

High resolution satellite images for environmental monitoring of oil production in Western Amazon: the case of Yasuní National Park

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Abstract

Direct and indirect ecological impacts of roads and their expansion are well documented: habitat degradation, ecosystem fragmentation, changes in natural drainage systems and water quality. Important landscape scale impacts concern roads about direct and indirect effects on deforestation and land use land cover change, that lead to habitat loss and fragmentation, edge effect, resources exploitation and changes in social behaviour like the increase of human invasion and social conflicts. The general aim of this study is to extract and to ecologically assess a new road track within the Yasuní National Park, one of the most biodiverse area on Planet, using very high resolution satellite images; specific aims are to quantify and to validate road track clearance, according different methodologies. Results show that combining different methodologies such as supervised and unsupervised classifications (NDVI and ISODATA) allow to cross validate features extraction of road track. However, display analysis seems to be the most powerful tool for feature interpretation of anthropic features in tropical forest.

Keywords: road ecology, biodiversity, Amazon forest, Yasuní

1 Introduction

Direct and indirect ecological impacts of roads and their expansion are well known and investigated worldwide: from effects strictly connected to abiotic components of ecosystems like changes in water quality, quantity and flow, the increase of erosion and sediment transportation and of noise and chemical pollutants, to the biotic ones, such as the increase of animals mortality and barrier effects or the increasing spread

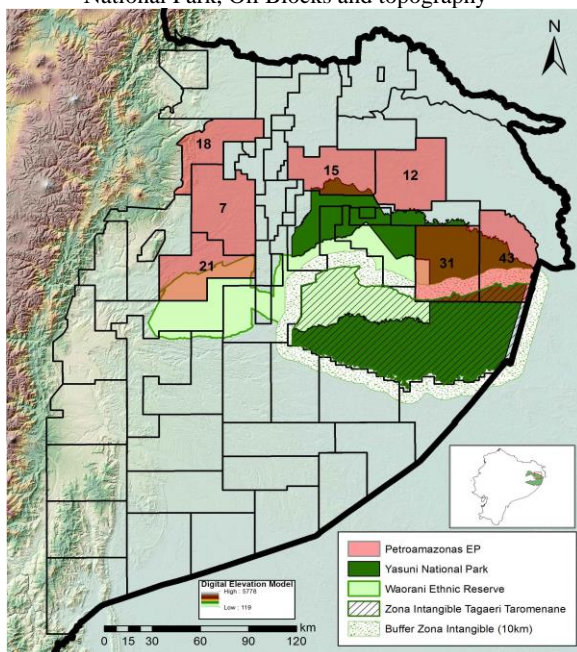
of alien species. Important landscape scale impacts concern roads direct and indirect effects on deforestation and land use land cover change, that lead to habitat loss and fragmentation, edge effect, resources exploitation and changes in social behaviour like the increase of human invasion and social conflicts (Coffin, 2007). Special attention and concern get the impacts and expansion of roads and linear clearings in high biological and culturally sensitive areas like tropical forest ecosystems, especially in the Amazon region (Laurance et al, 2009; Laurance et al., 2001; Goosem, 2007). In the last years

researchers start to focus their attention to propose measures to prevent or reduce these negative effects, studying, globally or locally, the possible buffers of roads impacts, the linear (actual and future planning) infrastructures location and their relationships with protected areas and roadless areas (Ibisch et al., 2016; Barber et al., 2014), suggesting strategically planning of new roads building, their design or where to avoid them (Ibisch et al., 2016; Laurance et al., 2014; Forman et al., 2003).

In the Amazon Region of Ecuador several hydrocarbon reserve exploitation projects are running in the area, overlapping the Yasuni National Park (YNP), one of the most biodiverse area on Planet (Finer et al. 2013; Pappalardo et al. 2013). A geographical framework of the area is shown in figure 1. Oil development in the Ecuadorian Amazon has already directly and indirectly caused important environmental changes to tropical ecosystems. Direct effects include deforestation for drilling platforms, pipelines, access roads, seismic prospecting activities, and chemical contamination of water bodies from wastewater discharges, oil spills and gas emissions (Pappalardo et al. 2013). Indirect effects are related to the opening of roads for oil exploration and transportation which turns terrestrial communications infrastructures into the main vector for colonization of primary forest, represented by the Moist Tropical Forest.

The general aim of this study is to extract and to ecologically assess the opening of a new road track within the YNP; specific aims are to quantify and to validate road track clearance, according to topography and ecosystems.

Figure 1: Geographical framework of the study area: Yasuni National Park, Oil Blocks and topography

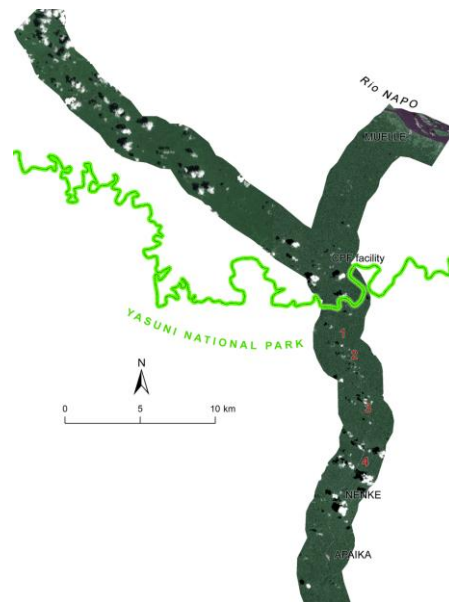


2 Data and methods

2.1 Image processing and spatial analyses

Landsat 8 of September 2013 was previously analysed to identify possible oil-related deforestation activities and advances in infrastructural operations within and around a 10 km buffer of the YNP, in oil blocks 31, 14 and 12 (figure 1). Therefore, high resolution satellite image of the area (Worldview-2) was acquired to perform spatial analysis and a synoptic ecological assessment. The satellite image is a panchromatic 0.5 m cell size and four 2 m cell size bands of blue, green, red and Near Infrared (NIR1). The image was scanned in September 1st, 2013 and it covers 110 km² of tropical rainforest between Rio Napo and Rio Yasuni (Ecuador), and it includes infrastructures and facilities for oil production inside the YNP. Oil communication infrastructures are basically divided into three main parts: i) from the industrial harbour on the orographic right-side of Rio Napo to the Rio Tiputini (hereafter, “Muelle” Rio Napo), ii) from Rio Tiputini to Apaika oil platform, and iii) from Rio Tiputini to the Eden well station. These three clearance lines draw a “Y-like” pattern and only a 1500 m buffer from the forest-cut was acquired from Worldview-2 (figure 2).

Figure 2: Worldview-2 imagery acquired of the study area: access routes within and around Yasuni National Park.



According to the different specific analyses for road track clearance and oil-related feature identification on and quantification of deforested areas, different image processing techniques were, therefore, performed:

1) A pansharpener enhancement of VNIR bands using Gram-Schmidt algorithm for Worldview-2 imagery, applying a local regression transformation in a 3x3 kernel;

pansharpening is useful in display analysis to have more data available for interpretation. VNIR bands were collected in color composite, in natural color (bands of blue, green and red), in NIR (green, red and NIR1), and in green enhancement (blue, NIR1 and red; green, NIR1 and red). The display analysis of such data consisted either by digitizing on screen or in unsupervised classification. The pansharpening technique is useful both in display analysis to have more data available for on screen interpretation and for unsupervised classification.

2) A supervised classification was performed to extract different landcover classes: the pavement and the bare soil of the road, the water of rivers, samples of vegetation, building of oil wells, clouds, shadows, were digitized in region of interest (ROI) and, therefore, spectral signatures were calculated.

3) An unsupervised analysis by automatic classification of the image through its four spectral bands was performed by ISODATA, Kmeans, ISOCCLUS and Cluster functions ran in IdrisiGISTM. Moreover, a sample analysis in mixed classes was performed to evaluate with more accuracy the extension of landcover classes, like clouds and its shadows, bare soil, and anthropic features related to oil operations.

4) A display analysis by on screen digitizing (OSD) separately performed by two skill GIS analysts along all the road track clearance. The clearance was mapped as a polygon feature. The two sides of the clearance were considered as the two main sides of this polygon, while at the start and the end of the polygon perpendicular lines close the feature. Visibility of the road track and the definition of ancillary geographic information are crucial elements in the interpretation process. Therefore, to avoid features extraction misinterpretation and to focus to the aim of the study, specific criteria were previously defined: i) bands combination and image processing which provide to the operator the best information, contrast and interpretation; ii) the interface between the road track clearance and the forest; iii) exclusion of ancillary oil facilities, deforested areas for oil operations, and secondary lateral forest cuts; iv) interpretation of the tree canopy from 20 to 40 m canopy diameter that sometimes covers the road track clearance; v) interpretation of the tree shadow on the road track. To reduce the subjective interpretation that leads the difference in the final feature extraction, the display analysis was performed by two operators with similar skill level, expert in remote sensing analyses in tropical forest, in the more complex road line, in southern part of the road track from Rio Tiputini to Apaika platform. The differences in deforested area and road track width were measured by the root-mean-square error (RMSE) in order to estimate level of uncertainty between results of two operators.

Moreover, overlay analysis were performed with topographic (SRTM, 1 arc-second resolution) and ecological data (Ministry of Environment, Ecuador), in order to visualize and quantify road track impact through the Amazonian landscape.

2.2 Clearance width calculation along the road track

To estimate and calculate the road track clearance by measurements on every regular intervals, several GIS operations were performed: i) conversion of digitized polygon to raster at 0.5 cell size resolution, ii) conversion of raster polygon in a vector line using the geometric median value, equidistant from the two sides of the clearance; iii) applying to the vector line derived a gentle smoothing, three points moving average, to remove “pixel pattern” effect; iv) applying to this vector line a tolerance band filter of 0.4 m value, in order to delete not relevant vertex points; vi) adding points to this vector line to have a vertex point at least every 10 m length; vii) measuring distance from every point to the next one; viii) Thiessen polygons calculation for points; xix) creation of distance raster image with distance values starting from the clearance sides, x) values extraction of maximum distance for every Thiessen polygon and multiplying it by 2. The present workflow allowed to construct a geodatabase with progressive distance values from the start of the road track and its corresponding clearance width value. It was chosen a 0.5 m raster cell resolution in order to minimize errors derived from image interpretation.

3 Results and discussion

3.1 Unsupervised classification

Identification by unsupervised classification showed cluster classes that clearly fall in the road track clearance: these are three or four, depending on resulting cluster number. The best result to identify road track class was obtained by ISODATA tool in IDRISIgisTM with 16 max clusters. Despite a result with mixed classes (eg. river water together with bare soil), class along the road track are homogeneous and contiguous: We can distinguish, in order of importance: i) a typical anthropic class, corresponding to bare soil; this is usually located in the center of the road track and corresponds to the road pavement. ii) A water body class that comprises river water, bare soil and anthropic building. iii) A class of shadow that divide lighted bare soil from high vegetation. iv) A class of mixed values that comprises cloud in shadow, shadow of building, dead trees, soil in shadow. Pixels of this four classes, when were contiguous, were grouped together to form a unique road track class. Results from unsupervised analyses highlights there was a deforestation of 99.5 ha to realize the oil communication infrastructure along the 20.4 linear kilometers from Rio Tiputini to Apaika platform (Table 1 and 2).

Table 1: Unsupervised classification: area and percentage for aggregate values of the main landcover classes from Rio

Tiputini to Apaika platform		
classes	hectares	%
vegetation	12486,8	92,8
cloud	447,9	3,3
bare soil - anthropic	99,5	0,7
water - bare soil	417,0	3,1
total	13451,2	100,0

Table 2 Root-mean-square error (RMSE) between the different methods for road track extraction

Road track	Root Mean Square Error (m)		
	ISODATA to NDVI	ISODATA to OSD	NDVI to OSD
Muelle Rio Napo – Rio Tiputini	4.8	5.4	7.7
Rio Tiputini – Apaika Platform	6.7	8.5	11.9

3.2 Road track analysis

Clearance width values were compared between the methods of road track identification. It can be seen quickly that unsupervised classification by vegetation index (NDVI) allows the narrower roadway, due to the very dense canopy influence. Moreover, the highest value in reclassification (0.4 in the range -1 to 0.4) was certainly too low to avoid the influence of high index value to its neighbour: the road track could be hidden under tree canopy in one or sometimes two of its sides by trees canopy with high NDVI value. The same happens for ISODATA cluster classification, but in this case the vegetation shadow class let us obtain a larger and more realistic area that can effectively span from vegetation of the clearance side to the opposite ones. The difference was measured by root mean square error, whose values are showed in table 2. The highest difference is between the OSD method and vegetation index (NDVI) classification by 12 m in the road track from Rio Tiputini to the Apaika Platform and 7.7 m from the Muelle Rio Napo to the Rio Tiputini. High values of RMSE are also from OSD to ISODATA, but these are more similar to those between ISODATA and NDVI, showing that the greater difference is from road track of NDVI classification and the other two methods (table 2). Road track total length is 64,026 m, divided in 28,810 m from Tiputini River (Central Processin Facility, CPF), 15,123 m from Muelle Rio Napo to Rio Tiputini, and 20,003 m from Rio Tiputini to Apaika Platform (Table 3, Figure 3). It is worth noting the comparison between the road track clearance polygons digitized by the two operators, especially along the road track from Rio Tiputini to Apaika Platform, the most irregular road track in the whole image. The width average difference between the operators is 0.8 m: 26.7 against 25.9 m, showing a good efficiency by interpretation and mapping. However, the RMSE is 6.2 m, showing the difficulty of the clearance sides interpretation. If we consider only width difference less than 40%, we can observe that the average difference is 0.6 m for the 95 % of the road length, while for width difference less than 20% the average difference is 0.3 m for 71% of the road length: and we have to keep in mind that the image resolution is 0.5 m (Table 4). The difference obtained by two operators interpreting road track feature on screen digitalization is less than the difference between automatic or semiautomatic individuation of the road track: this confirms the preference for a display analysis with skill analyst. However, it is interesting to compare statistics values of all methods adopted, as it is shown in table 5. By these analyses we noticed that the image classification methods are able to detect only the total visible part of the road track clearance, or the part with reflectance values having enough difference from those of contiguous classes. By these methods we observed smaller average values with greater Standard

Deviation values, probably due to the irregular shape of the road track.

The OSD method shows the greater average value with a smaller Standard Deviation. It is worth noting the Standard Deviation is very low in the road track from Muelle Rio Napo to Rio Tiputini road line clearance, showing a very regular shape. In the part from Rio Tiputini to the Apaika Platform road track show a very high average value with a significant Standard Deviation probably due to the work in progress of communication infrastructure, with also a duplicate road line crossing Pindoyaco valley (Figure 3). Standard Deviation also for the road track from CPF to Eden road is quite high, but this is due to two kind of road: from CPF to Eden complex, the road is smaller and it serves pipeline construction (14.2 m average, 2.4 m Standard Deviation); from the first Eden station to the others road line clearance is larger (29.8 m average, 5.4 m st. dev.).

Distribution values of 5 m bin size of the road clearances are also very interesting. For the road track from Rio Tiputini to Apaika Platform, the ISODATA reclassification method - a good method but lacking of hidden data - shows only 22% of the road track clearance less than 15 m wide. On the contrary 68% of clearance width is from 15 to 30 m. The OSD method shows only 5.2% of width less than 15 m for operator 2, and only 1.8% for operator 1. As you can see in the graph, operator 1 has a modal class in 30 m wide road track clearance and 74.7% of width ranges from 20 to 30 m; on the other side operator 2, indeed, has a modal class at 25 m of width and 75.2% of data that ranges from 15 to 30 m. Finally, very interesting that graph for both operators has a second modal class or a quite long queue of data toward high width: this corresponds to the Pindoyaco swampland crossing, where the road track clearance is doubled (Figure 3 and 4).

3.3 Road width, topography and ecosystems

Overlay analyses showed the spatial relationships between road track width, topography and ecosystems. As it showed in figure 5, all the road track clearance width was intersected with elevation data and ecosystem classes.

Data was carried out for the same points (1721) used for clearance width analysis. In the road track from Muelle Rio Napo to Rio Tiputini it is worth noting that there is no correlation between these variables; however, it is evident that in the major valley or terrain depression like swampland, generally the clearance width tends to increase. We also note that in the same terrain morphology vegetation type is generally swamp. On the other hand, along the road track from Rio Tiputini to the Apaika Platform there are some interesting elements, related to the “work in progress” of the infrastructure. In this tract, there is an excellent visibility of the road track and its supporting features like bridges, culverts, terrain arrangements (Figure 5).

Even if there is no statistical correlation between height and road clearance width, we have to note that along valleys and depressions - here bigger than in the previous case - the clearance seems to be systematically wider than in other morphologies. This also reflect the ecosystems such as swamp palms and swamp grassland. This relationship is probably due to the need of more space to build road track supports in a wet and difficult ground. Maybe the carriageway preparing is more onerous here and it needs morphology and terrain adjustments.

Figure 3: Distribution of road clearance width values from the Rio Tiputini to the Apaika Platform road track for three type of mapping methodologies

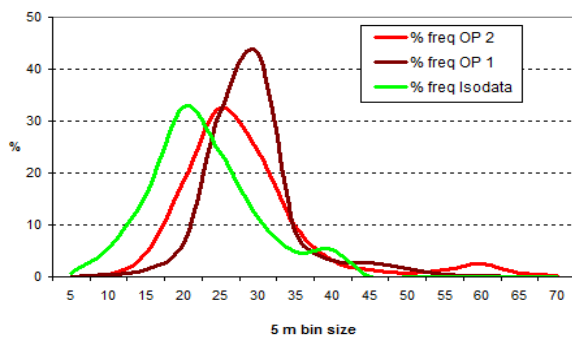


Table 3: Road track width comparison from Rio Tiputini to Apaika Platform, showing clearance width between polygon features made by two different operators

Road track	Total Length (m)	Visible length (m)	Points	Distance Average (m)
CPF Eden	28810	25443	2863	8.9
Muelle Tiputini	15123	15123	1721	8.8

Table 4: Comparison along the Rio Tiputini -Apaika Platform road clearance width between polygon features made by two different operators

	n. points	Road length (m)	RMSE (m)	width ave (m) Operator 1	width ave (m) Operator 2
total	2341	20093	6.2	26.7	25.9
delta < 40%	2246	19090	5.4	26.8	26.2
delta < 20%	1692	14380	3.2	26.6	26.3

Table 5 Statistic values of all methods applied for all the road track clearance identification. OSD 1, OSD 2 (for On Screen Digitizing by operator 1 and by operator 2), NDVI classification, and ISODATA.

road line	width measured every 10 m							
	Muelle - Tiputini			Tiputini - Apaika				CPF - Eden
method	ISODATA	NDVI	OSD 1	ISODATA	NDVI	OSD 1	OSD 2	OSD 1
average	9.1	5.4	12.1	20.4	15.2	26.7	25.9	17.6
St Dev	4.5	3.3	2.7	7.1	6.0	6.5	9.4	7.4
max	37.9	36.0	20.6	40.0	39.4	66.5	68.3	51.4
min	0.0	0.0	4.5	4.0	0.0	8.0	8.0	3.0

4 Conclusions

The use of high resolution satellite images is a powerful tool for synoptic analyses of road impacts on the landscape, especially in remote regions like Western Amazon. Combining different methodologies such as supervised and unsupervised classifications (NDVI and ISODATA) allow to cross validate features extraction of road track.

However, display analysis by OSD is still the most powerful tool for image interpretation. ISODATA, ISOCLUSTER and kmeans classification, vegetation indexes and supervised classification give us ancillary data or confirm results of the display interpretation.

Figure 4 Roadtrack clearance mapping: comparison between the two operators in four different section, from Rio Tiputini to Apaika Platform

Figure 4a



Figure 4b



Figure 4c

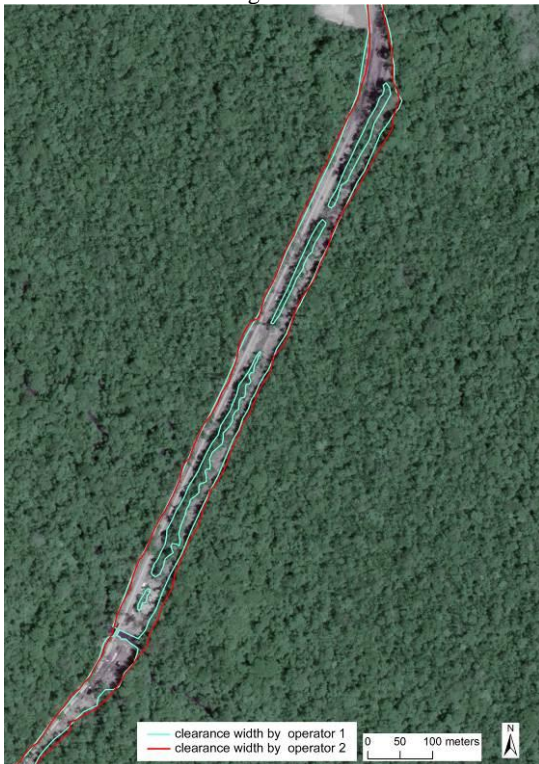


Figure 4d



Figure 5a: relationships between clearance width, topography and ecosystems from Rio Tiputini (CPF) to the Eden

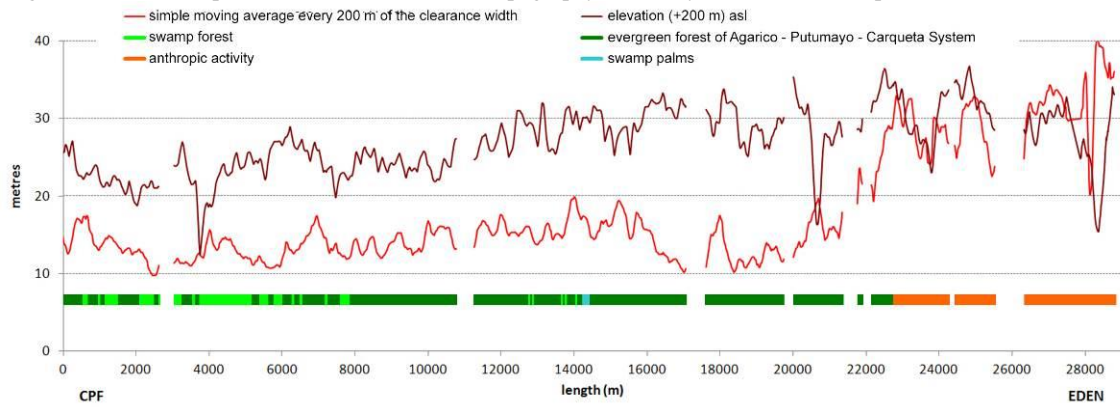


Figure 5b: relationships between clearance width, topography and ecosystems from Rio Napo to Rio Tiputini

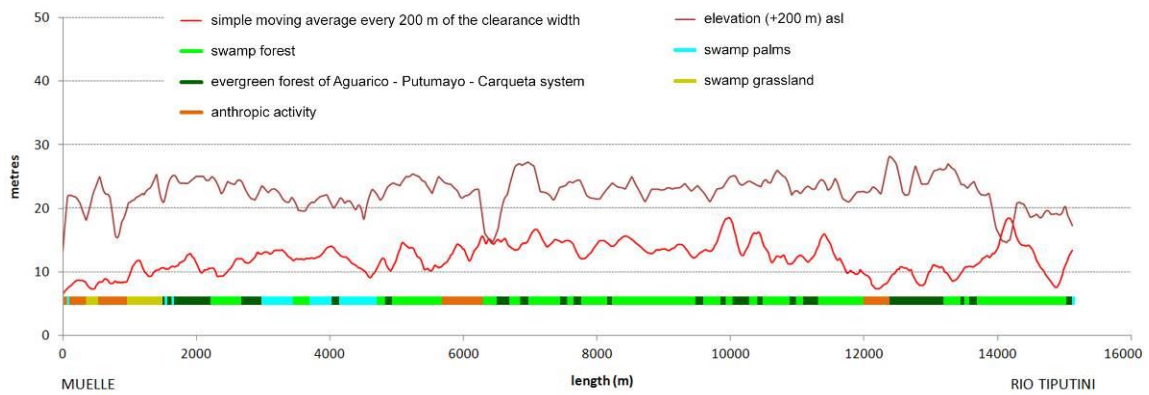
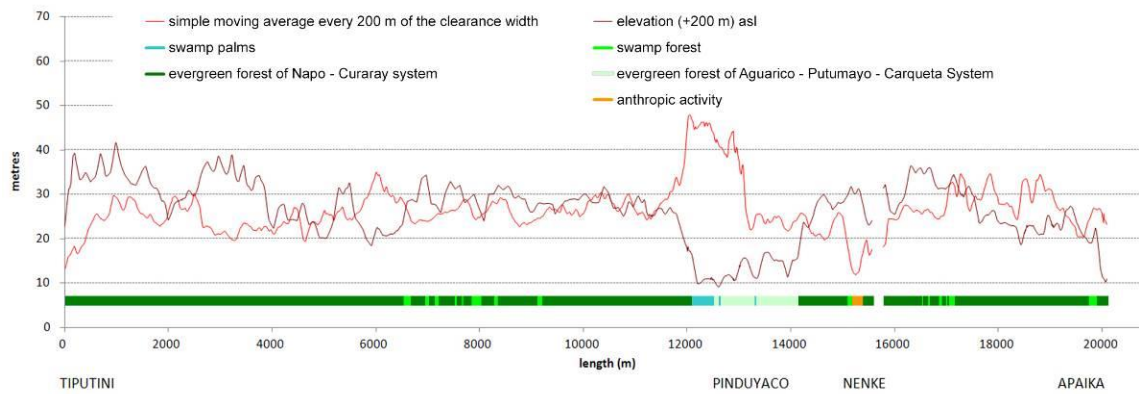


Figure 5c: relationships between clearance width, topography and ecosystems from Rio Tiputini to Apaika Platform



References

Geographical Validation of the Zona Intangible Tagaeri Taromenane (ZITT)". *PLoS One* 8, e66293.

- Barber, CP, Cochrane, MA, Souza Jr, CM & Laurance, WF 2014, 'Roads, deforestation, and the mitigating effect of protected areas in the Amazon', *Biological Conservation*, vol. 177, pp. 203–209. Available from: <http://dx.doi.org/10.1016/j.biocon.2014.07.004>. [Accessed 20 January 2017].
- Coffin, AW 2007, 'From roadkill to road ecology: A review of the ecological effects of roads', *Journal of Transport Geography*, vol. 15, pp. 396-406. Available from: www.sciencedirect.com. [Accessed 20 January 2017].
- Finer, M., Babbitt, B, Ferrarese, F, Novoa, S, Pappalardo, SE., De Marchi, M, Saucedo, M & Kumar A, "Future of Oil and Gas Development in the Western Amazon". *Environ. Res. Lett.* 10 024003 doi:10.1088/1748-9326/10/2/024003
- Finer, M., Jenkins, C. N. & Powers, B. Potential of best practice to reduce impacts from oil and gas projects in the Amazon. *PLoS One* 8, e63022.
- Finer, M., Vijay, V., Pappalardo, S. E. & De Marchi, M. 2013, Stunning aerial photos reveal Ecuador building roads deeper into richest rainforest on Earth (Yasuní National Park). *Mongabay.com* : <http://news.mongabay.com/2013/1112-yasuni-secret-oil-road-finer.html> [Accessed 20 January 2017].
- Forman, RT, Sperling, D, Bissonette, JA, Clevenger, AP, Cutshall, CD, Dale, VH, Fahrig, L, France, R, Goldman, CR, Heanue, K, Jones, JA, Swanson, FJ, Turrentine, T & Winter, TC 2003, *Road Ecology; Science and Solutions*, Island Press, Covelo, CA.
- Goosem, M 2007, 'Fragmentation impacts caused by roads through rainforests', *Current Science*, vol. 93, no. 11, pp. 1587-1595. Available from: <http://researchonline.jcu.edu.au/2442/>. [Accessed 20 January 2017].
- Ibisch, PL, Hoffmann, MT, Kreft, S, Pe'er, G, Kati, V, Biber-Freudenberger, L, DellaSala, DA, Vale, MM, Hobson, PR and Selva, N 2016 'A global map of roadless areas and their conservation status', *Science*, vol. 354, no. 6318, pp. 1423-1427. Available from: <http://science.sciencemag.org/content/354/6318/1423> [Accessed 20 January 2017].
- Laurance, WF, Clements, GR, Sloan, S, O'Connell, CS, Mueller, ND, Goosem, M, Venter, O, Edwards, DP, Phalan, B, Balmford, A, Van Der Ree, R & Arrea, IB 2014, 'A global strategy for road building', *Nature*, vol. 513, no. 7517, pp. 229–232. Available from: <http://dx.doi.org/10.1038/nature13717>. [Accessed 20 January 2017].
- Laurance, WF, Cochrane, MA, Bergen, S, Fearnside, PM, Delamônica, P, Barber, C, D'Angelo, S & Fernandes, T 2001, 'The Future of the Brazilian Amazon', *Science*, vol. 291, no. 5503, p. 438 LP-439. Available from: <http://science.sciencemag.org/content/291/5503/438>. [Accessed 20 January 2017].
- Laurance, WF, Goosem, M & Laurance, SGW 2009, 'Impacts of roads and linear clearings on tropical forests', *Trends in Ecology & Evolution*, vol. 24, no. 12, pp. 659–669. Available from: <http://dx.doi.org/10.1016/j.tree.2009.06.009>. [Accessed 20 January 2017].
- Pappalardo, SE., De Marchi, M. & Ferrarese, F. 2013, "Uncontacted Waorani in the Yasuní Biosphere Reserve: