil, (8) Southeast Brazil 1; (9) Northern Brazil 1; (10) Southeast Brazil 2; (11) Northern Brazil 2. The pink areas in scene 7 are cloud and shadow coverage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

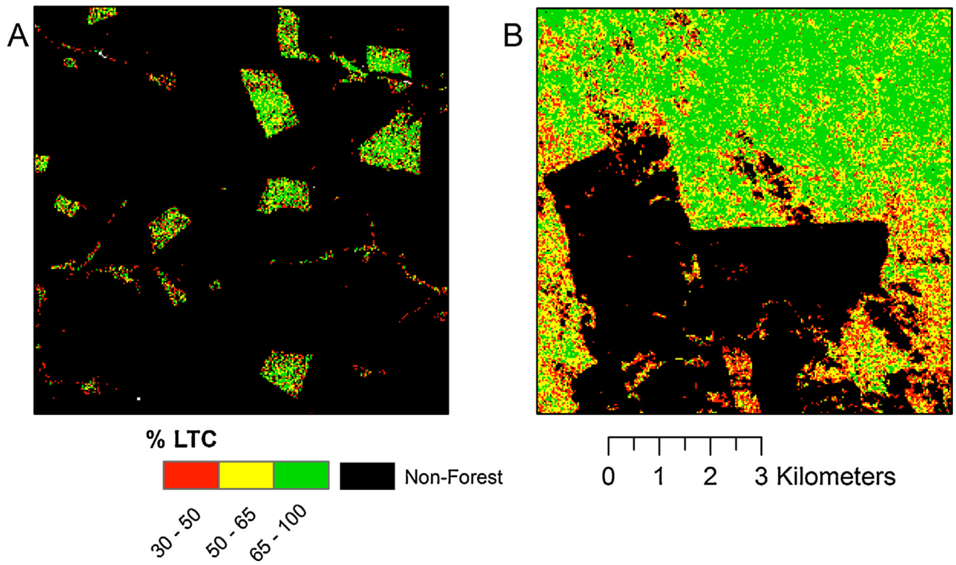

Fig. 3. Detail of two scenes ((A) scene number 10. SEB2. (B) Scene number 11. NORB2), showing typical LANDSAT Tree Cover (LTC) values grouped into 3 categories. Note that low LTC values (red pixels) occur often close to deforested areas (black), but also many medium (yellow) and high (green). The scale bar is valid for the two scenes, and water bodies are a separate class. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

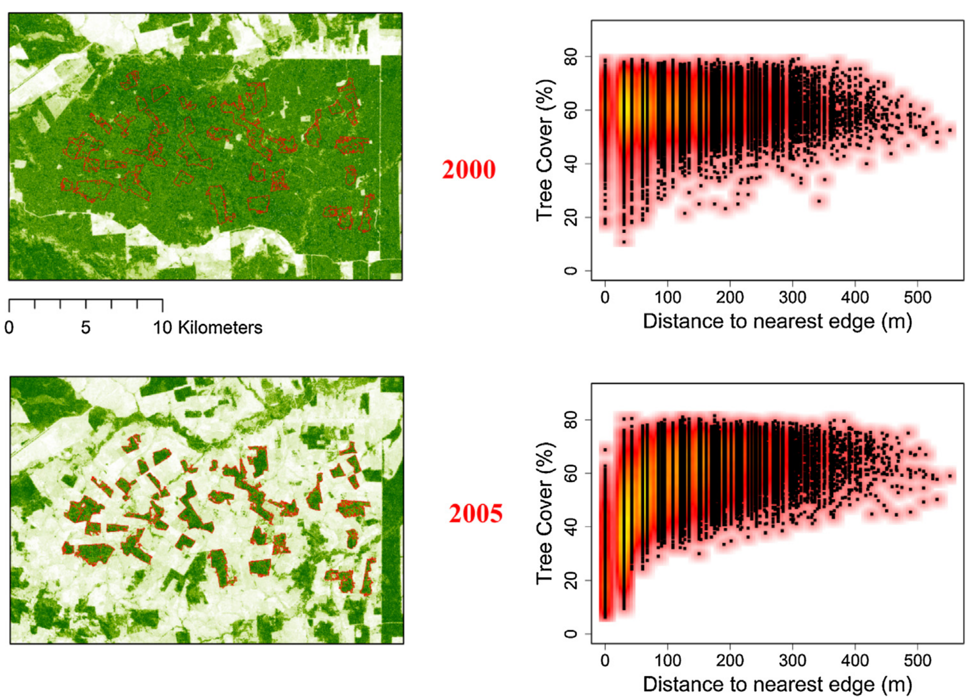

Fig. 4. Analysis of the rapid breakup of a large fragment in the Araguaia region, Northern Brazil (part of LTC scene 11, N. Brazil 2) The scatterplots compare tree cover values before and after fragmentation. Colors indicate low (red) to high (yellow) point density, representing the amount of pixels which have a particular tree cover value at this distance. It can be seen that there are more points with low LTC is in the 2005 scatterplot for the first 100 m edge distance, pushing the mean LTC significantly lower than in the 2000 image for this distance class. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

plots in Fig. 4 show that the range of LTC values between 30 and 100 m from the edge between 2000 and 2005 increased, with more lower LTC values in the 2005 image than in the 2000. If we consider the mean for this distance class, it is significantly lower in the 2005 image (T test, LTC mean 2000 = 60.55 ± 7.489 SD; LTC mean 2005 = 49.63 ± 11.975 SD; $p \ll 0.05$), and the variance increased from year 2000 (56.09) to year 2005 (143.4).

The graphics for the 11 LTC scenes (Fig. 5) show an interesting similarity for the heterogeneity of tree cover in edges, even when including temperate regions. All 11 scenes have a significant trend on lower tree cover for edge habitats, but a more striking pattern is the great variability in sampled tree cover near edges. In this graph all scenes have reduced standard deviation of LTC as edge distance increases, although the steepness and leveling value of the curves differ for each scene. From the mean LTC values in Fig. 5 it is also possible to observe higher values and less variation as we penetrate into the core, indicating that these areas can be considered "interior forest". These areas far from edges are of course only present in larger forest tracts. Tree cover therefore seems to exhibit a characteristic "fan shape" pattern in relation to edge, reducing variability as distance from the edge increases. This pattern shows similarity with the forest carbon-edge distance plot from Fig. 1.

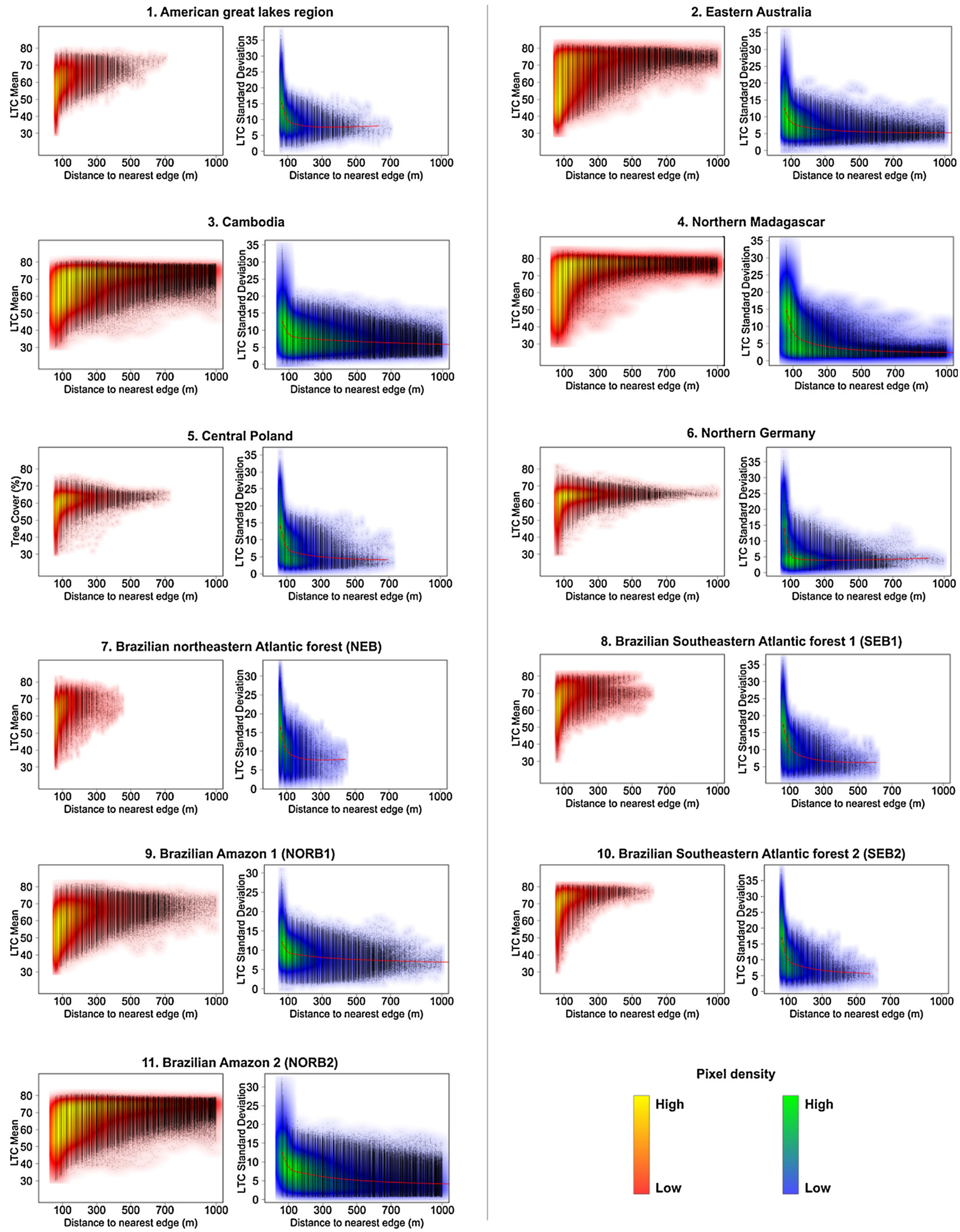

Fig. 5. Graphs of neighborhood (4 pixel window) means and standard deviation of LANDSAT Tree Cover (LTC) pixel values in relation to edge distance for the 11 scenes. Colors indicate low (red or blue) to high (yellow or green) pixel density. In the standard deviation graphs, the red line represents the LOESS fitted curve, which suggests possible thresholds for the end of edge-affected habitats. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

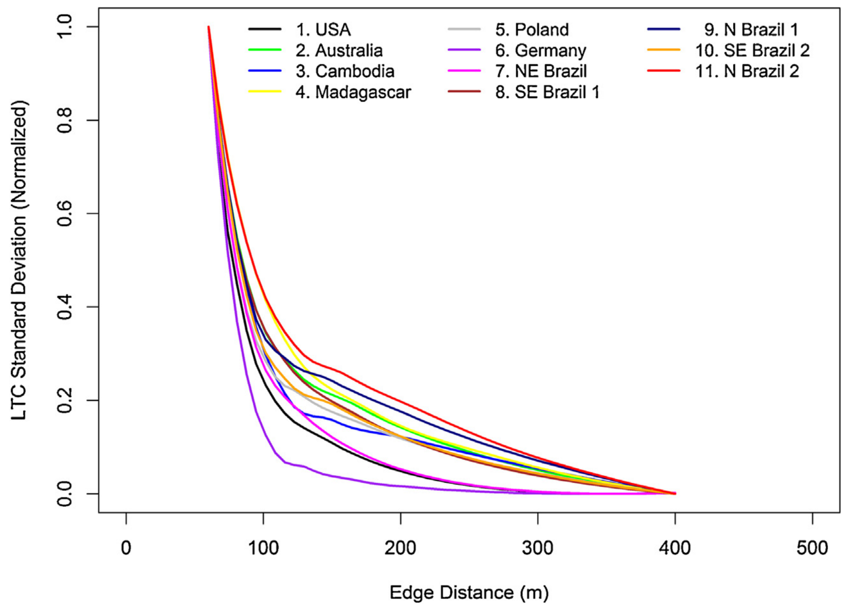

Fig. 6. LTC Standard deviation LOESS (locally weighed scatterplot smoothing) curve in relation to edge distance for each region, normalized in relation to maximum and minimum values, within the first 400 m.

In order to better visualize the standard deviation curves and compare our 11 analysed regions, we plotted them into a single graph, and normalizing the SD values in relation to its maximum (Fig. 6). Here we can observe the difference between the steepness of the LOESS curves, greater for some regions such as 6. Germany, and lower for 9. N. Brazil 1 and 12. N. Brazil 2.

4. Discussion

In this study although we are considering only one environmental variable, LANDSAT Tree Cover (LTC), to quantify habitat quality using remote sensing, we have reason to believe that it can be an invaluable tool for assessments of edge effects in forested landscapes and fragment conditions. We decided to maintain our approach data driven and not specify a function to fit the patterns we observed. However, we believe the approach we have shown here can be a step up from defining core areas through a fixed distance from the literature. We suggest that researchers in forest fragmentation to acquire freely LTC data from the global landcover facility (http://glcf.umd.edu/data/) for their study region and plot LTC variation in relation to edge distance in order to objectively define forest edge habitats.

For ecosystem and ecological processes that correlate to tree cover, we can expect their values to also vary with a fan pattern in relation to edge distance. Indeed, in a recent study using biomass maps, a fan pattern can be glimpsed from the biomass density/edge distance correlation, even though their map resolution was 1 km × 1 km (Chaplin-Kramer et al., 2015). Our initial expectations in relation to the behavior of tree cover in relation to edge distance, was that it had lower average values, and that standard deviation remained constant. After observing our results, we can say that LTC values present a "fan shape" pattern in relation to forest edge distance, with high variance near the edge and lower variance towards the forest interior. The fan shape suggests the distance in which the variation significantly reduces (this can also be well observed in Fig. 6). This has important implications for conservation, since fragments that have forest area beyond this point will probably retain undisturbed conditions. We can infer the extent of the penetration of edge effects by observing the LOESS curves in Fig. 5 and its steepness in Fig. 6, and while for some scenes the standard deviation curve steepness is larger and the values level off at around 100 m (ex. 5, Poland; 6, Germany; 7, NE Brazil), for others the steepness of the curve is lower and it levels at around 500 m (4, Madagascar) or not at all within the plotted 1000 m (3, Camboja; 11, N. Brazil 2). This estimation is of course still at a subjective state, but we can nevertheless speculate on the possible mechanisms behind these patterns.

We suggest that this large variance in edges and "fan pattern" arises from three possible causes: Degradation debt, Hyperdynamism and Landscape Heterogeneity.

4.1. Degradation debt

Here we define "degradation debt" as a broad term referring to the mentioned three debts identified for fragmented forests (extinction, immigration and ecosystem function debts). In any landscape undergoing forest change, we can expect to see simultaneously several stages of edge degradation at any particular time, as is the case of a satellite image "snapshot". This means that the observed fan pattern could arise from edges areas that still had no time to degrade. In landscapes with no or little deforestation, based on degradation debt we should see edge areas having low tree cover values.

If degradation debt is the main cause for high edge LTC variation, then the steepness of the standard deviation curve should be lower in landscapes undergoing recent change, and higher in landscapes without recent change (since in these the edges had time to degrade). We have not analyzed forest change data for our scenes, but in future work it would be interesting to combine our results with recent forest change maps, such as (Hansen et al., 2013). In Fig. 6 we can observe that scenes 1 (USA), 5 (Poland), 6 (Germany), 7 (NE Brazil) and 8 (SE Brazil 1), areas where fragmentation has occurred furthest in time have the largest steepness of the SD curve. The scenes known to present higher and recent rates of forest change, such as N. Brazil (9 and 11), Australia (2) and Cambodia (3) have lower steepness in the LTC SD curves, which seems to confirm the role of degradation debt in generating the fan pattern. However, the LTC standard deviation—distance graphs from Fig. 6 still show a large amount of edge variation for all scenes, highlighting the need for a more thorough study of how much deforestation patterns and rate influence the difference between edge and interior tree cover variation.

4.2. Hyperdynamism

The observed fan pattern can be related to the hyperdynamism concept presented by (Laurance, 2009), which states that population and community dynamics of forest edges will become unstable. Edge areas and small fragments are more prone to environmental stochasticity and are strongly affected by the human influenced areas that surround them. Field observations has been consistently showing a large variation in several abiotic and biotic measurements in edge habitats, even though average values are as a rule significantly different from interior fragment areas (Ibáñez et al., 2014; Haddad et al., 2015). For example, edges located at same distances from the forest border have been found to exhibit different microclimatic conditions (Camargo and Kapos, 1995; Pinto et al., 2010). This edge variance can also be noted clearly in our study. Since LTC is considered as an indicator of several processes, we should expect large variation in LTC in the vicinity of edges due to hyperdynamism.

One of the questions proposed during the formulation of the hyperdynamism concept is whether this process is chronic (edge areas will always be unstable) or not (will tend to an equilibrium after some time). Analyzing tree cover as a function of edge distance (Fig. 5), we can observe that standard deviation in edges is always larger than in interior forests, even in what we consider to be older and more stable landscapes. This would seem to support the chronic nature of hyperdynamism in fragmented forests. Further studies therefore are necessary to elucidate the role of hyperdynamism in the edge variation of tree cover.

4.3. Landscape heterogeneity

Since edges are considered altered habitat up to a certain distance for a given process, it is assumed that a distance "buffer" strip alongside a fragment's edge represents the region affected by degradation effects. It has been shown however that "edges" take complex shapes, and may be completely absent (i.e. they may retain interior forest conditions), as shown by (Camargo and Kapos, 1995; Pinto et al., 2010). One of the reasons for this could be heterogeneity in the landscape: topography, soil conditions, prevalent wind conditions, proximity to water bodies, and any other factors that affect microclimatic and tree survival conditions in edge areas. We should definitely then expect large LTC variation due to varying conditions of the landscape in forest edges, since degradation intensity would be dependent on local conditions. This hypothesis could be tested in a fairly straightforward way, by crossing the LTC data with other landscape maps such as topography. Finally, it is possible that differences between interior forest SD values of each scene, as seen in Fig. 5 are caused by different forest dynamics in each region, which lead to tree cover heterogeneity. It is natural to assume that different forest types would react differently to edge effects, but within the GLOBCOVER categorization forest types did not seem similar in relation to standard deviation of tree cover. This does not exclude the possibility of finding patterns of edge effect penetration in relation to forest types. Such a pattern if found would be very interesting, and should be explored in future studies.

4.4. Implications for conservation

Since in severely fragmented forests most remaining habitat is located in small fragments comprised entirely or in part of edge forests, we can expect that these forest remnants will exhibit the same variance observed for the sampled edges in our study. This means surprisingly, that some forest fragments completely consisting of edge areas can also retain high tree cover values. In these fragments, the mortality of large trees predicted for edge dominated habitats (Oliveira et al., 2008) has probably not taken place with the same intensity as in other remaining patches of forest. This still does not mean that these smaller fragments are a substitute for larger tracts of forest, due to their lower connectivity and higher vulnerability to human encroachment (Tabarelli et al., 2004). But it does seem possible that if protected, they will retain good habitat conditions and would be invaluable as stepping stones. Also, forest restoration efforts in such areas could be much facilitated in relation to known degraded edge areas (Rodrigues et al., 2011). Although much can and should be investigated correlating the varied edge tree cover data with other landscape characteristics (soil, topography, distance to roads), the fact that such edge-effect resistant areas could exist and readily identified is already great news for the development of biodiversity-friendly landscapes, where human management can promote species coexistence (Melo et al., 2013).

The concept that edge habitats are necessarily inferior to core areas has motivated the emergence of many conservation strategies. For example, fragment size and shape are used as proxies for high quality habitats, as well as fragment core area presence, according to typical edge effect distances (Villard et al., 2014). This approach is frequently complemented in landscape analysis categorizing fragment area into edge and interior forest, separating both by a distance buffer. Considering the extreme variation of edge habitats, of which small fragments mainly consist, we have shown that this approach is limited and can lead to imprecise large-scale estimations of any particular edge affected variable, as well as the neglect of important small forest remnants. On the other hand, in this study areas far from the edge have shown consistently high tree cover values, confirming the importance of large fragments that are able to exhibit these regions. In summary, fragment size can be considered as a measure of habitat quality (using as LTC environmental indicator of quality), but the high variability of smaller fragments and different distances where edge effects are detected for each region must be considered.

5. Conclusion

Based on our results on the 11 LANDSAT scenes, we conclude here that forest edges in fragmented landscapes have low average and high variation in tree cover values. As the distance from the forest edge increases, tree cover variation decreases and its average values becomes higher. The resulting tree cover-edge distance graph resembles a fan, which can be used to characterize edge effects. This variation of tree cover in relation to edge distance (fan shape) varies depending on the analyzed region, meaning that maximum edge effect penetration distance and intensity differs between landscapes.

A tool such as Landsat Tree Cover can be very useful for ecologists to analyze large scale habitat conditions in fragmented forests. Its use, along with maps of forest cover change which are now available, should be encouraging for research, since LTC can offer much information on the influence of fragmentation in the tree structure of forests. As degradation becomes a relevant process in relation to forest carbon emissions and threat to biodiversity, identifying its drivers and management options are increasingly important research topics. Although here we have not tested drivers for our pattern, we suggest that degradation debt, hyperdynamism and landscape heterogeneity are the possible underlying causes for our observed fan shape pattern and high edge variability. Land use history will definitely also play a major role (Lambin et al., 2003), highlighting once more the importance of direct and indirect measurements of habitat quality for suitable assessments of human modified landscapes.

For conservation actions it is essential to accurately quantify habitats, and not simply consider fragments as homogeneous tracts of forest. Correctly identifying edge and core areas is essential in this aspect, and LTC can be used as an objective tool in order to point out thresholds between both habitats—however more studies are needed in order to construct an edge limit identifying framework which can be incorporated into standard methodologies. As new remote sensing products such as Landsat Tree Cover become available, landscape and regional scale studies can be greatly improved, helping to understand habitat change in the very dynamic landscapes of fragmented regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.04.018.

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