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Road Impact Assessment Using Remote Sensing Methodology for Monitoring Land-Use Change in Latin America: Results of Five Case Studies

Louis Reymondin
Karolina Argote
Andy Jarvis
Carolina Navarrete
Alejandro Coca
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Acronyms

ABT	Audit Authority for Social Control of Forests and Land
ANAM	National Environmental Authority
CIAT	International Center for Tropical Agriculture
FN	False Negative
FP	False Positive
HANTS	Harmonic Analysis of Time Series
HEIG-VD	School of Engineering and Business Vaud
IIRSA	Initiative for the Integration of the Regional Infrastructure in South America
KCL	King’s College London
MINAM	Ministry of the Environment of Peru (Ministerio de Ambiente del Perú)
MLP	Perceptron
MODIS	Moderate-Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared Spectrum
PR	Precipitation Radar
TN	True Negative
TNC	The Nature Conservancy
TP	True Positive
TRMM	Tropical Rainfall Measuring Mission

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Introduction and Acknowledgements

Deforestation risks as part of potential indirect impacts and how to minimize them in projects, have been on the minds of project officers and environmental safeguard specialists in development banks for many years. With the potential release of carbon in addition to the threat to biodiversity and to other ecosystem services, the issue of deforestation has gained weight.

The Inter-American Development Bank (IDB) is particularly interested to address these risks in view of the increasing pressure on the remaining areas of forests and their global and local importance for development. As one of several approaches to better understand the interrelationship between development projects and deforestation, IDB's Environmental and Social Safeguards unit within the Vice-Presidency of Sectors and Knowledge (VPS/ESG) has explored the use of remote sensing i.e. satellite data to observe and analyze habitat changes following the implementation of infrastructure projects situated along or crossing forested areas, analyze and develop lessons for future projects. Conversations with research organizations and NGO and the development of methodologies led to a series of five case studies on "Road Impact Assessment Using Remote Sensing Methodology for Monitoring Land-Use Change in Latin America".

The present publication is a summary of the results from the five case studies including an overview of the methodology. VPS/ESG is further examining the possibilities of this methodology to use it for prospective purposes, as the basis for land use management and other potential applications in the development of infrastructure projects. The potential value of the methodology examined is based on being able to take into account the specific conditions of the respective cases, relevant drivers and their strength and the potential enabling effect of a project. This work complements other ex post analyses of infrastructure projects based on project documents, published as IDB Technical Notes titled "Managing the Environmental and Social Impacts of Major IDB-Financed Road Improvement Projects." VPS/ESG will further explore the use in its work of remote sensing and, in addition, study the options of modeling land use and land cover change.

I would like to acknowledge the pioneering efforts of the ESG staff who led the initiative, in particular, Paul Suding and Alberto Villalba. My sincere thanks go to all the partners who made this work possible. This Consultancy Project was conducted by the International Center for

Tropical Agriculture (CIAT), the Nature Conservancy (TNC), and the Conservation Biology Institute (CBI) for the Environmental and Social Safeguards Unit of the Inter-American Development Bank. This project was supported with funds from the German Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) (Federal Ministry for Economic Cooperation and Development) within the framework of a cooperation program between the Inter-American Development Bank (IDB) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Janine Ferretti, IDB ESG Chief
July, 2013

Executive Summary

Habitat conversion is contributing to widespread loss of biodiversity and other critical ecosystem services, yet, in many parts of the world, the scale and pattern of habitat loss goes unmonitored. The main goal of this study is to provide tools that will allow the analysis of the impact of large-scale road infrastructure projects on natural habitats. The study analyzes the impact of five road infrastructure projects (Figure 1) in Latin America: (1) the Santa Cruz-Puerto Suarez Corridor in Bolivia; (2) the BR-364 Highway in Brazil; (3) the Pan-American Highway section in Darien, Panama; (4) the Trans-Chaco Highway in Paraguay; and (5) the Initiative for the Integration of the Regional Infrastructure in South America (IIRSA) Integration Corridor in Peru.

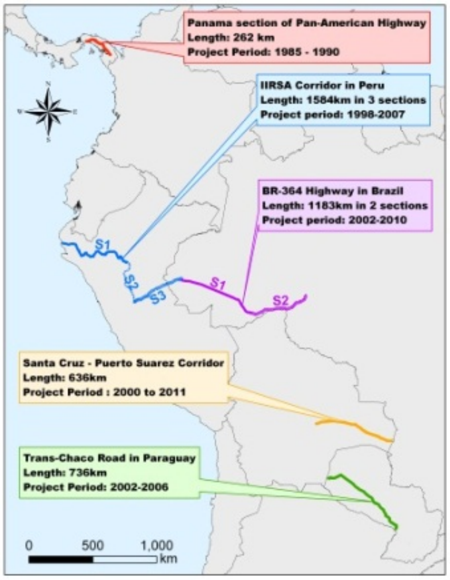

Figure 1. Locations of the Five Road Infrastructure Projects

The development of road projects in high-value ecosystems and nearby protected natural areas increases pressure on natural habitats, threatens biodiversity conservation, and encourages the conversion of forest land into agricultural and/or livestock systems.

Roads provide access to previously remote areas. This opens the way to drivers of deforestation and land-use change, as demonstrated by all five road infrastructure projects presented in this study. The patterns of deforestation following road projects over time are extremely diverse, which points to a wide variety of these drivers and variations in the influence they have on

different countries and their economies, as well as on natural factors and policies that channel, impede, or influence the dynamics of land-use and land-cover change.
Local, national, and international land management and environmental protection policies are essential and should be in place before, during, and after road construction, as they can significantly reduce the number of hectares deforested during and after project completion.

It is anticipated that infrastructure development allows for the expansion of economic activity. In this sense, national and regional policies and incentives to promote sustainable and environmentally friendly agricultural practices are also important.

Introduction

Land-use change, often taking the form of tropical deforestation, poses a significant threat to protected areas, biodiversity, and the provision of important ecosystem services to society. Left unchecked, deforestation destroys natural ecosystems, endangers wildlife, and wreaks havoc on crucial freshwater systems that are depended on for clean, safe drinking water. Still, deforestation continues at an alarming rate. In the face of climate change and the potential negative impact of forest conversion on human communities, scientists and world leaders are working to curb the continued loss of the world’s tropical forests.

Decision makers at multiple levels require the most recent and accurate information available on land-cover change in order to prioritize interventions and respond to new land-cover change patterns in a timely manner. Furthermore, decision makers increasingly demand accurate information to be used for the integration of environmental factors into the design of more efficient and sustainable development programs.

The goal of this research is to assess the impact of road infrastructure development on land-use change in five Latin American countries: Brazil, Peru, Panama, Bolivia, and Paraguay. Remote sensing and neural network techniques were used to detect deforestation patterns and trends.

Methodology (see also Annex)

In order to quantify the impact of the road construction projects on their respective ecosystems, the study employed a remote sensing methodology, Terra-i (Reymondin et al., 2012). This system was developed by the International Center for Tropical Agriculture (CIAT), based in Colombia, in collaboration with The Nature Conservancy (TNC), the School of Engineering and Business Vaud (HEIG-VD), based in Switzerland, and King's College London (KCL). Terra-i is a near-real time monitoring system that monitors satellite-based rainfall and vegetation data (Tropical Rainfall Measuring Mission (TRMM) and Moderate-Resolution Imaging Spectroradiometer (MODIS) data, respectively) to detect deviations from natural vegetation phenology patterns that may be attributed to the impact of anthropogenic factors on natural ecosystems. Disturbances are detected when the greenness of the landscape changes from its baseline values. When major changes in the vegetation index are identified (outside of the usual pattern of seasonal change), it is assumed that they are due to instances of human intervention. These instances are, therefore, flagged in near-real time as events that land managers, conservationists, and policy makers should be aware of. Since Terra-i is based on vegetation index data, it cannot identify the root causes of vegetation change. For that reason, all information on deforestation drivers in this report is derived from secondary sources.

Due to the relative newness of the technology, the data sets have their respective limitations. MODIS is relatively new and contains data from February 2000 onward. Similarly, the Terra-i model requires a prescribed time period for calibration. Data from the years 2000 to 2003 were used for calibration, which means that the system is operational for modeling beginning in January 2004. In some cases, other satellite data sets were used, such as the Landsat Image Time Series, in order to calculate road impacts that occurred prior to 2004. Therefore, as a monitoring tool, Terra-i is useful for analysis of projects after 2004. In the cases of Acre-Rondônia in Brazil, Peru, and Paraguay, Terra-i was used to its full capacity.

Results

Synthesis of Findings

Roads are clearly linked to deforestation and land-use change, as demonstrated in all five projects studied (Table 1). Roads have both direct and indirect impacts, and the size and characteristics of their "footprint" depend largely on the ecosystem affected (Andes <10 km, Amazon ~50 km, Chaco >50 km). Deforestation rates generally increase significantly after road construction; however, the rates vary markedly, depending on the geophysical situation, the strength of the socio-economic diversity, the effectiveness of land management policies, and other factors to be studied in more detail and case by case.

Table 1. Synthesis of Findings

Road	**Rondônia**	**Acre**	**IIRSA, Section 1**	**IIRSA, Section 2**	**IIRSA, Section 3**	**Trans-Chaco Highway**	**Santa Cruz - Puerto Suarez**	**Pan-American Highway, Panama**
Con-struction period	2002-2010	2002-2010	1998-2007	1998-2007	1998-2007	2002-2006	2000-2011	2000-2011
Pre-road deforesta-tion rate (ha/yr)	79,000	18,700	4,900	2,300	7,600	23,000	11,392	N/A
Post-road deforesta-tion rate (ha/yr)	113,000 (+43%)	32,400 (+72%)	6,100 (+25%)	5,200 (+125%)	7,500 (-1%)	97,000 (+319%)	N/A	55,256 (N/A)
Peak deforesta-tion	2006	2008	2010	2010	2005	2010	2010	1992-2000
Footprint	20-30 km	20-30 km	0-10 km	10-20 km	10-20 km	30-40 km	20-30 km	0-10 km

Trans-Chaco Highway in Paraguay

In Paraguay, Terra-i monitored habitat status every 16 days from January 1, 2004, until December 31, 2010 (Figure 2). The cumulative habitat loss detected during the 7 years analyzed amounted to 1,767,163 hectares nationwide, equivalent to an annual rate of 252,452 hectares/year. The departments with the highest rates of habitat loss were Boquerón, which registered a total loss of 1,015,363 hectares between 2004 and 2010, and Alto Paraguay, which registered a total loss of 471,988 hectares during the same period of time.

Of the roads analyzed, the Trans-Chaco Highway in Paraguay experienced the greatest increase in the rate of deforestation (+319%)—the largest footprint—and one of the highest annual deforestation rates post-road construction (97,000 hectares/year). The peak of deforestation was recorded in 2010 post-road construction. The highway's impact is witnessed mainly in a buffer area of 10 km around it, as well as around the Mariscal Estigarribia secondary road and the Pilcomayo River. The most affected ecosystem was the Dry Chaco, where a deforestation rate of 93% was recorded. Within this ecosystem, the Closed Deciduous Forests were the most affected. The main drivers of change are: the indiscriminate conversion of forest to pasture or agricultural land influenced by high commodity prices, land colonization, and a near absence of land-use control (Gasparri and Grau, 2009; Glatze, 2009; Guyra, 2010).

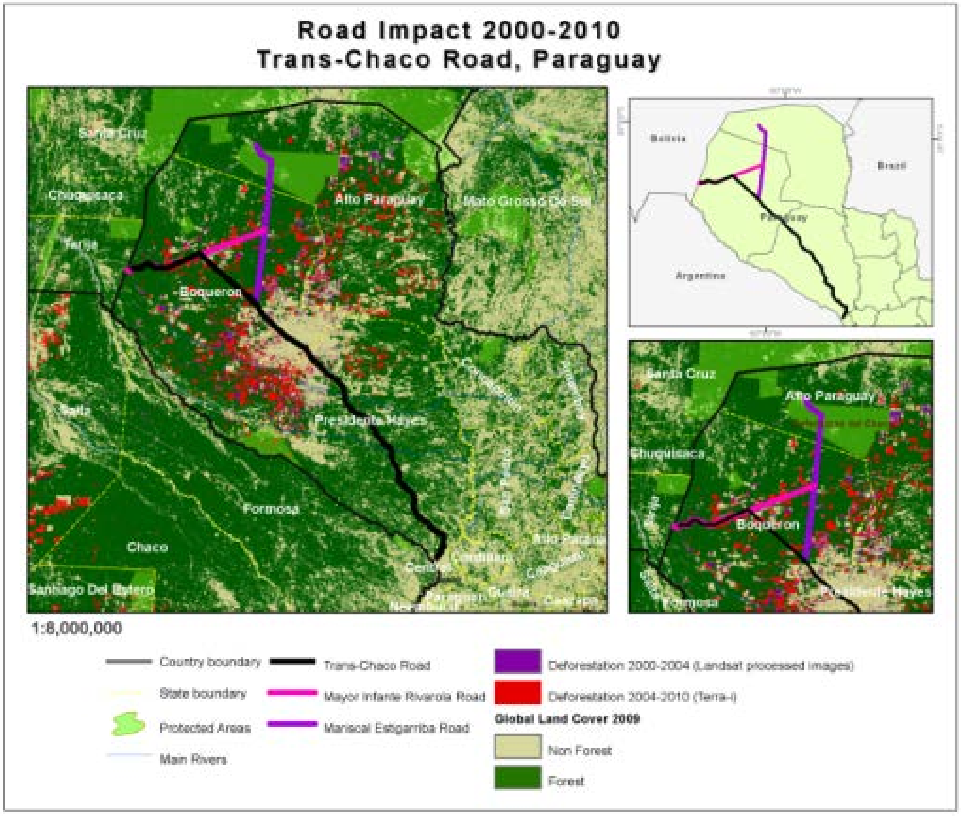

Figure 2. Road Impact 2000-2010, Trans-Chaco Highway

BR-364 Highway in Brazil

In Brazil, Terra-i performed habitat status monitoring every 16 days from January 1, 2004, until June 10, 2011 (Figure 3). In the 7.5 years studied, a cumulative habitat loss of 40,850 hectares was recorded in the state of Acre and 1,849,494 hectares in the state of Rondônia, equivalent to an annual loss rate of 40,850 hectares/year. The highest rates of deforestation were detected in the Amazonia states of Pará and Mato Grosso.

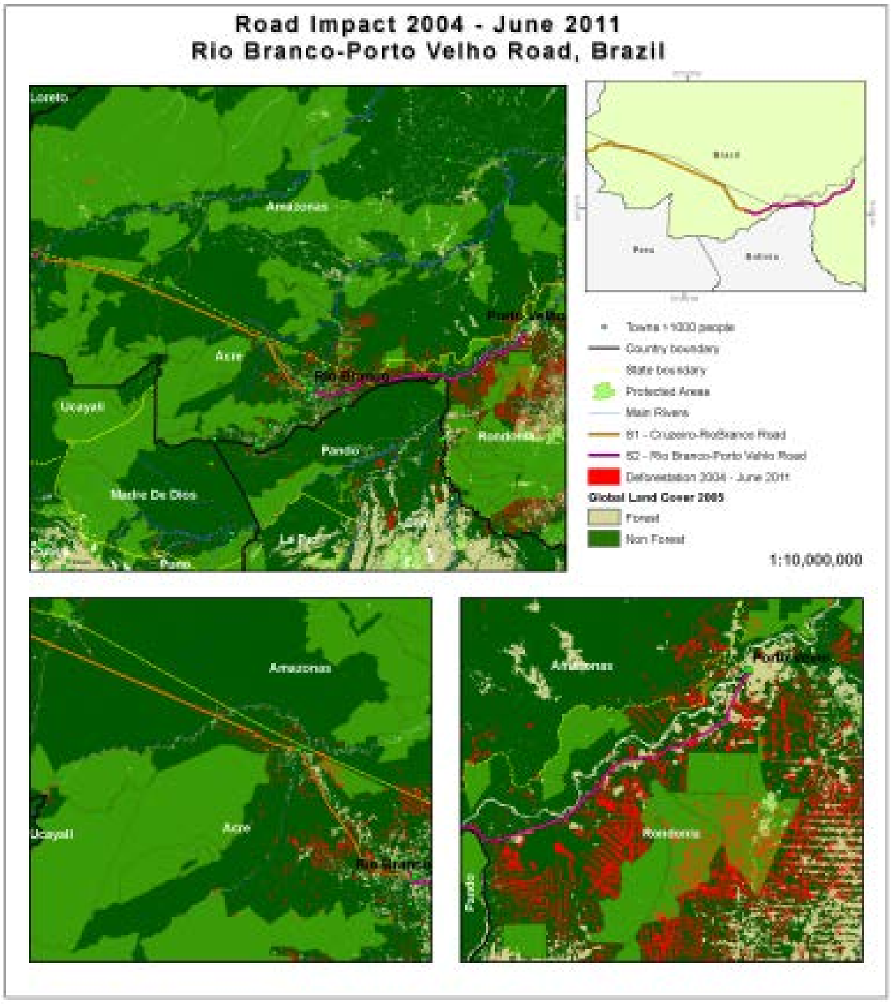

Figure 3. Road Impact, 2004-June 2011, BR-364 Highway (A)

The two sections of the BR-364 Highway in Brazil are characterized by similar footprints (20-30 km), showing 40-70% increased deforestation rates after road completion. The cumulative value of the post-road completion deforestation rate in S2 (state of Rondônia) has reached 113,000 hectares/year, far greater than the rate recorded around S1 (state of Acre), which is 32,400 hectares/year. In both cases, the peak of deforestation was recorded during the road construction, in 2006 in the state of Acre and in 2008 in the state of Rondônia. The main drivers of change in these two states are the extension of livestock areas and the implementation of large monoculture farms, particularly soybeans (Greenpeace, 2008).

The impact of the BR-364 Highway has been less severe in Acre. It seems that conservation policies implemented in Acre have been much more effective in reducing deforestation. A relevant antecedent is the Acre Sustainable Development Project − BR0313 − (IDB 2011a), which helped to regularize land tenure, increase protected areas, promote cultural centers, and empower local and regional authorities to enhance management and the use of natural resources and sustainable agricultural practices.

IIRSA Integration Corridor in Peru

In Peru, Terra-i monitored habitat loss every 16 days from January 1, 2004, until June 10, 2011 (Figure 4), detecting a cumulative habitat loss of 350,894 hectares during the 7.5 years analyzed, equivalent to an annual rate of 46,786 hectares/year. The highest rates of deforestation were detected in the departments located in the Amazon, including Amazonas, Loreto, Madre de Dios, San Martin, and Ucayali. The main deforestation driver, according to a study by the Ministry of the Environment of Peru (MINAM), is agricultural expansion (MINAM Peru, 2009). This study notes that Amazon soil is not suitable for agriculture. When soil fertility inevitably begins to decrease, settlers are forced to move and start anew with the same agricultural practices.

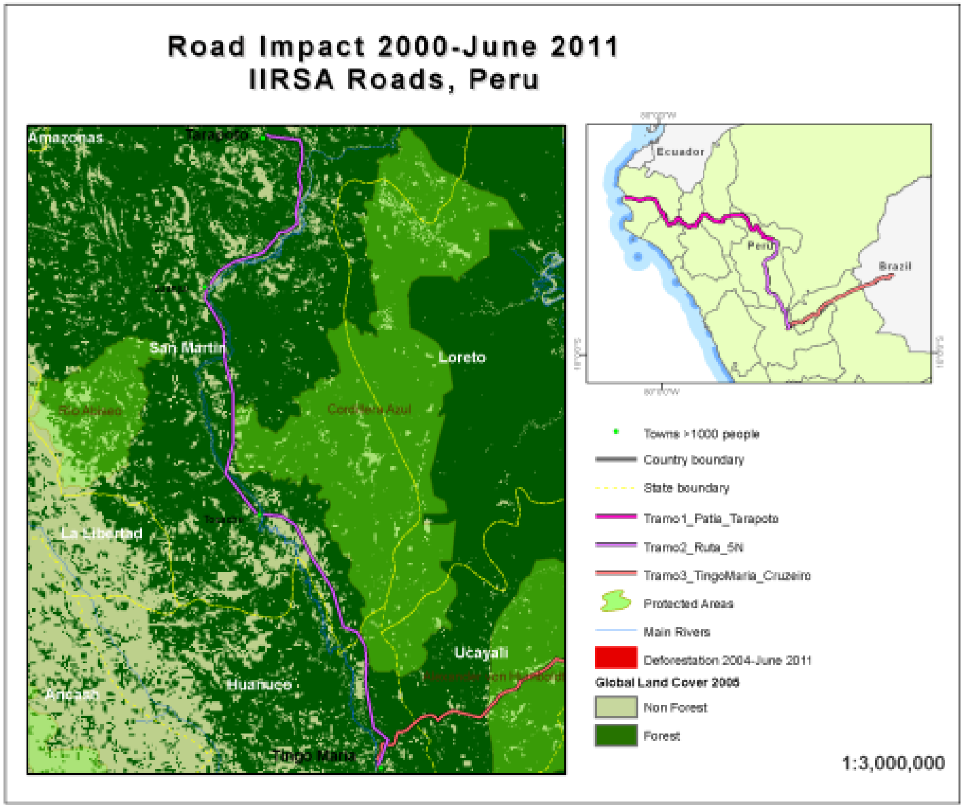

Figure 4. Road Impact 2004-June 2011, IIRSA Road in Peru

Road impact analysis shows that the buffer zone of 10 km around the road is the most affected area. For Section 1 of the road (Patia-Tarapoto), which crosses the departments of Piura, Lambayeque, Cajamarca, Amazonas, and San Martin, an average annual loss rate of 2,464 hectares was measured between 2004 and 2011. Section 2 (Tingo Maria-Tarapoto) lost 1,148 hectares/year, and Section 3 (Tingo Maria-Cruzeiro) lost 1,623 hectares/year.

An interesting finding is that the IIRSA corridor affects the three sections differently. An examination of all three sections indicates that the annual deforestation rate is now around 5,000 hectares, but it has increased much more in Section 2 (Andes), 125%, than in the other sections. The footprint is smaller in Section 1 (desert), compared to Section 2 and Section 3 (Amazon). In the Peruvian Amazon, deforestation has increased in the medium and long term while roads or pathways have been built due to human settlement and a shift to cultivation (MINAM Peru, 2009).

Pan-American Highway in Panama

The Terra-i monitoring system has only been operational since 2004. Hence, it could not be used to analyze the road construction in Panama, which took place before that date. Therefore, to detect habitat change in the ecosystem during the construction and development of the Pan-American Highway (IDB 2011b), a data set of land cover produced by the Forestry Information System Project of the National Environmental Authority (ANAM) was used. This product provided two land cover maps from 1992 and 2000. It was then possible to use Terra-i data to detect forest cover loss from 2004 to 2010 (Figure 5).

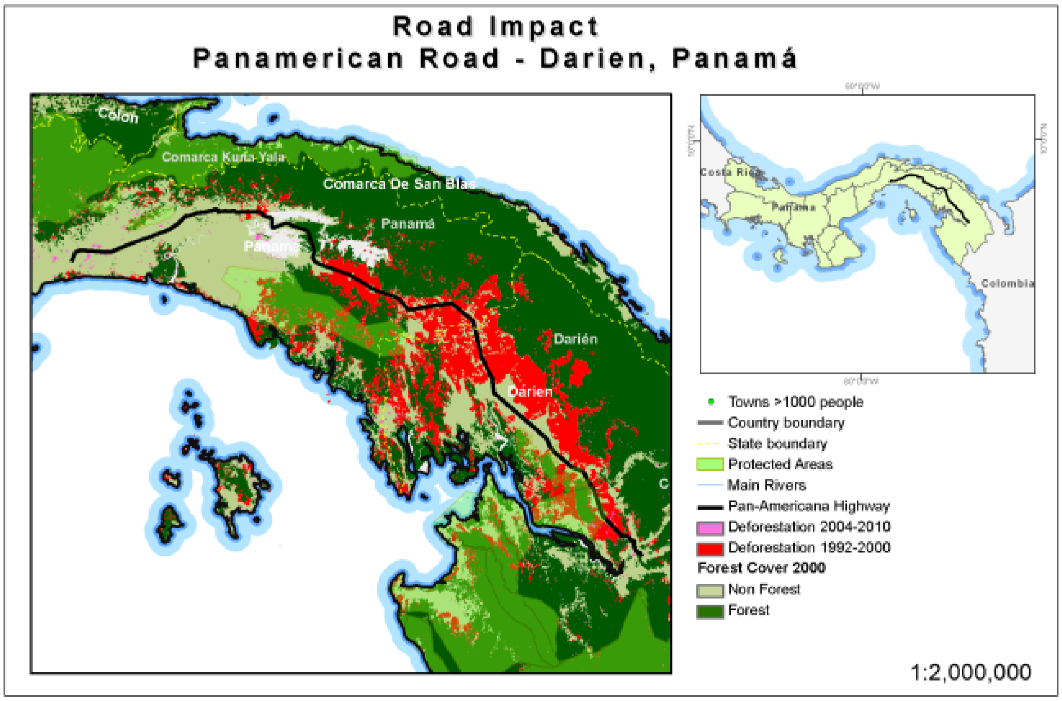

Figure 5. Road Impact, Pan-American Highway, Panama

Between 1992 and 2000, there was an alarming loss of 7% of the total national forest cover of Panama, equivalent to 497,306 hectares. This deforestation is localized mostly in the provinces of Panama and Darien, less than 30 km from the Pan-American Highway. The impact of the Pan-American Highway construction mainly occurred in immediate area of influence, from 0 to 10 km from the road, between the years 1992 and 2000. Panama's greatest loss of habitat was logged in this area during the analyzed period (1992-2010) of this study, with a cumulative area of 77,930 hectares, or the equivalent of 32% of the 10 km buffer around the analyzed road. The habitat loss clearly decreases in proportion to the distance of the analyzed buffer from the road.

Santa Cruz-Puerto Suarez Corridor in Bolivia

In Bolivia, Terra-i detected a cumulative habitat loss of 1,727,525 hectares during the 7.5 analyzed years (2004-June 2011), or the equivalent of a national annual rate of 230,337 hectares/year (Figure 6).

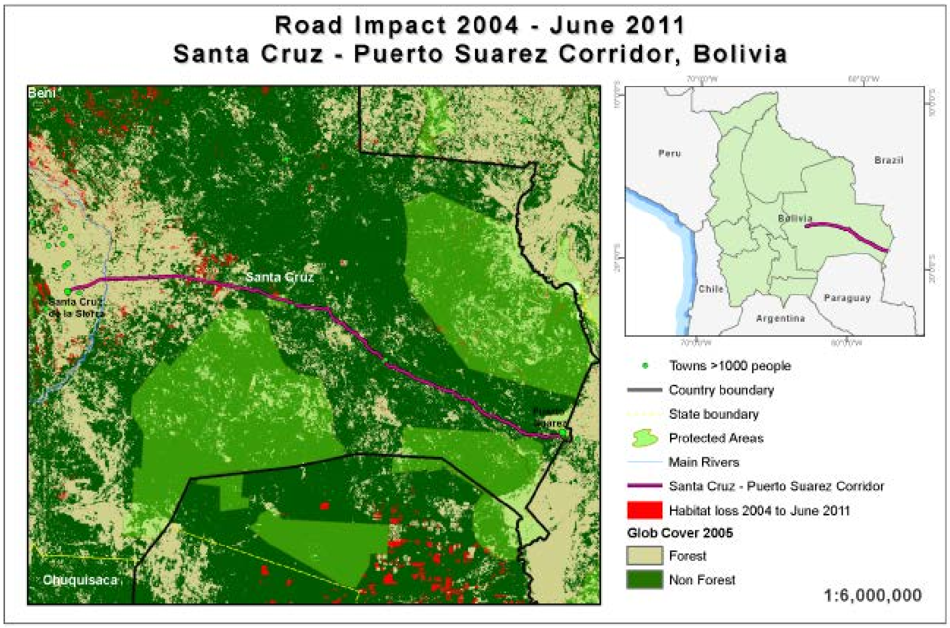

Figure 6. Road Impact 2004-June 2011, Santa Cruz-Puerto Suarez Corridor

This figure corresponds to about 1.6% of the nation's total terrestrial area. The department of Santa Cruz has one of the highest conversion rates nationwide: 124,498 hectares per year. Its greatest losses occurred in 2010, surpassing all historical records of habitat loss in the area. Due to the road construction's recent date of culmination (IDB 2011c), a complete analysis of its impact could not be done. In a 50 km buffer area of the road, Terra-i detected an annual rate of habitat loss of 11,392 hectares/year between 2004 and 2011. These high figures were mainly due to forest fires that occurred during these years (Rodriguez, 2010). In addition, according to Rodriguez (2010), many of these fires occurred because of agricultural practices that rely on "slash and burn" methods, which consist of burning certain areas of forest in order to expand the agricultural frontier and create new areas for livestock. In addition to forest fires, according to reports from the Audit Authority for Social Control of Forests and Land (ABT), deforestation in Bolivia between 1997 and 2010 can be explained by the following drivers, in order of importance and magnitude: livestock production, conversion to industrial agricultural land, colonization of land by new settlers, and, to a lesser extent, agricultural and livestock systems implemented by small farmers and indigenous peoples.

Policy Recommendations and Conclusions

Regional and national environmental policies may significantly reduce the number of hectares deforested during and after a road construction project. The most outstanding case can be found in Brazil, where Rondônia has higher deforestation rates than Acre (Keck, 2001).

Most of the protected areas impacted directly or indirectly by road construction were affected after the road construction was completed. In cases where critical ecosystems are endangered, policy makers and development planners should consider, well in advance, the critical natural habitats and biodiversity hotspots to be designated for conservation.

It is anticipated that infrastructure development allows for the expansion of economic activity. Policies and incentives to promote sustainable and environmentally friendly agricultural practices are also important. Thus, it is fundamental that national and regional policies and incentives for infrastructure and agriculture projects are carried out in a concerted sustainable, environmentally friendly manner. In the case of the slash and burn methods in Bolivia and Peru causing multiple forest fires, more national policies and programs to promote sustainable practices, such as the Slash and Mulch Agroforestry Systems, should be implemented. Increased productivity is also key to food security, livelihoods, and a reduction in the footprint of agriculture. Effective land policy and law enforcement, as well as sound development plans, are also relevant in terms of reducing the negative environmental impact of road infrastructure.

It is clear that the development of road infrastructure has a positive impact on economic growth, but roads also provide access to remote areas and, as a result, have a considerable negative environmental impact within their area of influence. The construction of roads should, therefore, always be framed within development plans that consider strategic areas of conservation. Furthermore, there should be strong environmental and agricultural policies in place, enforced by local and regional authorities, which can considerably reduce negative environmental impacts associated with road infrastructure development. The lack of proper environmental management and appropriate conservation strategies before, during, and after road construction is the primary driver in the complex process of degradation, deforestation, and desertification. Furthermore, this is what leads to negative impacts on ecosystems, such as the alteration of vegetation cover, habitat change, hydrological changes, and the loss of biodiversity, among others.

Most of the protected areas affected directly or indirectly by road construction were established after the roads were built. Development planning and policy formulation should prioritize the critical ecosystems to be preserved well in advance, and infrastructure development should be planned accordingly. Therefore, policies and incentives should be in place to promote sustainable agricultural practices and increased productivity. Land policies with a sound distribution of productive activities and protected areas in the territories, as well as law enforcement, are also relevant in terms of reducing the negative environmental impacts of road infrastructure.

Finally, as a monitoring tool, Terra-i is only useful for analyzing projects after 2004. In the cases of Acre-Rondônia in Brazil, Peru, and Paraguay, Terra-i showed its full power.

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This document is a summary of five extensive analysis reports. All the original reports can be found on http://www.terra-i.org/terra-i/publications.html.

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Annex: Methodology Overview

Habitat loss detection, the Terra-i approach

Terra-i is a near-real time monitoring system that mines satellite-based rainfall and vegetation data to detect deviations from the usual pattern of vegetation change, which it interprets as possible anthropogenic impacts on natural ecosystems. The model uses a multilayer Perceptron (MLP) neural network combined with Bayesian theory to identify abnormal behavior in a time series of vegetation change. The implementation of the system pan-tropically is a considerable challenge from a computer science perspective, as the resolution of the MODIS sensor (250 m) means that even the Amazonian basin alone represents more than 1 billion individual values for each time frame (every 16 days). This means that more than 26 billion values must process per year. Such a large data set necessitates the use of data mining technologies and distributed programming.

Human activities create disturbances that alter the usual cycle of vegetation greenness in an area. Disturbances can be detected when the Normalized Difference Vegetation Index (NDVI) of the landscape changes from its baseline values (Figure A1). The general approach adopted here is to build a forecasting model capable of predicting the evolution of vegetation greenness for a site, based on the relationship between previous greenness measurements and simultaneous climatic measurements at that site. Such a model is then used to predict future NDVI values (16 days ahead, given the current climatic conditions) and to identify anomalies or abrupt changes in vegetation where NDVI observations from MODIS differ from the model predictions. The model calculates an anomaly probability based on the difference between predicted and observed values. It is assumed that vegetation evolution (NDVI evolution at a site) is influenced by recent and seasonal rainfall trends. When major changes in the vegetation index are detected (outside of the usual pattern of seasonal evolution), it is assumed that they are due to human intervention. These events are, therefore, flagged in near-real time as events that land managers, conservationists, and policy makers should be aware of.

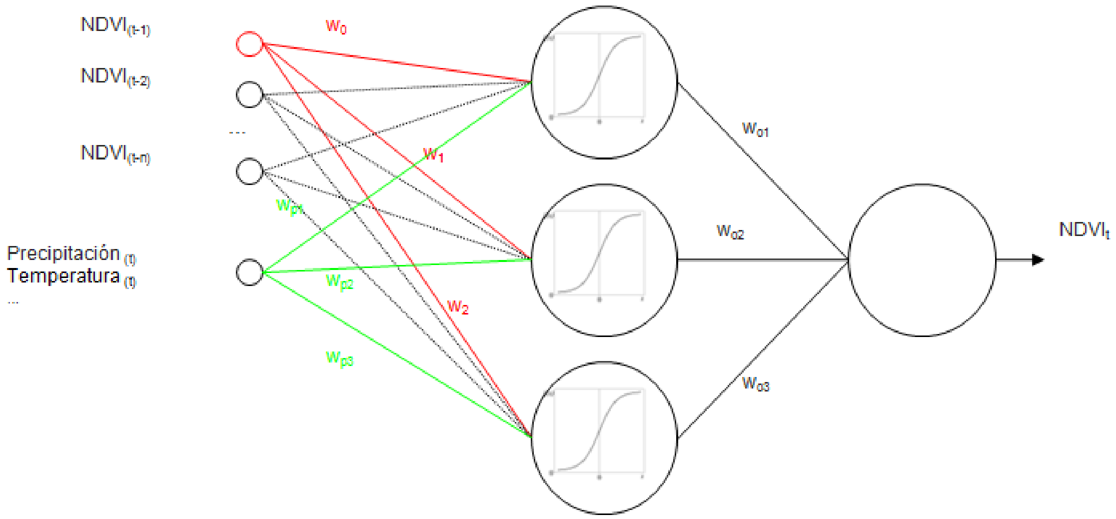

Figure A1. Structure of the Artificial Neural Network Implemented

To model the evolution of the NDVI vegetation index at a given point (i.e., a pixel) and time, artificial neural networks are trained using machine learning algorithms exploiting the NDVI data for a given number of preceding measurements, thus indicating the recent NDVI trend and the accumulated rainfall (derived from the TRMM daily rainfall product 3b42) for the preceding 16 days in order to fit the MOD13Q1 temporal resolution.

Because the MODIS data is not noise free, NDVI time series cleaning is needed as a first step. As the methods based on Fourier analysis and curve fitting have been shown to perform better than the other methods, the Harmonic Analysis of NDVI Time Series (HANTS) algorithm has been chosen as a cleaning algorithm to remove the effects of noise, atmospheric distortion, and cloud.

Although the approach is based on the training of a forecasting model on a per-pixel basis, it is not computationally efficient to train this model on a pixel basis pan-tropically. To operationalize the model, the forecasting model is, therefore, trained on a land-use class basis rather than a pixel basis on the assumption that, within a given climatic region, the NDVI response to climate should be fairly consistent within a given land use. The approach, therefore, first uses an unsupervised clustering algorithm to find representative prototypes of time series dynamics that correspond to different land use. The clustering procedure is applied on MODIS-NDVI time series from the same period of time as the training data set. This will group together the pixels that had similar trends over these years and that can be modeled by the same forecasting model.

A given period of time series for each cluster is then randomly selected and used as the training data set for the modeling. As the system should be easily operational over large areas, it should be possible to perform the clustering step without having prior knowledge about the study area. Thus, the unsupervised KMeans algorithm has been selected to perform this task.

Once the area has been clustered, Bayesian forecasting models are trained using the training data set previously generated on a pixel-by-pixel basis in order to capture vegetation evolution trends and relationships based on past NDVI and TRMM data. After this "learning" step, the resulting models will be used to predict the greenness of these pixels for subsequent dates. By using Bayesian Neural Networks, the probability that the observed value is an anomaly is extracted based on the predicted value and some properties of the data set found during model training. Whenever the probability of being an anomaly exceeds a defined threshold, it is tagged as a potential anomaly. If the anomaly flag is repeated for a given number of consecutive dates, the system reports an anomaly at the given pixel.

The calibration step consists of finding the set of rules that gives the best results. To do that, we must evaluate the quality of the detection using a specific rule. For this reason, the calibration and the quality estimation are grouped together in this section. The computation of an evaluation of the detection involves an image where we know which pixels are deforested and which are not (this is done manually over small regions). With this tagged image, and the resulting image of the Terra-i processes (applied on the same region), one can count the pixels contained in four categories:

(1) True positive (TP): the pixel indicates a detection in both images.
(2) False positive (FP): the pixel indicates a detection in the result of Terra-i, but not in the human tagged image.
(3) True negative (TN): the pixel indicates "not detected" in both images.
(4) False negative (FN): the pixel indicates "not detected" in the result of Terra-i, but not in the human tagged image.

With these four numbers, we can compute two measures quite often used in information retrieval and pattern recognition: the precision and the recall. The formulas of these two measures are given by the following equations, where tp is the number of true positive pixels, fp the number of false positive pixels, and fn the number of false negative pixels:

$$pecision = \frac{tp}{tp + fp}$$

$$recall = \frac{tp}{tp + fn}$$

The precision measures the probability that a pixel detected by the Terra-i processing is really a deforested one, and the recall measures the probability that a deforested pixel is given as detected by the Terra-i algorithms. We cannot use these measures independently, because it is possible to have a recall giving 1 by setting all the pixels to detected (in this case, fn = 0 and the recall becomes $\frac{tp}{tp} = 1$). Precision will be low (and fp excellent) in this case.

Therefore, we need a third measure that takes into account both the precision and the recall. The F-Measure is perfectly suitable in this case, because it is based on a harmonic mean. This implies that, to get a good value, the precision and the recall must both be good. If only one of them is good, the result will be bad. The generalized formula of the F-Measure is given by the formula 2.14, where β is a parameter indicating how many times the user attaches as much importance to the recall as to the precision.

$$\frac{(1+\beta^2)D_1D_2}{\beta^2 D_1 + D_2}$$

By applying different detection rules and by computing the F-Measure on each cluster, we can find the one rule for each cluster that gives the best results.

When these rules are found, we can use them to apply a detection step, after which we can compute one more time the F-Measure (but in a global manner). This process will give us an estimation of the quality of the detection.

Anthropogenic events are not the only cause of unusual long-term anomalies in NDVI time series. Events such as floods could also be detected by the system. The set of detections resulting from the previous steps should, therefore, be filtered, and the drivers of the disturbance should be identified. To do so, the water mask from the MODIS MOD35 product will be used.

Figure A2 is a graphical description of the various steps involved, from the raw NDVI data processing to the creation of the anomaly probability maps.

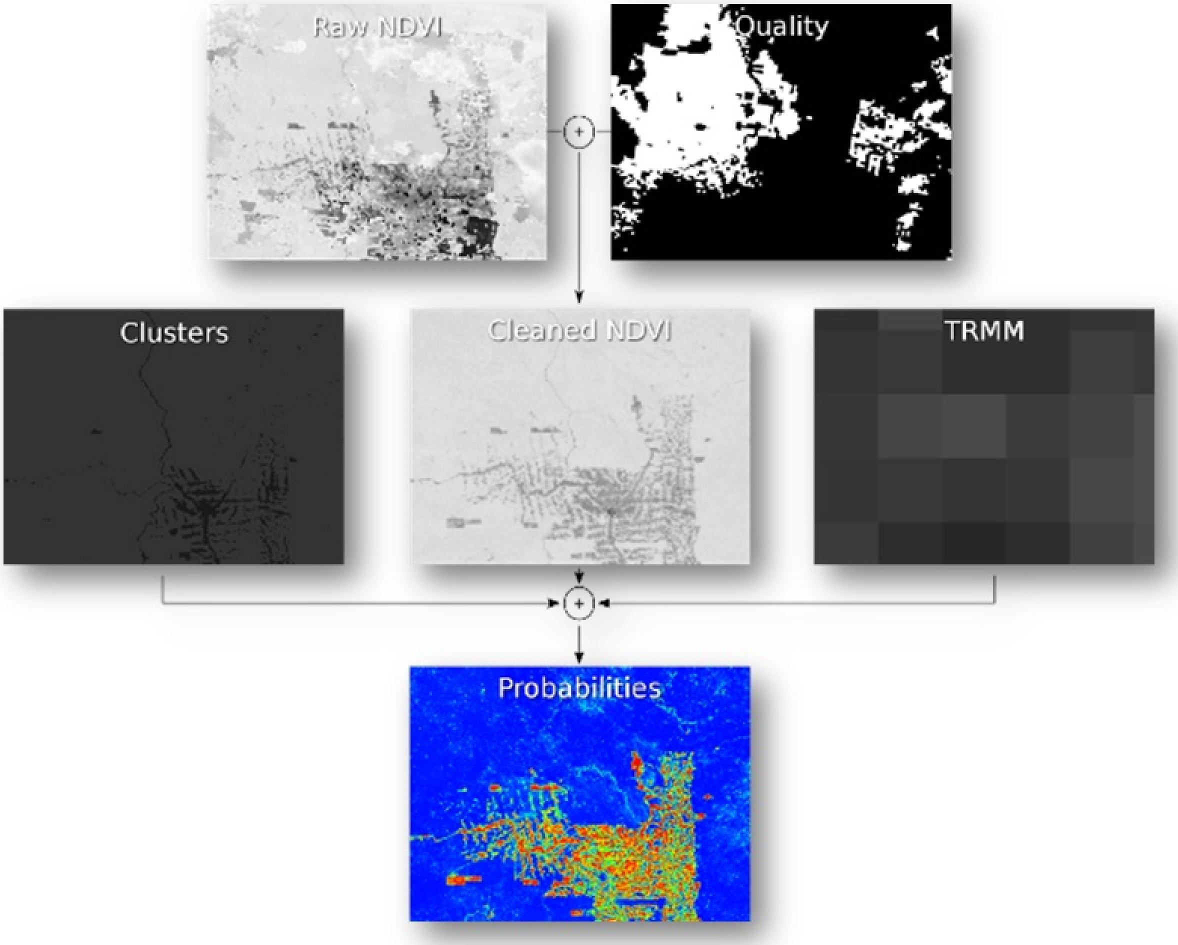

Figure A2. Visual Overview of the Methodology Used

While anomalies are reported at the pixel level every 16 days, this information can be synthesized to provide summary statistics for administrative units (municipalities, departments or states, and countries), critical ecosystems, or protected areas.

Input data

Terra-i uses data from the MODIS sensor, which provides images of the entire surface of the globe every 1 to 2 days. This sensor has a high radiometric sensitivity and provides images for 36 bands of the electromagnetic spectrum.

The coverage area is divided into 10 x 10 degree “tiles” or boxes, with a global coverage and a spatial resolution of 250 m every 16 days from February 18, 2000, to the current date (Figure A3). For the detection of changes in the habitats, Terra-i uses the MODIS vegetation indexes from the product MOD13Q1 (Figure A4) and precipitation data from the TRMM sensor.

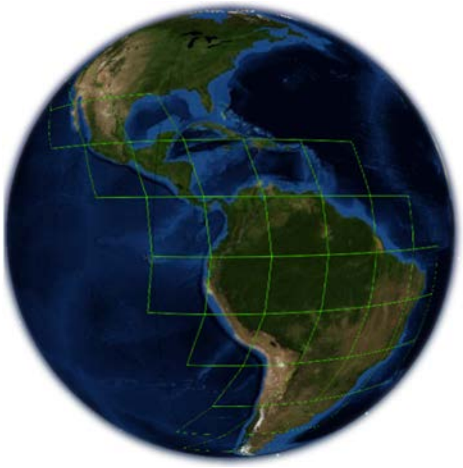

Figure A3. Analyzed MODIS Tiles

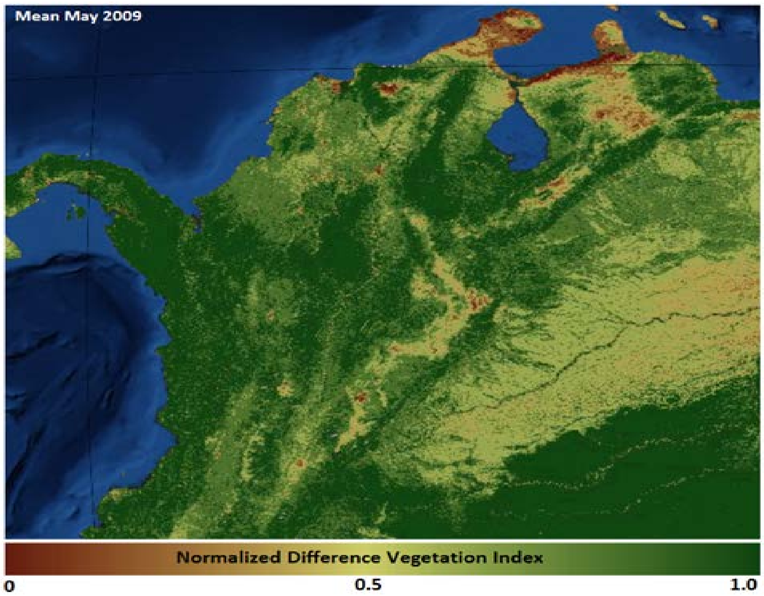

Figure A4. MOD13Q1: Normalized Difference Vegetation Index

MODIS vegetation indexes data

The vegetation indexes are designed to provide a permanent and consistent comparison of the temporal and spatial changes in vegetation by responding to the amount of photosynthetically active radiation in a given pixel, the chlorophyll content, the leaf area, and the structural characteristics of plants. The NDVI is an indicator of whether a given area contains live green vegetation or not. NDVI measures the spectral response of the vegetation. If the vegetation is degraded, it will reflect the blue and especially the red (R) visible spectrum. On the other hand, if the vegetation is healthy, it will reflect the near-infrared spectrum (NIR). Following this principle, many studies analyze NDVI time series to derive robust phenology markers, such as the start and the end of growing seasons for vegetation.

Terra-i uses NDVI data as well as the quality assessment data provided with a 16-day frequency and a 250 m spatial resolution by the MOD13Q1 product.

TRMM precipitation data

The Precipitation Radar (PR) aboard the satellite TRMM is the first weather radar designed to measure the vertical structure of tropospheric precipitation in the tropics and subtropics (Figure A5). Terra-i uses data from the TRMM precipitation sensor with a measurement frequency of 3 hours and a resolution of 28 km.

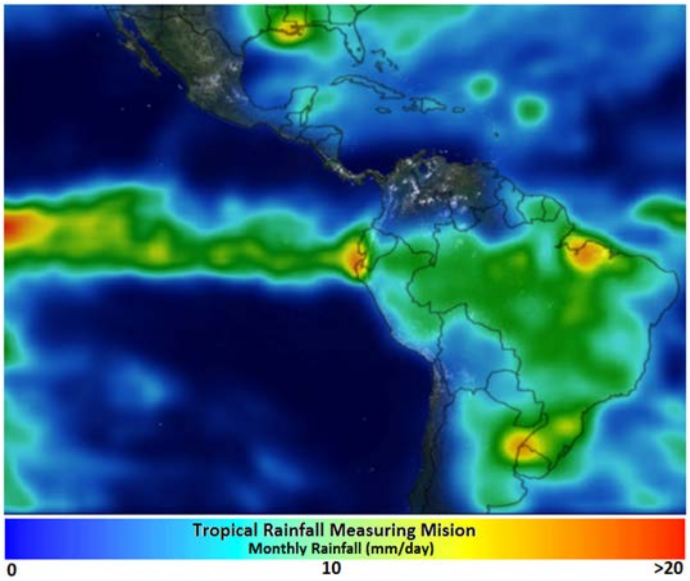

Figure A 5. Tropical Rainfall Measuring Mission, Monthly Rainfall (mm/day)

Water bodies presence data from MODIS

Terra-i uses the product MOD35 (Cloud Mask) (Figure A6) in its final stage of processing to mask the presence of water pixels and thus filter habitat change detections due to flooding and/or increases in water bodies.

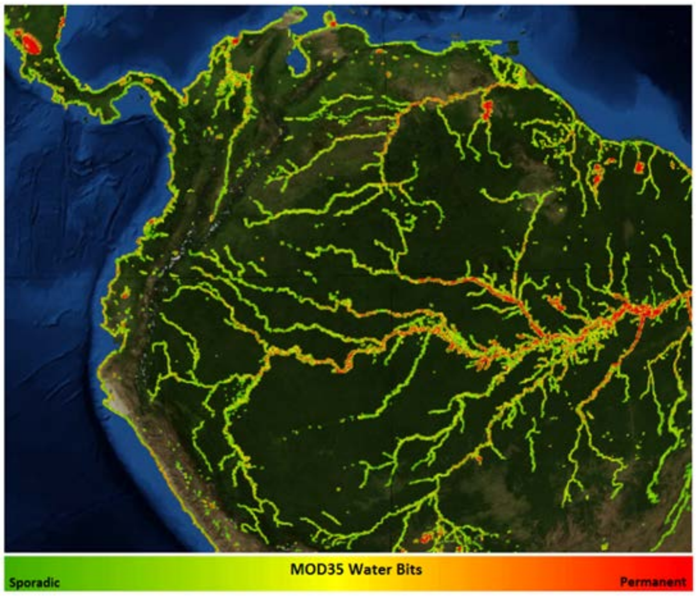

Figure A6. MODIS MOD35 Water Bits

Output data

Terra-i generates maps of habitat changes every 16 days for each MODIS tile in Latin America from 2004 to the current date. See the results at www.terra-i.org.