Research Article

Mapping recent deforestation and forest disturbance in northeastern Madagascar

Thomas F. Allnutt[1, 2], Gregory P. Asner[3], Christopher D. Golden[4], George V. N. Powell[5]

[1] University of California, Berkeley, Department of Environmental Science, Policy and Management, 130 Mulford Hall, Berkeley, CA, USA.
[2] Wildlife Conservation Society, Madagascar Program, B.P. 8500 Soavimbahoaka, Antananarivo 101, Madagascar
[3] Department of Global Ecology, Carnegie Institution for Science, 260 Panama Street, Stanford, CA 94305, USA. gpa@stanford.edu
[4] Harvard University Center for the Environment, 24 Oxford St. 3rd Floor, Cambridge, MA, 02138, USA. cgolden@fas.harvard.edu
[5] World Wildlife Fund-US, Conservation Science Program, 1250 24th St., NW Washington, DC 20012 USA. george.powell@wwfus.org
* Corresponding author: Thomas Allnutt. Email: tom.allnutt@berkeley.edu (+1 5106428414)

Abstract. We conducted an analysis of deforestation and forest disturbance from 2005-2011 in Masoala National Park, the largest federal protected area in Madagascar. We found that the annual rate of forest change in 2010-2011 within the park (1.27%) was considerably higher than in 2005-2008 (0.99%), and was higher than the most recently published deforestation rate for all of Madagascar. Although deforestation and disturbance immediately following the 2009 coup d'état were lower than in the other time periods analyzed, the longer-term increase in forest change over the study period corroborates recent ground-based accounts of increased illegal activities in national parks, including logging of precious hardwoods. We also analyzed forest disturbance patterns in relation to rivers and travel distance from permanent villages. Forest disturbances were significantly closer to rivers than expected by chance, and 82% of disturbance was within the mean maximum travel distance to villages surrounding the park. Both results strongly indicate that most of the mapped disturbance in the study area is anthropogenic, despite two cyclones during the study period. High-resolution forest monitoring ensures that forest change statistics accurately reflect anthropogenic disturbances and are not inflated by forest losses resulting from natural processes.

Keywords: CLASlite, deforestation, forest disturbance, illegal logging, Madagascar, protected areas

Received: 23 January 2013; Accepted: 14 February 2013; Published: 18 March 2013.

Cite this paper as: Allnutt, T. F., Asner, G. P., Golden, C. D. and Powell, G. V. N. 2013. Mapping recent deforestation and forest disturbance in northeastern Madagascar. *Tropical Conservation Science* Vol. 6(1):1-15. Available online: www.tropicalconservationscience.org

Introduction

Since the onset of a political crisis in 2009, there have been widespread and increasing reports of illegal activities in Madagascar's national parks, including deforestation, logging of precious hardwoods, mining, and poaching of endangered species [1,2]. From 2008 to 2009, for example, trade records show that exports of rosewood (*Dalbergia* spp.) from Madagascar to China, the world's largest consumer of Malagasy hardwoods, nearly tripled [3,4]. This increase is generally attributed to illegal logging in Masoala and Marojejy protected areas in northeastern Madagascar following a transfer of presidential power in March 2009 [5], which has been widely characterized as a "coup d'état" [6]. Despite the attention this issue has received, there are insufficient recent quantitative data showing the impacts of these activities on Madagascar's national parks [7]. The most recent, peer-reviewed, high-resolution forest cover analysis of Madagascar, for example, only covers up to the year 2000 [8].

Madagascar is a top global conservation priority for high levels of species endemism and threat [9,10]. Madagascar's vertebrate phylogenetic beta-diversity is greater than all of central and south America, and second only to that of Australia in less than one-tenth of the area [11]. Any additional loss of remaining forest risks extinction [12].

International donors have invested at least US$450 million in Madagascar's environmental sector since 1990 [13–15]. One tangible result has been the recent expansion of terrestrial protected areas, from 3.2 to over 10 million hectares [16,17]. Illegal logging and forest clearing directly threaten these investments by eroding the legal authority of protected areas and corrupting conservation incentives in surrounding communities, thereby undermining the integrity of the entire protected area system in Madagascar. Rapid, reliable ways to document and monitor this activity at high spatial and temporal resolution within protected areas are urgently needed.

In addition, Madagascar is in the process of implementing carbon payment projects in exchange for reduced emissions from deforestation and forest degradation (REDD+) at the national level. At least three projects are already actively trading reduced emissions from avoided deforestation in voluntary carbon markets [18]. The success of REDD+ projects such as these depends on reliable documentation of changes in forest cover and forest disturbance over time [19]. To date, however, insufficient attention has been paid to the separation of natural from anthropogenic forest disturbance, despite the relevance of this issue to accurate carbon accounting.

Remote sensing provides a synoptic view of changes in forest cover across tens of thousands of square kilometers [20]. Routine monitoring of selective logging, however, is challenging, as the area of direct impact may be limited to one or a few pixels in a satellite image [21–23]. A few approaches are now available to reliably map these small-scale disturbances, including CLASlite [24], a computer program for mapping forest cover, regrowth, deforestation and forest disturbance over time at 0.1 ha resolution or less. CLASlite has now been extensively validated in forests on all continents [24], and is widely employed as a method for forest monitoring provided to more than 290 organizations in a dozen countries [25]. It has also been recently used in carbon mapping and forest change research in Madagascar [26].

Here, we combine CLASlite and spatial analyses to test two hypotheses regarding the amount and rate of forest change from 2005-2011 in Masoala National Park in Northeast Madagascar. First, we expect mapped deforestation and disturbance pixels to be significantly closer to human access routes (e.g. trails and rivers) than a random distribution of pixels across the study area. Second, we expect an increase in deforestation and forest degradation following the 2009 coup d'état. We also present a new method for separating natural from anthropogenic disturbance in order to estimate the total amount of human-caused deforestation and disturbance within the study area. Our aim was not to validate CLASlite, as this has been done elsewhere [24,26]. Instead, we demonstrate its potential use as a tool for rapid and timely monitoring on an issue of immediate policy concern and relevance – illegal logging and forest clearing in remote national parks.

Background

In recent years, monitoring deforestation across large areas with remote sensing has become common practice [27]. Despite this, the most widespread anthropogenic forest activities often occur at small scales and therefore cannot be readily detected with traditional remote sensing methods [28]. This includes selective logging of high-value hardwoods, the removal of individual trees or tree parts for fuel and construction, and small-scale sub-canopy (or "shade") agriculture, among other activities. These small but significant forest uses can have major implications for conservation, for monitoring forest cover and carbon stocks, and for protected area management [29,30]. For example, a study of deforestation in the Brazilian Amazon showed that the inclusion of methods for measuring selective logging increased forest change (deforestation + degradation) totals by 60-123% [31]. Therefore, efforts to map and monitor forest change that do not account for selective logging and small-scale disturbances can grossly underestimate forest changes [28], particularly in regions such as Madagascar, where forest clearing and deforestation are dominated by small-scale disturbances associated with swidden agriculture, selective logging, removal of individual trees for fuel-wood, charcoal and building materials, and artisanal mining [32,33].

Sub-pixel analysis of satellite imagery, also known as mixture modeling or spectral unmixing [34], provides a powerful approach for monitoring small scale forest changes, including selective logging. Unlike traditional image classification that assigns pixels to discrete landcover classes, these techniques produce percentage or "fractional" landcover estimates for primary cover types or endmembers within single pixels. Here, we use CLASlite to measure the fractional cover of three ecosystem components: live vegetation, dead vegetation, and bare substrate, on a per-pixel basis. CLASlite also detects changes in these fractions over time, exploiting the fact that selective logging and small-scale clearing lower the proportion of live vegetation relative to dead vegetation and bare substrate within individual pixels. Following Asner [24,31], we define deforestation as the complete removal of forest cover, anthropogenic forest disturbance as a diffuse thinning of the forest canopy caused by human activity, and forest degradation as extensive and persistent anthropogenic forest disturbance through space and time. Finally, we define forest change as the sum of deforestation and disturbance measured over time.

Methods

Study Area

Our study area is located in northeastern Masoala National Park, in the Ankavanana drainage of the upper Onive river valley, centered on latitude -15° 16' 43.93", longitude 50° 9' 23.90" (Figure 1). We chose this as a study area because of an apparent concentration of infractions (stumps, log piles, clearing) in 2008 to 2010 park guard patrol data provided by Madagascar National Parks staff (Figure 1 inset), as well as first-hand reports of widespread timber cutting, logging camps and transport of precious wood in this region in 2009 [3] and 2010 [35].

Image acquisition and processing in CLASlite

CLASlite works with a variety of image types, including SPOT and Landsat. Image acquisition was hampered by the near total absence of recent, relatively cloud free (<10% cloud cover) imagery, as northeast Madagascar is one of the rainiest regions in the country, receiving more than 3-5m of precipitation per year on average [36]. Furthermore, due to the failure of the scan line corrector in Landsat 7 in 2003, most recent Landsat 7 imagery is not adequate for use in forest change mapping. We acquired 10m and 20m multispectral SPOT satellite imagery from four eras, corresponding to the pre- and post-coup d'état period: 26 February 2005, 23 February 2008, 15 January 2010 and 19 February 2011.

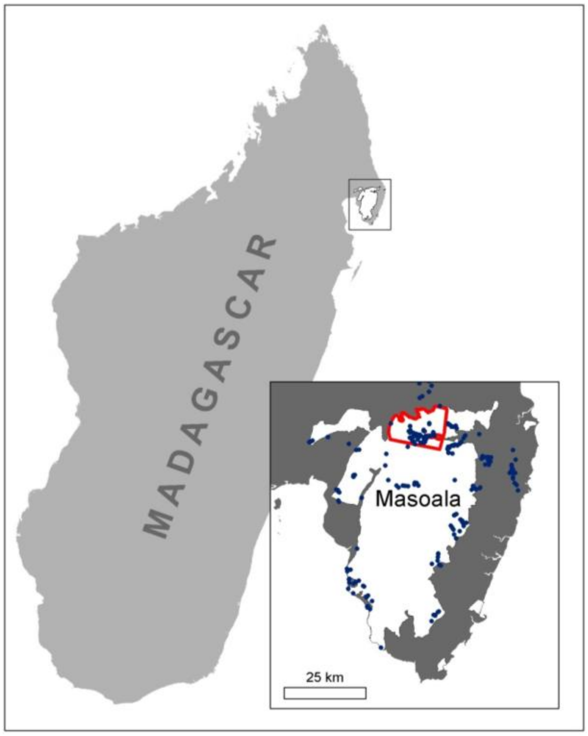


Fig. 1. Study area in Madagascar's Northern Masoala National Park, shown in red outline in the inset map. Blue dots represent infractions reported during Madagascar National Park patrols, 2008-2010. The apparent concentration of infractions on the upper Onive river influenced our choice of study area

We used image-to-image registration to georeference all four images to an existing orthorectified Landsat image from the GeoCover archive (Landsat 5 image, path 158 row 071 from 7 October 2001; http://www.glcf.umd.edu/research/portal/geocover/). All images were registered to an average RMS error of less than one pixel. We subset the resulting images to a common extent cropped to the park boundary, resulting in a total study area of 152.8 km^2, or about 7% of the total park area of 2,140 km^2.

Following image co-registration, we processed the four scenes using CLASlite (version 2.1 [24]). The CLASlite system is largely automated, and requires only basic user interaction in four main steps. First, we imported all four images, providing required ancillary information and metadata. Second, CLASlite applies an automated atmospheric correction and converts the results to reflectance images. Third, CLASlite uses a built-in Monte-Carlo spectral unmixing algorithm (AutoMCU [21]) to partition each image into fractional cover types which show the proportional fraction of bare ground, live vegetation and dead vegetation in every pixel. Fourth, CLASlite converted these images to maps of deforestation and disturbance for each era, then compared eras. The results show changes in forest cover, deforestation and forest disturbance in three eras: 2005-2008, 2008-2010, and 2010-2011.

Analysis

To test whether disturbance is significantly associated with human access to the study area, we first digitized all observable rivers in the satellite imagery. Rivers are the primary means of human access into the area [37,38]. We then measured the distance of each classified disturbance pixel to the nearest river. Next, we generated a set of pixels in random locations throughout the study area, matching the number of observed disturbance pixels, and measured the distance from every randomly located pixel to the nearest river. We repeated this randomization and distance measurement 1000 times and compared the mean distance of each run to the mean observed distance. This allowed us to test whether the location of observed disturbance is significantly different from a random distribution with respect to river proximity.

Separating natural and anthropogenic disturbance

CLASlite measures deforestation and disturbance based on changes in spectral characteristics alone. Unlike CLAS, the original version of the software which ran on supercomputers with pattern recognition algorithms for isolating selective logging, CLASlite is not designed to distinguish between different types of disturbance (e.g. anthropogenic vs. natural). Therefore, we performed a second analysis to distinguish between anthropogenic and natural disturbances. To do this, we used survey data collected in 2010 and 2011 from 13 villages on the Masoala peninsula (C. Golden unpubl. data). The research team used systematic random sampling methods to select 418 households and then asked household members about their use of various forest products (firewood, timber, construction materials, and traditional medicines) and the minimum and maximum time needed to travel to a location to access them. From these survey results, we averaged mean minimum and maximum travel time for the four uses we expected to have the most substantial impact on live vegetation, and therefore be visible in the satellite imagery as disturbances in CLASlite: collection of trees and other forest products for housing materials, boats, timber and firewood. To convert time to distance, we applied a cost-distance function that estimates distance traveled as a function of time and slope [39]. We used this function to create distance buffers representing mean minimum and maximum travel time around all permanent villages in the vicinity of the study area, and then used these buffers to separate natural from anthropogenic disturbance.

Results

We found 0.71 km^2 of forest disturbance (0.72% of total area analyzed) and 0.27 km^2 (0.27%) deforestation from 2005-2008, 0.06 km^2 (0.06%) disturbance and 0.01 km^2 (0.01%) deforestation from 2008-2010, and 0.58 km^2 (0.52%) disturbance and 0.84 km^2 (0.75%) deforestation from 2010-2011 (Table 1). The largest total amount of forest change was observed 2010-2011, followed by 2005-2008, and then 2008-2010 (Table 1, Fig. 2, Appendix 1-3).

Mean distance to closest river of disturbance over the study period was 835.5 m. When we compared this to 1000 runs where we chose pixel locations at random and measured distance to the closest river, the average of the 1000 mean distances was 1005.8 m. None of the 1000 random mean distances was closer to rivers than the mean observed distance of 835.5 m; therefore disturbance between 2005 and 2011 was significantly closer to rivers than the randomly distributed set (two-sample paired t-test, $t(49,128)= -23.3586$, $p < 0.001$) (Fig. 3).

Table 1. Change statistics per era. Forest change is the sum of disturbance and deforestation

Era	Disturbance total	Disturbance percent	Deforestation total	Deforestation percent	Forest change total	Forest change percent
2005-2008	0.71 km^2	0.72%	0.27 km^2	0.27%	0.98 km^2	0.99%
2008-2010	0.06 km^2	0.06%	0.01 km^2	0.01%	0.07 km^2	0.07%
2010-2011	0.58 km^2	0.52%	0.84 km^2	0.75%	1.42 km^2	1.27%

We found a mean minimum travel time of 1.17 hours and a mean maximum travel time of 1.91 hours to collect the four forest products reported by survey respondents. When we applied distance buffers generated from these mean travel times to all permanent villages near the study area, we found 74.0% and 23.1% of the total study area was within the mean maximum and minimum travel distance, respectively (Fig. 4). When we compared disturbance patterns to these travel buffers to help distinguish natural from anthropogenic disturbance, we determined that 69.3% were inside the minimum mean travel distance (23.1% of the study area) while 82.1% of mapped disturbance pixels fall within the maximum mean travel distance (74.0% of the study area). Comparing these in terms of disturbance per unit area, we found that there was more than seven times the amount of disturbance per unit area inside the mean minimum travel distance than outside. Furthermore, when we compared total disturbance per era to the maximum mean travel distance, we found the proportion of disturbance inside the maximum travel distance increased from 76.9% in 2005-2008, to 83.5% in 2008-2010, and 85.6% in 2010-2011 (Table 2).

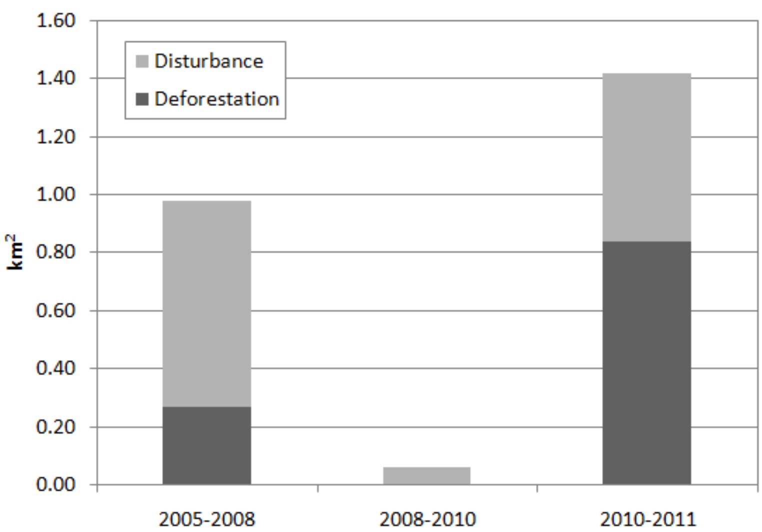


Fig. 2. Change in deforestation and disturbance. Change in total observed deforestation and disturbance over the study period showing an overall increase in total deforestation and a decrease in disturbance, and an overall increase in forest change (disturbance plus deforestation). Units are square kilometers.

Discussion

In the study area within Masoala National Park, we found the most recent annual (2010-2011) rate of forest change (1.27%) was higher than the most recent annual deforestation rate published for all of Madagascar [8], a disturbing result given that Masoala has the highest level of legal forest protection in Madagascar. This highlights an important and persistent problem within

Madagascar's largest national park. Despite nominal protection, support and financing from national and international organizations for the last 15 years, the current deforestation rate in our national park study area is higher than in many forests that lack protection altogether.

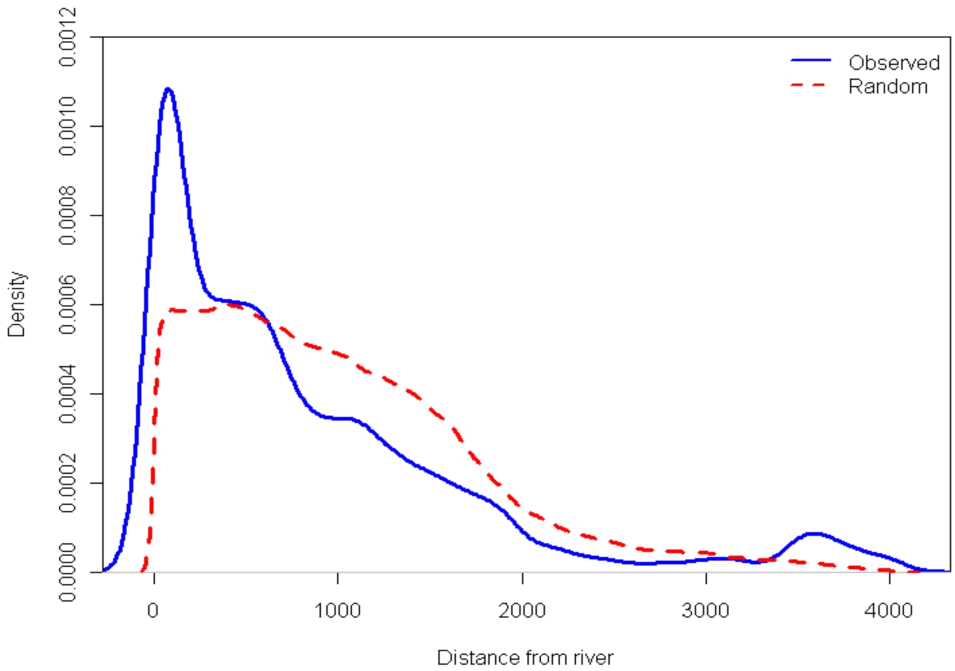


Fig. 3. Observed vs. random disturbance. Density plot showing the distance of observed disturbance pixels to the nearest river compared to 1000 randomly distributed sets of pixels. Observed disturbance is significantly closer to rivers than the randomly distributed sets

It is important to note that our methods cannot distinguish between two widely reported but very different sources of forest change, clearing for agriculture and illegal logging of precious hardwoods. Both of these activities are illegal in Masoala, however, and both can have similar impacts. For example, the clearing of trees in valley bottoms for logging camps, floats for logs, or small agriculture fields will appear similar in satellite imagery (Appendix 3, Fig. 5).

Table 2. Percent of observed forest disturbance. Percent of observed forest disturbance that was inside the mean maximum travel distance for forest products.

Era	Percent disturbance inside mean maximum distance
2005-2008	76.9%
2008-2010	83.5%
2010-2011	85.6%

We present a new approach for separating natural and anthropogenic disturbance, and this method has broad utility beyond this one study. For example, monitoring, reporting and verification (MRV) within most REDD+ programs requires routine, repeat measurements of forest cover and importantly, forest disturbance and degradation over time. Our approach can help ensure that change statistics accurately reflect anthropogenic disturbances and are not inflated by forest loss that occurs as a result of senescence, disease, cyclones and other natural processes.

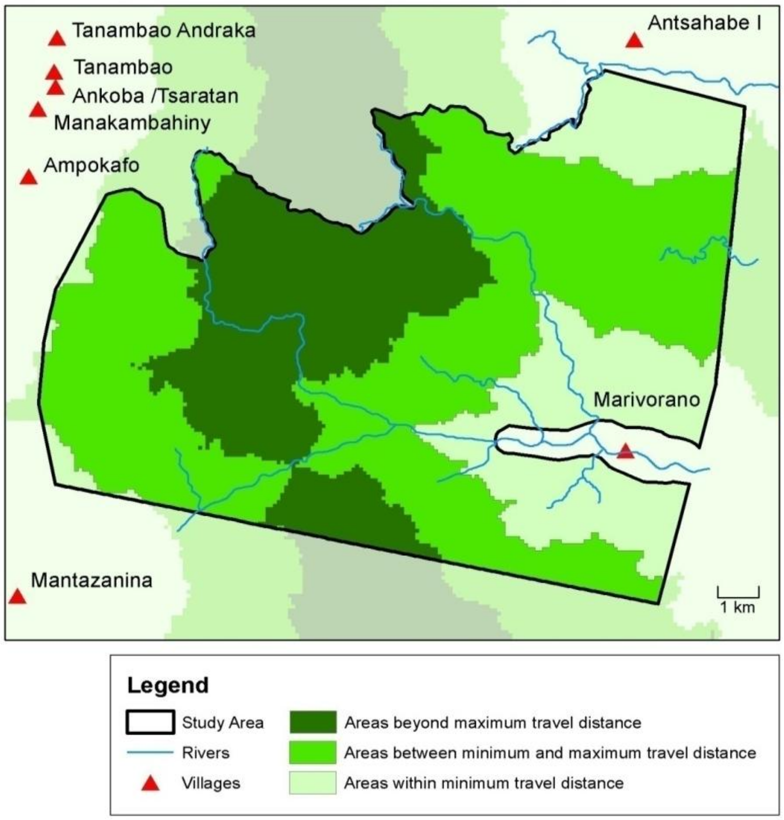


Fig. 4. Travel times map. Classification of study area according to mean minimum and maximum reported travel times to collect forest products from permanent villages. Villages are shown as red triangles. Areas in dark green are outside the maximum mean travel time from the nearest village and therefore the most remote. Areas in light green are between minimum and maximum mean travel times. Areas in blue-green are between villages and the minimum mean travel time, and are the least remote.

Our results from the application of this new method indicate that a substantial proportion (82.1%) of disturbance mapped within the study area falls within the reported mean maximum travel distance from permanent villages to collect forest products even though this area represents only 74.0% of the study area. In addition, our results show that disturbance per unit area is more than seven times as concentrated inside the reported mean minimum travel distance to villages as it is outside. Furthermore, we found that the percentage of forest disturbance within the mean maximum travel distance increased over the study period (Table 2). Together, these measures are important indicators of relative levels of human and natural disturbance, and provide evidence for an increasing proportion of anthropogenic disturbance over the study period. Additional work on the ground may be necessary to test and refine this result. For example, there were also two major cyclones during the study period, which would be expected to cause impacts such as tree falls and landslides across the study area (Category 3 Jaya 2007, Category 1 Jade 2009). A more complete measure is needed to estimate the probability of these various causes based on travel distance in conjunction with expected background rates of human and natural disturbance. We note that extending this method to other regions or jurisdictions will require local data on travel distance to calibrate a model similar to the one demonstrated here.

We did not find clear trends in deforestation and disturbance directly before and after the 2009 coup d'état. Our analysis shows that both deforestation and disturbance were lower in 2008-2010 than in eras before and after. Although we do not have direct evidence, our results suggest two main possibilities. First, anecdotal reports could be overstated, and this may be seen as a long term, ongoing issue – not only one resulting from the political crisis. Second, reports may be correct, but trends in exports may reflect release from existing stockpiles rather than what is happening in the forest at any given time [40].

Despite these possibilities, we acknowledge that many people who have worked and lived in the region for a long time reported significant and unprecedented increases in illegal activity in 2009. Therefore it is also important to note that our work is limited geographically, and illegal logging is certainly happening in other places in Masoala and regionally. Furthermore, because image masking in CLASlite is intentionally conservative to avoid areas of poor spectral quality, reported deforestation and disturbance statistics should be seen as minimum values. Importantly, the overall trend 2005-2011 shows an increase in deforestation, and about the same level of disturbance, as expected and widely reported following the political crisis.

Fig. 5. Logging camp in Masoala National Park, 2010. Source: Mongabay.com

Implications for conservation

Ongoing deforestation, logging and wildlife poaching raise serious questions about the long-term viability of Madagascar's protected area system. Here we show how remote sensing tools such as CLASlite can provide an objective and long-term view of trends in both small scale disturbance and deforestation, complementing policy and management needed to safeguard forests in protected areas.

Regardless of the ultimate causes of disturbance and deforestation, more regular forest monitoring is needed in Madagascar at higher resolution and frequency than currently available, given the relative scarcity of remaining forests, their global significance and biological irreplaceability. For example, as noted, the most recent published analysis of Madagascar's forest cover only reaches up to the year 2000 [8], so it is not clear whether the rates of forest change observed here are indicative of a general trend across Madagascar, or simply an isolated problem. In either case, this work describes a general approach with great promise for routine, high-frequency forest monitoring and conservation efforts across Madagascar and globally.

Acknowledgements

This work was supported in part by grants from the John D. and Catherine T. MacArthur Foundation, the Mohammed Bin Zayed Species Conservation Fund, and the Margot Marsh Biodiversity Fund. We thank Madagascar National Parks for providing park patrol data, World Wildlife Fund and the SPOT Image Corporation (Astrium Geo)/Planet Action for donating a portion of the imagery used in the analysis, and the Wildlife Conservation Society Madagascar Program for providing village location data. In addition, we thank Evelin Jean Gasta Anjaranirina for research assistance, and Aravindh Balaji, John Clark, and David Knapp for assistance with image processing and CLASlite analysis. The Carnegie Institution's CLASlite team is supported by the Gordon and Betty Moore Foundation and the John D. and Catherine T. MacArthur Foundation. Zuzana Burivalova provided comments that greatly improved an earlier draft. Finally, we thank Nicholas Tripcevich for help with path distance examples

References

[1] Schuurman, D., Lowry, II P. P. 2009. The Madagascar rosewood massacre. *Madagascar Conservation and Development* 4: 98–102.

[2] Barrett, M. A., Brown, J. L., Morikawa, M. K., Labat, J-N., Yoder, A. D. 2010. CITES designation for endangered rosewood in Madagascar. *Science* 328: 1109–1110.

[3] Global Witness and The Environmental Investigation Agency. 2009. *Investigation into the illegal felling, transport and export of precious wood in SAVA Region Madagascar*. Global Witness, Washington, DC.

[4] Randriamalala, H. and Liu, Z. 2010. Rosewood of Madagascar: Between democracy and conservation. *Madagascar Conservation and Development* 5: 11–21.

[5] Wilmé, L., Schuurman, D., Lowry, II P. P. and Raven, P. H. 2009. *Precious trees pay off – but who pays?* Poster prepared for the World Forestry Congress. Buenos Aires, Argentina 18-23 October 2009.

[6] United States Department of State. 2012. *Background Note: Madagascar.* http://www.state.gov/r/pa/ei/bgn/5460.htm. Accessed: 11 January 2012.

[7] Waeber, P. O. 2009. Madagascar – "down the river without a paddle" or "turning the corner"? *Madagascar Conservation and Development* 4: 72–74.

[8] Harper, G. J., Steininger, M. K., Tucker, C. J., Juhn, D. and Hawkins, F. 2007. Fifty years of deforestation and forest fragmentation in Madagascar. *Environmental Conservation* 34: 325–333.

[9] Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A. B. and Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.

[10] Goodman, S. and Benstead, J. 2005. Updated estimates of biotic diversity and endemism for Madagascar. *Oryx* 39: 73–77.

[11] Holt, B. G., Lessard, J.-P., Borregaard, M. K., Fritz, S. A., Araujo, M. B., et al. 2012. An update of Wallace's zoogeographic regions of the World. *Science* 339: 74–78.

[12] Allnutt, T. F., Ferrier, S., Manion, G., Powell, G. V. N., Ricketts, T. H., et al. 2008. A method for quantifying biodiversity loss and its application to a 50-year record of deforestation across Madagascar. *Conservation Letters* 1: 173–181.

[13] GEF. 2008. *GEF country portfolio evaluation: Madagascar (1994–2007)*. Global Environment Facility Evaluation Office, Washington DC.

[14] Horning, N. R. 2008. Strong support for weak performance: Donor competition in Madagascar. *African Affairs* 107: 405–431.

[15] Freudenberger, K. 2010. *Paradise lost? Lessons from 25 years of USAID environment programs in Madagascar*. US Agency for International Development, Washington, DC.

[16] Kremen, C., Cameron, A., Moilanen, A., Phillips, S. J., Thomas, C. D., et al. 2008. Aligning conservation priorities across taxa in Madagascar with high-resolution planning tools. *Science* 320: 222–226.

[17] Corson, C. 2011. Territorialization, enclosure and neoliberalism: non-state influence in struggles over Madagascar's forests. *Journal of Peasant Studies* 38: 703–726.

[18] FCFP. 2010. *Readiness preparation proposal (R-PP) Madagascar*. Carbon Finance Unit, World Bank, Washington, DC.

[19] Herold, M. and Skutsch, M. 2011. Monitoring, reporting and verification for national REDD+ programmes: two proposals. *Environmental Research Letters* 6: 1–10.

[20] Jensen JR. 2007. *Remote sensing of the environment: An earth resource perspective.* Pearson Prentice Hall, Upper Saddle River, New Jersey.

[21] Asner, G. P. and Heidebrecht, K. B. 2002. Spectral unmixing of vegetation, soil and dry carbon cover in arid regions: comparing multispectral and hyperspectral observations. *International Journal of Remote Sensing* 23: 3939–3958.

[22] Matricardi, E. A. T., Skole, D. L., Pedlowski, M. A., Chomentowski, W. and Fernandes L. C. 2010. Assessment of tropical forest degradation by selective logging and fire using Landsat imagery. *Remote Sensing of Environment* 114: 1117–1129.

[23] Eckert, S., Ratsimba, H. R., Rakotondrasoa, L. O., Rajoelison, L. G. and Ehrensperger, A. 2011. Deforestation and forest degradation monitoring and assessment of biomass and carbon stock of lowland rainforest in the Analanjirofo region, Madagascar. *Forest Ecology and Management* 262: 1996–2007.

[24] Asner, G. P. Knapp, D. E., Balaji, A. and Paez-Acosta, G. 2009. Automated mapping of tropical deforestation and forest degradation: CLASlite. *Journal of Applied Remote Sensing* 3: 33524–33543.

[25] Asner, G. P. 2011. Painting the world REDD: addressing scientific barriers to monitoring emissions from tropical forests. *Environmental Research Letters* 6: 21002.

[26] Asner, G. P. Clark, J., Mascaro, J., Vaudry, R., Chadwick, K. D., et al. 2012. Human and environmental controls over aboveground carbon storage in Madagascar. *Carbon Balance and Management* 7: 2.

[27] Achard, F., DeFries, R., Eva, H., Hansen, M., Mayaux, P., et al. 2007. Pan-tropical monitoring of deforestation. *Environmental Research Letters* 2: 1–11.

[28] Asner, G. P. Rudel, T. K., Aide, T. M., Emerson, R, E. 2009. A contemporary assessment of change in humid tropical forests. *Conservation Biology* 23: 1386–1395.

[29] Bowles, I. A., Rice, R. E., Mittermeier, R. A. and Da Fonseca ,G. A. B. 1998. Logging and tropical forest conservation. *Science* 280: 1899–1900.

[30] Broadbent, E. N., Asner, G. P., Keller, M., Knapp, D. E., Oliveira, P. J. C., et al. 2008. Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. *Biological Conservation* 141: 1745–1757.

[31] Asner, G. P., Knapp, D. E., Broadbent, E. N., Oliveira, P. J. C., Keller, M., et al. 2005. Selective logging in the Brazilian Amazon. *Science* 310: 480–482.

[32] Jarosz, L. 1993. Defining and explaining tropical deforestation: Shifting cultivation and population growth in colonial Madagascar (1896-1940). *Economic Geography* 69: 366–379.

[33] Gorenflo, L. J., Corson, C., Chomitz, K. M., Harper, G., Honzák, M., et al. 2011. Exploring the association between people and deforestation in Madagascar. In: *Human population: Its influences on biological diversity*. Cincotta, R. P. and Gorenflo, L. J. (Eds.), pp.197–221. Springer, Berlin.

[34] Somers, B., Asner, G. P., Tits, L., Coppin, P. 2011. Endmember variability in spectral mixture analysis: A review. *Remote Sensing of Environment* 115: 1603–1616.

[35] Butler, R. 2010. Extensive logging, lemur hunting in Madagascar national park despite moratorium. WildMadagascar.org. Available: http://news.mongabay.com/2010/1116-masoala_rosewood.html#lQ4uxieDZUv1MW4Q.99. Accessed 12 October 2012.

[36] FAO. 2001. *FAOCLIM 2.0: A world-wide agroclimatic database.* FAO, Rome.

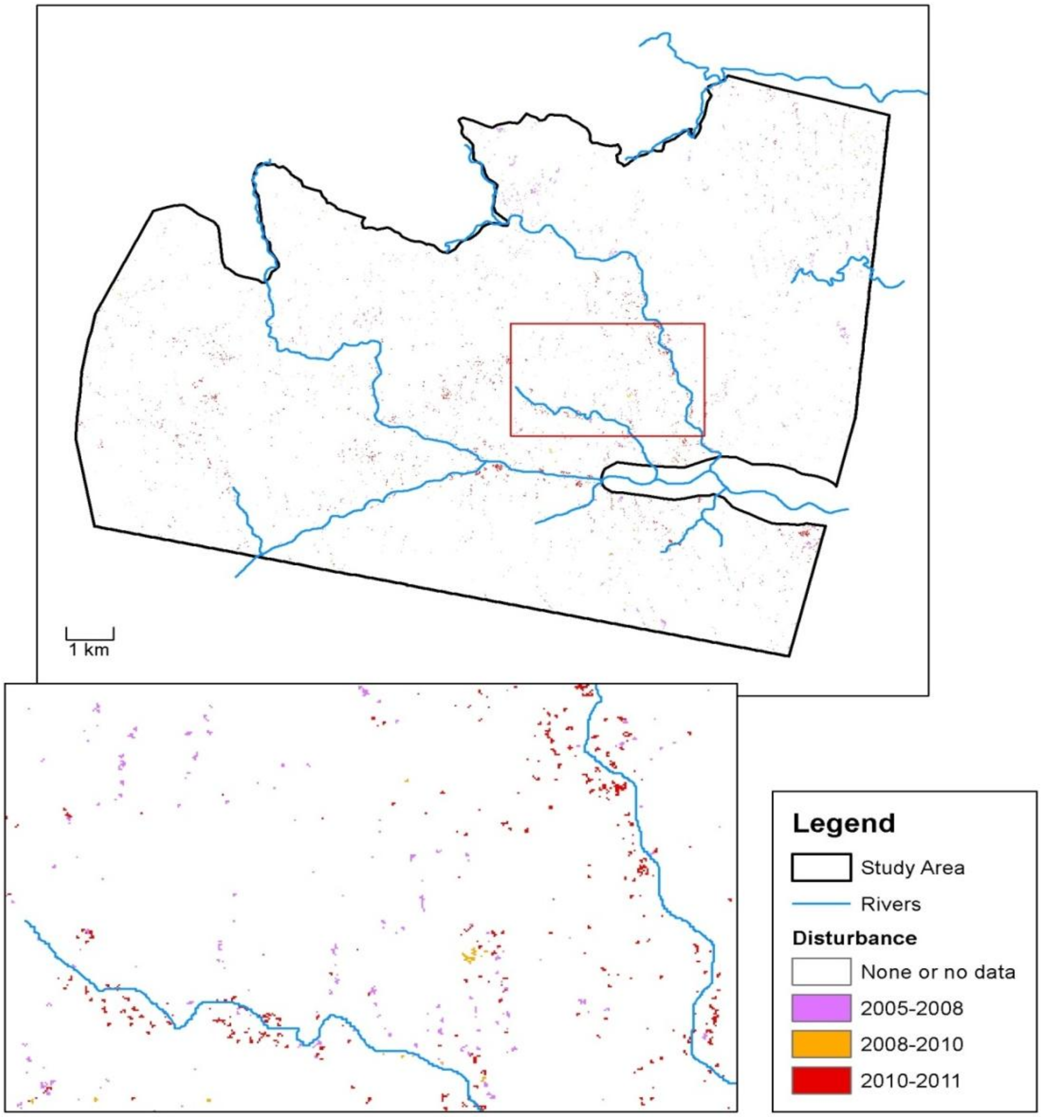
[37] Kremen, C., Razafimahatratra, V., Guillery, R. P., Rakotomalala, J., Weiss, A., et al. 1999. Designing the Masoala national park in Madagascar based on biological and socioeconomic data. *Conservation Biology* 13: 1055–1068.

[38] Golden, C. D. 2009. Bushmeat hunting and use in the Makira Forest, north-eastern Madagascar: a conservation and livelihoods issue. *Oryx* 43: 386–392.

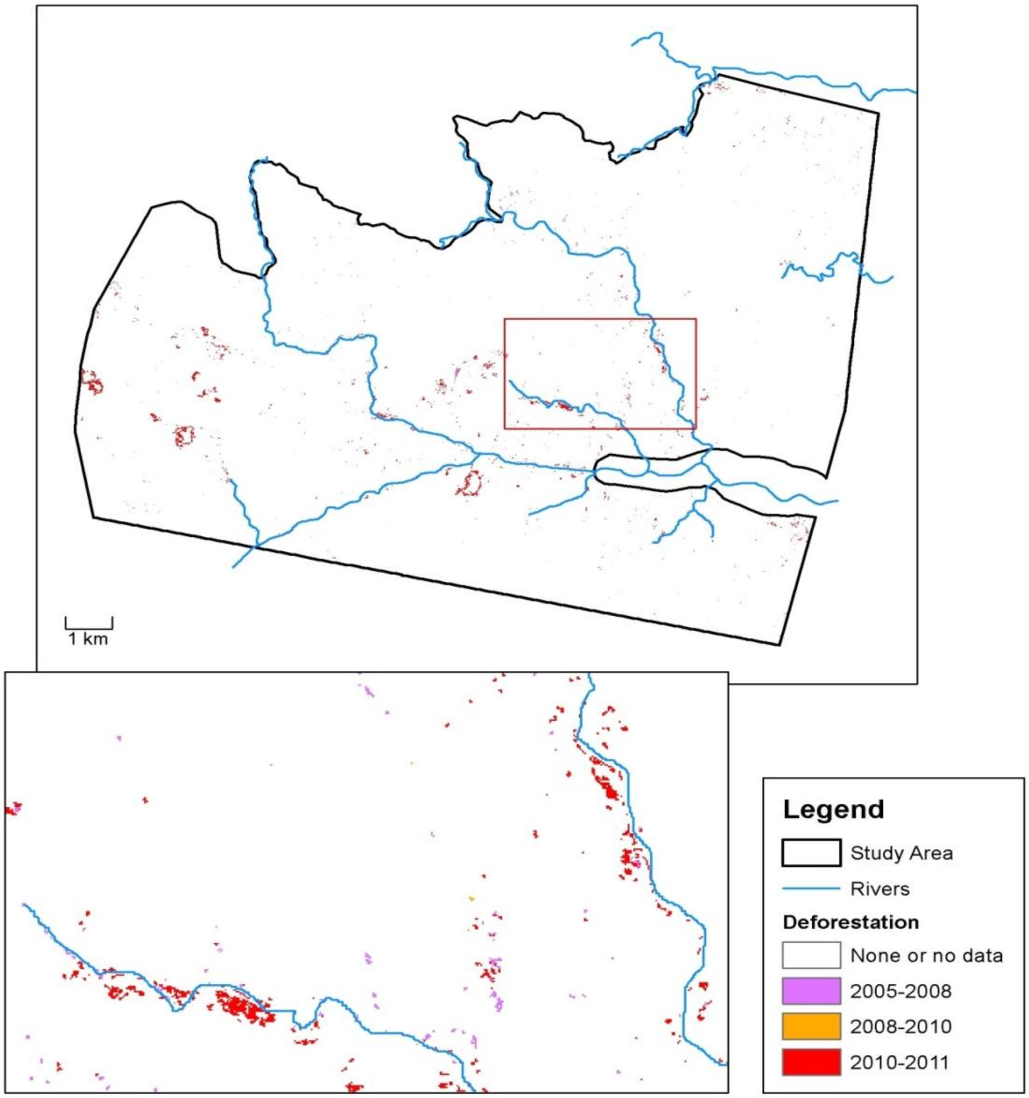
[39] Tobler, W. 1993. *Three presentations on geographical analysis and modeling: 1) non-isotropic modeling, 2) speculations on the geometry of geography, 3) global spatial analysis.* UC Santa Barbara, National Center for Geographic Information and Analysis, Santa Barbara, CA.

[40] Global Witness and The Environmental Investigation Agency. 2010. *Investigation into the global trade in Malagasy precious woods: Rosewood, ebony and pallisander.* Global Witness, Washington, DC.

Appendix 1. Forest disturbance. Disturbance 2005-2011 across study area (above) and zoomed to a subset shown in the red box (below).



Appendix 2. Deforestation. Deforestation 2005-2011 across study area (above) and zoomed to the subset shown in the red box (below).



Appendix 3. Raw and classified image subset. Raw SPOT imagery for (a) 2005 and (b) 2011 compared to (c) forest change (disturbance and deforestation) results from CLASlite, within the same subset shown in Appendix 1 and 2.