Combining airborne lidar and acoustic remote sensing to characterize the impacts of Amazon forest degradation

Danielle Rappaport[1]
Douglas Morton[2]

[1]University of Maryland
College Park - MD - 20740, USA
drappap@umd.edu

[2]NASA Goddard Space Flight Center
Greenbelt - MD - 20771, USA
douglas.morton@nasa.gov

Abstract. Frontier forests in the Brazilian Amazon have been heavily altered by nearly a half-century of deforestation for agriculture and degradation from fire and logging. The long-term effects of forest degradation on habitat structure and habitat use remain poorly understood, largely due to the limitations of traditional field methods for characterizing heterogeneity at relevant spatial and temporal scales. This work demonstrates the opportunity to assess degradation impacts on ecosystem structure and biodiversity at landscape scales (200 km^2) by combining airborne lidar and acoustic remote sensing across two municipalities in Mato Grosso, Feliz Natal and Nova Ubiratã. Among degradation classes, our results indicate that repeated fire events have the most destructive legacy for both habitat structure and habitat use. Lidar analyses reveal that repeated fire events can result in a total loss of original canopy trees. Similarly, our acoustic analyses suggest that repeated fires may fundamentally transform animal community composition. The combination of remote sensing approaches bridges the scale gap between ground-based and satellite observations to support a regional-scale investigation into the complex consequences of Amazon forest degradation.

Key words: bioacoustics, fire, logging, biodiversity, sensoriamento remoto, lidar aéreo

1. Introduction

The Brazilian Amazon contains approximately 25% of the world's forest carbon stocks, the largest catchment of freshwater, and one of the richest holdings of biological diversity worldwide. Degradation from large-scale understory fires (Morton et al. 2013) and logging (Asner et al. 2005) continues to threaten those resources. In 2010 alone, the area affected by fires was about eight times larger than the area of deforestation for agricultural expansion (Morton et al. 2013); and more recently, widespread fires were reported during the 2015-2016 El Niño drought in central and northern Amazonia (INPE 2016).

The extent of forest degradation from logging and fire can be routinely monitored using Landsat and MODIS, but much less is known about the long-term effects of these disturbances, particularly the insidious impacts to ecosystem structure and biodiversity that are not readily apparent from space. Amazon frontier landscapes are expansive mosaics of fragmented and degraded forests with heterogeneous structural and floristic properties based on the legacy of decades of land use. Successfully characterizing change means being able to measure fine-scale variability across broad spatial extents. This poses an enormous monitoring challenge, as conventional field techniques seldom translate to landscape scales. Field plot networks traditionally used to characterize ecosystem change can be costly to establish and difficult to maintain in dynamic frontier landscapes. A key focus of forest monitoring with remote sensing technology has been to extend field data to estimate carbon emissions in support of efforts to Reduce Emissions from Deforestation and Forest Degradation and enhance forest carbon stocks

(REDD+). Yet, REDD+ activities may also confer valuable co-benefits beyond carbon storage, and the remote sensing community is in a unique position to help inform investigations into the ecological benefits of avoiding degradation from fire and logging.

In addition to eroding carbon stocks, fire and logging can also fundamentally transform the distribution and composition of vegetation through selective removal or mortality of tree species, suppressed regeneration, altered soils, and depleted seed banks (e.g. Brando et al. 2014). Such changes can reduce the availability of resources for fauna, such as habitat for nesting, foraging and predator protection, but we know very little about the long-term consequences (Barlow and Peres 2004; Barlow et al. 2006). Previous research into the short-term impacts of forest degradation on birds has shown that low-intensity understory fires and high-intensity logging result in changes to the avian community that are akin to the most severe forms of forest fragmentation (1-10 ha) (Barlow et al. 2006). However, there is little information on how vertebrate communities shift over time, and how these responses vary with degradation frequency or severity. These knowledge gaps should represent a “call to action” to the remote sensing community to develop methods that can help extend field-based biodiversity data over policy-pertinent extents (Pettorelli et al. 2014; Bustamante et al. 2015).

Lidar and acoustic remote sensing are two emerging remote sensing technologies that complement field and satellite data for studies of ecosystem structure and biodiversity, yet the synergies between these two approaches have hardly been explored (Bergen et al. 2009; Aide et al. 2013, Bustamante et al., 2015). Lidar is arguably the most accurate remote sensing method for collecting detailed information on forest vertical structure, and it can retrieve fine-scale parameters over extents large enough to support ecosystem investigations at the landscape scale. Lidar-derived structural parameters, such as canopy height, leaf area, and aboveground carbon density, have been successfully used for habitat and species modeling (Bergen et al. 2009).

Acoustic remote sensing, or bioacoustics, is an emergent monitoring approach that has garnered tremendous research interest over the past five years for its potential to support efficient and accurate assessments of biodiversity across diurnal and seasonal time scales and broad geographic extents (Blumstein et al. 2011; Aide et al. 2013; Fuller et al. 2015). One of the key advantages over traditional surveys is that automated recorders can be deployed in multiple sites to simultaneously sample the acoustic environment at the landscape scale. In the species-rich humid tropics, taxonomic expertise can be scarce and expensive, limiting most field-based surveys to the local scale. Automated bioacoustic approaches can dramatically reduce the effort and cost associated with large-scale monitoring due to the cost-effectiveness and reliability of off-the-shelf units; and rapid advances in battery technology support long-term monitoring (>20 days) in a non-invasive manner. Further, acoustic recordings provide a permanent digital record that can be repeatedly analyzed and independently validated following data collection to support future investigations well beyond the original scope of the acquisition. The resulting datasets can be classified in terms of species composition through machine-learning algorithms that identify species-specific acoustic signatures—much like classification techniques with other remote sensing data (Aide et al. 2013). Bioacoustic data can also be aggregated to assess community diversity based on changes in the acoustic environment across space or time (Sueur et al. 2008).

This work pioneers an approach that combines airborne lidar and acoustic remote sensing, together with field inventories and Landsat time series, to characterize the variability in ecosystem structure and species diversity across a degraded frontier landscape. This work directly responds to recent requests for more parallel ecosystem-biodiversity assessments to ensure that policies such as REDD+ yield positive outcomes for both biodiversity and biomass (Pettorelli et al. 2014; Bustamonte et al. 2016).

2. Methodology

2.1 Study area and data

The study area is located in the municipalities of Féliz Natal and Nova Ubiratã in northern Mato Grosso state in the southern Brazilian Amazon (Figure 1). Positioned in one of the Amazon's most dynamic land-use frontiers, this is an optimal site for studying the impacts of degradation. This region has among the highest rates of single and recurrent fires across the entire Amazon basin, and has been subjected to selective logging and fragmentation for over four decades (Morton et al. 2013).

Multiple data sources were combined to assess habitat structure and species diversity based on degradation history (i.e. disturbance type, frequency, and age). Time series of annual Landsat data from 1984-2016 were used to reconstruct the history of forest degradation for three Landsat tiles (225/068, 226/068, 226/069), resulting in a spatially-explicit inventory of fire and logging events (Morton et al. 2011; Morton et al. *in prep*). Time-series approaches can overcome the challenges in mapping cryptic landcover changes by tracking the temporal differences in vegetation recovery to differentiate among disturbance agents (Morton et al. 2011).

Between 2013 and 2016, high-density airborne lidar and forest inventory data were collected across a range of intact and degraded forest types as part of the Sustainable Landscapes Brazil project (data available at: https://www.paisagenslidar.cnptia.embrapa.br/webgis/). By using long strips of sampled lidar (Figure 1), the spatial length scales and characteristic patterns of variability in habitat structure and canopy damage can be characterized at the landscape scale. The space-for-time sampling of lidar and field plots specifically targeted a range of degraded forest conditions to support an analysis of the role of degradation history in shaping contemporary vegetation patterns.

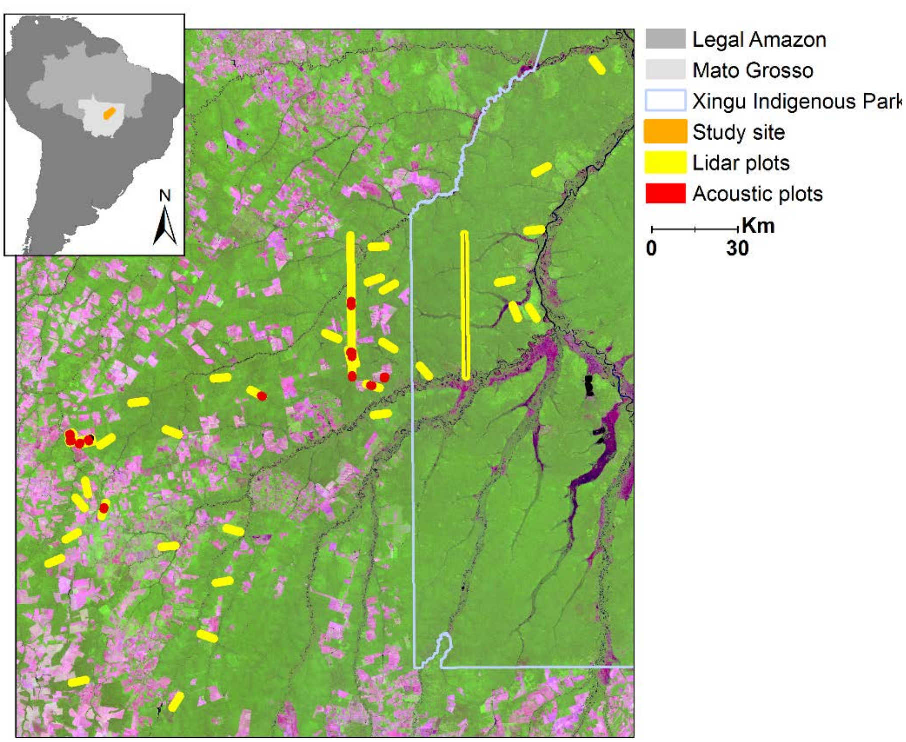

Figure 1. A 2014 Landsat 543-RGB image of the study site with locations of the 2014-2016 lidar acquisitions (yellow) and the 2016 acoustic samples (red).

Passive acoustic recording sensors designed by Automated Remote Biodiversity Monitoring Network (ARBIMON; Aide et al. 2013) were deployed between August and October 2016 across a range of degraded forest sites where lidar and field data were acquired. A total of 13 degraded forest sites were sampled that comprise a broad gradient of degradation attributes in terms of disturbance type and timing (Figure 1). Three replicates were installed within each treatment to capture the characteristic spatial heterogeneity within degraded forest stands. Samples were spaced 300m from one another and from the non-forest matrix, following a standard protocol for avoiding edge effects and establishing spatial independence (Aide et al. 2013). The acoustic sensors recorded all activity between 0 to 22kHz, and were programmed to automatically record one minute of sound every five minutes for a minimum of five days at each site (n = 56,160 recordings). In total, more than 936 hours of acoustic data were collected across the study region.

2.2 Analysis

A suite of lidar canopy structure metrics were generated from the high-density discrete return airborne lidar using standard methods (Cook et al. 2013). A space-for-time approach was used to evaluate the structural impacts of fire and logging, including changes from recurrent degradation events, as well as recovery dynamics following disturbance. The fraction of remaining canopy trees from the original forest stand in logged and burned forests was evaluated by calculating the percentage of the degraded canopy that exceeded the mean canopy height of the nearby intact reference forests, based on the 1m canopy height model (CHM), and aggregated to $10m^2$.

The bioacoustics data were summarized in the time and frequency domains to investigate how animal communities respond to differences in forest structure from degradation. Spectrograms were computed from the recordings using a short-time Fourier transform that decomposed the audio signal using 512 samples per temporal interval into 256 frequency bands of 86.13Hz. To generate site-level acoustic summaries, the spectrograms, or time-frequency representations of the acoustic signals collected as one-minute samples, were aggregated by hour and site. The resulting sound summaries, or soundscapes, provided a synthesis of all the acoustic activity at a given site rendered as a three-dimensional matrix (x=hour, y=frequency, z=amplitude). Acoustic space can be thought of as a competitive resource, and the amplitude, or sound intensity, is an indication of the relative importance of each of the available channels of transmission/reception for animal communication within each site. A normalized amplitude threshold of 0.01 was used to isolate animal-generated noise from abiotic noise, such as wind.

To characterize differences in acoustic activity along the gradient of degradation impacts, a Ward's hierarchical cluster analysis was computed to calculate the difference in acoustic composition (i.e. utilization of the time/frequency cells) across sites based on Euclidian distances between all combinations of soundscape matrices. For each of the resulting clusters, p-values were calculated through a multiscale bootstrap resampling routine based on 10,000 iterations, and clusters that were strongly supported by the data (AU>95) were highlighted. All analyses were conducted within the open-source statistical software R version 3.1.1.

3. Results and discussion

Lidar-based estimates of forest height varied by degradation type (Figure 2). Logged forests, both young and old, harbored taller trees than forests subjected to repeated fires. To further differentiate disturbed stands by successional stage, measures of canopy complexity (e.g., the skewness or kurtosis of the lidar returns) were generated to highlight contrasting patterns between remnant canopy and regrowth following disturbance. Vertical structure within forests with similar disturbance histories was also highly variable, highlighting the importance of lidar data to capture habitat variability over a range of spatial scales.

The lidar data also provided key insights into the remnant forest structure following disturbance events (Figure 3). Intact forests in the study region had mean canopy heights of 21m (55% of intact forest canopies exceeded this threshold). Using the intact canopy height threshold as a reference, we estimated the proportion of remaining canopy cover following different degradation frequencies and intensities. Recently logged forests were found to have lost an average of 51% of their original canopy trees within three years of logging. Older logged forests were able to recover 87% of their original canopy, on average, after a decade of regrowth. We found recurrent fires to have the most profound effect on forest structure. In the most extreme case, forests subjected to five fire events within one decade were found to have lost 100% of their original canopy.

The bioacoustic-based analyses also demonstrated that forests with a history of multiple fires underwent the most dramatic biodiversity transformations. The hierarchical cluster analysis revealed two major clusters of acoustic diversity and composition that can be characterized in terms of previous degradation history (Figure 4). Forests that were subjected to repeated fire events were distinctly dissimilar from all other disturbed forests that were evaluated. To assess the acoustic parameters responsible for the differentiation of logged and burned forests, soundscapes were interpreted to evaluate spatiotemporal variability in the utilization of acoustic space across sites (Figure 3). The peaks of acoustic activity between dusk and dawn that were most pronounced in logged forests were obfuscated by mid-day peaks in the repeatedly burned forests. This greater temporal homogeneity within the biophony range (2-11 Hz) of the repeatedly burned forests may indicate that a small number of species are monopolizing the acoustic space. Previous research suggests that communities with a higher diversity of species produce more heterogeneous soundscapes (Sueur et al. 2008).

The results from our rapid remote sensing-based assessment of differences in logged and burned forest communities is consistent with field studies, which have documented the unparalleled consequences of repeated fire events for Amazonian fauna (Barlow & Peres 2004; Barlow et al. 2006). Barlow & Peres (2004) report that most avifauna associated with primary forests became locally extinct after just one fire, with effectively no overlap in bird species in unburned forests compared to repeatedly burned forests.

Lidar-based assessments of habitat structure in this study are also consistent with field reports, as the biodiversity response to fire is strongly driven by the corresponding changes in canopy structure (e.g. mortality of large trees) and associated reductions in resource availability (e.g. nesting sites) (Barlow & Peres 2004; Barlow et al. 2006). Having adapted in near isolation from fire for millennia, most Amazonian tree species are ill equipped to survive even low-intensity ground fires. Fire vulnerability is further compounded by logging, fragmentation, and drought, which, together, serve to lock remnant frontier forests into feedback cycles of fire-induced mortality. Each fire event increases the availability of combustible fuels, which triggers a cascade of damages that transform stand structure and floristic composition (Brando et al. 2014). With models predicting longer and more frequent drought events, the remote sensing community needs to play a critical role in constraining predictions about what this means for the fate of Amazonian frontier forests and the resident fauna. However, due to the challenge in collecting structural information from the ground, there remain large gaps in our understanding of how disturbance-mediated changes to structure drive such dramatic species extirpations. The combination of acoustic remote sensing with lidar offers a promising new perspective that can help disentangle the complex associations between biodiversity and forest ecosystems under a changing landcover and climate regime.

Most efforts to characterize ecological change through bioacoustics have focused on evaluating the distribution of individual species through machine learning; however, fine-tuning models for each species is extremely time-consuming, especially when looking to evaluate higher-order community responses in diverse ecosystems. Bypassing species identification altogether, soundscapes may promote rapid biodiversity assessments by aggregating site-level acoustic signals that can be regarded as abstractions of the faunal community (Sueur et al. 2008). Yet, most soundscape analyses to date have discarded much of the rich soundscape detail by summarizing the acoustic signal into indices that have not yet been time-tested or proven to be consistent across sensors and ecosystems (Fuller et al. 2015). Here, we highlight the need for alternative methodological approaches that utilize the full acoustic domain for investigating biodiversity change. Future work will focus on understanding the structural attributes that drive the site-level clustering of acoustic activity reported here, with a focus on parsing apart the taxonomic contributions to the variability in diurnal signals.

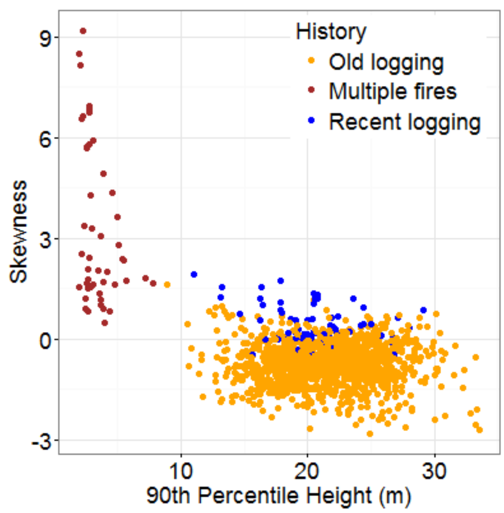

Figure 2. A scatterplot of the distribution of two lidar-derived structural parameters aggregated to 25m, the 90th percentile height of all lidar returns, and the skewness of all return heights, used to differentiate the structural profiles of logged and burned stands.

4. Conclusion

When combined, lidar and acoustic remote sensing represent a powerful suite of tools that can help bridge ground-based and satellite observations to support biodiversity and ecosystem assessments at policy-relevant scales. Our results suggest that contemporary habitat structure and use are strongly driven by degradation history. Lidar was shown to be a reliable tool for discriminating the fine-scale canopy damages resulting from selective logging and understory fires, and the changing distribution of canopy material with post-disturbance recovery. Repeated fires were found to be the most destructive agents of change, and in some cases, resulted in 100% loss of the original canopy. Similarly, the stark dissimilarity in acoustic activity between logged and repeatedly burned forests indicate that repeated fires most likely transform community composition. Recent developments in non-invasive, high-density and scalable remote sensing technology hold tremendous promise for supporting rapid ecosystem and biodiversity assessments of the impacts of human disturbance across frontier Amazon landscapes.

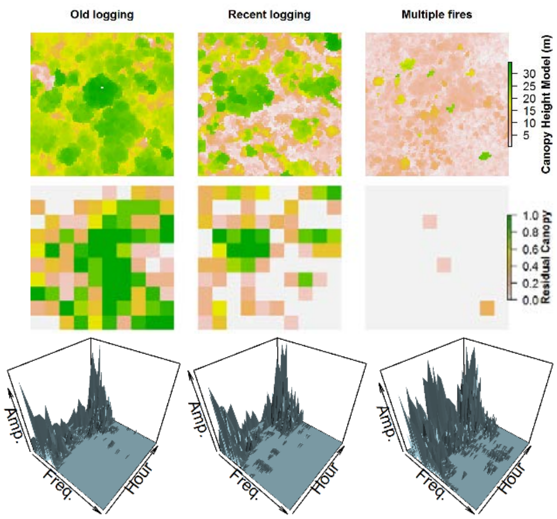

Figure 3. Examples of the characteristic heterogeneity of degraded forest habitat structure and habitat use. The variability in canopy height across a disturbance gradient is exemplified with a canopy height model (row 1; 1m resolution) and an estimation of the fraction of original canopy remaining (row 2; 10m resolution). Acoustic activity is compared through a soundscape aggregation (row 3) with hour of day on the x axis (0-24 hrs), frequency on the y axis (0-22 kHz), and amplitude (>0.01) on the z axis.

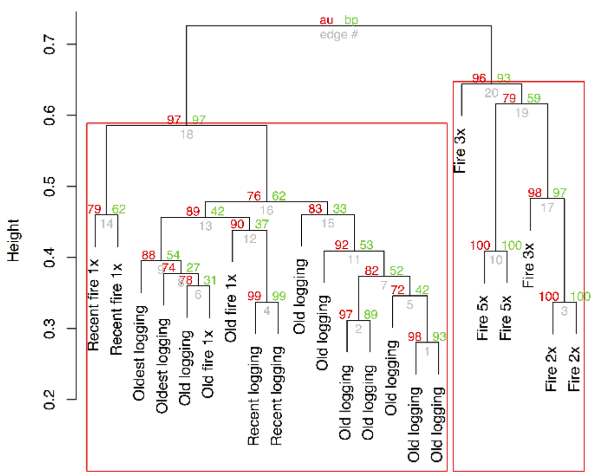

Figure 4. A dendrogram computed with a Ward's hierarchical cluster analysis used to quantify the differences in acoustic activity across sites. The two resulting clusters underscore the distinct dissimilarity of repeatedly burned forests from all other disturbed forests in the study site.

Acknowledgements

This work was partially supported by a NSF Doctoral Dissertation Research Improvement Grant, a NASA Earth and Space Science Fellowship, and NASA's Carbon Monitoring System program. Additional support was provided by the Brazilian National Council for Scientific and Technological Development (CNPq, grant 457927/2013-5) and Ciências sem Fronteiras (award to D. Morton). We also thank Michael Keller and Maiza Nara dos-Santos for assistance with lidar and forest inventory data collection.

References

Aide, T.M.; Corrada-Bravo, C.; Campos-Cerqueira, M.; Milan, C.; Vega, G.; Alvarez, R. Real-time bioacoustics monitoring and automated species identification. **PeerJ** p. 1e103, 2013.

Asner, G.P.; Knapp, D.E.; Broadbent, E.N.; Oliveira, P.J.; Keller, M.; Silva, J.N. Selective logging in the Brazilian Amazon. Science v. 310, n. 5747, p. 480–482, 2005.

Barlow, J.; Peres, C.A. Avifaunal responses to single and recurrent wildfires in Amazonian forests. **Ecological Applications** v. 14, n. 5, p. 1358–1373, 2004.

Barlow, J.; Peres, C.A.; Henriques, L.M.P.; Stouffer, P.C.; Wunderle, J.M. The responses of understorey birds to forest fragmentation, logging and wildfires: an Amazonian synthesis. **Biological Conservation**, v. 128, n. 2, p. 182–192, 2006.

Bergen, K.M.; Goetz, S.J.; Dubayah, R.O.; Henebry, G.M.; Hunsaker, C.T.; Imhoff, M.L.; Nelson, R.F.; Parker, G.G.; Radeloff, V.C. Remote sensing of vegetation 3-D structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions. **Journal of Geophysical Research: Biogeosciences**, v. 114, n. G2, 2009.

Blumstein, D.T.; Mennill, D.J.; Clemins, P.; Girod, L.; Yao, K.; Patricelli, G.; Deppe, J.L.; Krakauer, A.H.; Clark, C.; others. Acoustic monitoring in terrestrial environments using microphone arrays: applications, technological considerations and prospectus. **Journal of Applied Ecology**, v. 48, n. 3, p. 758–767, 2011.

Brando, P.M.; Balch, J.K.; Nepstad, D.C.; Morton, D.C.; Putz, F.E.; Coe, M.T.; Silvério, D.; Macedo, M.N.; Davidson, E.A.; Nóbrega, C.C.; Alencar, A.; Soares-Filho B.S. Abrupt increases in Amazonian tree mortality due to drought–fire interactions. **PNAS**, v. 111, n. 17, p. 6347–6352, 2014.

Bustamante, M.; Roitman, I.; Aide, T.M.; Alencar, A.; Anderson, L.; Aragão, L.; Asner, G.P.; Barlow, J.; Berenguer, E.; Chambers, J.; others. Towards an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity. **Global Change Biology**, v. 22, n. 1, p. 92-109, 2015.

Cook, B.D.; Nelson, R.F.; Middleton, E.M.; Morton, C.M.; McCorkel, J.T.; Masek, J.G.; Ranson, K.J.; Ly, V.; Montesano, P.M.; others. **Remote Sensing**, v. 5, n. 8, p. 4045-4066, 2013.

Fuller, S.; Axel, A.C.; Tucker, D.; Gage, S.H. Connecting soundscape to landscape: Which acoustic index best describes landscape configuration? **Ecological Indicators**, v. 58, p. 207–215, 2015.

INPE. **Portal do Monitoramento de Queimadas e Incêndios**. São José dos Campos, Brazil. Available at: http://www.inpe.br/queimadas/. Accessed on: 15 Oct. 2016.

Morton, D.C.; DeFries, R.S.; Nagol, J., Souza Jr., C.M.; Kasischke, E.S.; Hurtt, G.C.; Dubayah, R. Mapping canopy damage from understory fires in Amazon forests using annual time series of Landsat and MODIS data. **Remote Sensing of Environment**, v. 115, n. 7, p. 1706-1720, 2011.

Morton, D.C.; Page, Y.L.; DeFries, R.S.; Collatz, G.J.; Hurtt, G.C. Understorey fire frequency and the fate of burned forests in southern Amazonia. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 368, n. 1619, p. 20120163, 2013.

Pettorelli, N.; Safi, K.; Turner, W. Satellite remote sensing, biodiversity research and conservation of the future. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 369, n. 1643, p. 369, 2014.

Sueur, J.; Pavoine, S.; Hamerlynck, O.; Duvail, S. Rapid Acoustic Survey for Biodiversity Appraisal. **PLoS ONE,** v. 3, n. 12, p. e4065, 2008.