Land use Status and Trends in Amazonia

A report for the Amazonia Security Agenda Project

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terra-i
An eye on habitat change

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Executive Summary

The following document presents a brief summary of land-use change in Amazonia. With 6 million km^2, the Amazon is the largest tropical forest in the world. The Amazon basin covers nine countries: Brazil (58.4%), Peru (12.8%), Bolivia (7.7%), Colombia (7.1%), Venezuela (6.1%), Guyana (3.1%), Suriname (2.5%), French Guyana (1.4%) and Ecuador (1%).

Historical literature from published papers of public and private institutions have been compiled in order to determine the status and trends of land-use and land cover change within the focus countries of Bolivia, Brazil, Colombia, Ecuador and Peru. The report identifies a land cover change pattern between the Amazon countries, with agricultural activities being the key driver. The scale of stakeholders' agricultural activities is dependent on their economic production and the political model which varies by country.

Additionally, the Terra-i monitoring system has been used to provide data on land cover change in Amazonia for the period 2004 to 2011. Terra-i is the first tracking system of land-use and land-cover change in Latin America and the Caribbean. It 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.

During the 8 year period analyzed, Terra-i detected a cumulative habitat loss of 14,159,913 million hectares across the nine countries. Brazil, with an average habitat loss of 1,431,755 ha yr^{-1}, was by far the country which contributed the highest percentage, around 80% of the cumulative habitat loss. Although Bolivia covers a much smaller area of Amazonia than Brazil, it also showed considerable average land cover change of 0.29% per year in this period.

Finally, multi-approach analysis using Terra-i detections were carried out on biomes, ecoregions and protected areas to allow us to identify where and to what extent changes in natural vegetation are occurring, and to better understand the underlying environmental and social drivers of this change. Eighty-eight percent (88%) of the detected land cover change occurred in moist forest, although this should not detract from the other habitats which should also be of concern to the scientific, political and general community.

Acronyms and abbreviations

CIAT	International Center for Tropical Agriculture
CUMAT	Proyecto Capacidad de Uso Mayor de la Tierra, Bolivia
DETER	System of Deforestation Detection in Real Time
IDEAM	Institute of Hydrological, Meteorological and Environmental Studies
INPE	National Institute for Spatial Research
LAC	Latin America and the Caribbean
LUCC	Land use and land cover change
MINAM	Ministry of the Environment of Peru
FAO	Food and Agriculture Organization of the United Nations
PA	Protected Area
PRODES	System of Deforestation Detection in Real Time
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

Both planned and unplanned land use change is a significant threat to protected areas, biodiversity and the continued provision of important ecosystem services to society. It is estimated that the human footprint has affected 83% of the global terrestrial land surface (Sanderson *et al.*, 2003) and has degraded about 60% of the ecosystems services in the past 50 years alone (MEA, 2005). Global trends indicate that agricultural commodities produced for international markets have increasing weight in tropical landscapes as drivers of land-use and land cover changes.

Amazonia contains the world's most extensive tropical forest ecosystem and accounts for more land-use change than any other region in the world. Yet deforestation continues at an alarming rate, making the status of the forest one of the most important issues for consideration in land-use change studies for the entire region.

Decision-makers at multiple scales (local - national - regional) are eager to get information on land-use change, requiring the information to be as accurate and up-to-date as possible, in order to prioritize interventions and respond quickly to new land-use change patterns. Furthermore, decision makers need accurate information to use in the design of more efficient and sustainable development programs that integrate the environment as a key component for their implementation.

The main goal of this report is to provide a brief summary of land-use change in Amazonia within the focus countries of Bolivia, Brazil, Colombia, Ecuador and Peru. This report will mainly focus on the analysis and discussion of land-use change status and trends since 1970's, a period when considerable changes started to be evident. Analyses were supported from a literature review and land use databases and maps for Andean countries (CIAT) and Brazil (INPE). Additionally, data available from the Terra-i tool, the first habitat-loss tracking system for Latin America, was used to analyze the critical changes in land-use cover reported by several authors in the last decade (2000 to present date).

Annex 1 describes the Terra-i methodology applied for the assessment of land-use change in Amazonia during the eight year period 2004-2011. In addition, although Terra-i is not currently able to specify directly the land-use change for each detected loss, by examining data at the biome and ecoregion scales it is possible to determine where and to what extent changes in natural vegetation are occurring, and to better understand the underlying environmental and social drivers of this change.

2. An Overview of Amazonia

Land-use change context

With 6 million km^2, the Amazon is the largest tropical forest in the world. The Amazon basin covers nine countries: Brazil (58.4%), Peru (12.8%), Bolivia (7.7%), Colombia (7.1%), Venezuela (6.1%), Guyana (3.1%), Suriname (2.5%), French Guyana (1.4%) and Ecuador (1%) (Killeen, 2012).

During the last 40 years, human-induced deforestation has been very prominent and continues unabatedly in the region (Aguiar, 2012). Both monocultures and cattle-ranching expansion have been the key drivers of land-use change, followed by, in order of importance, the demand for firewood, mineral exploitation, the cultivation of illicit crops and forest fires (some caused by practices such as slash-and-burn) (Sombroek and Higuchi, 2012). Additionally, the construction of highways, such as those implemented by the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA), is a crucial factor which increases the extent and impact of other drivers of land use change.

According to the latest GEO Amazon Report, the total cumulative area deforested by 2005 was 85766600 million ha, and of this total area deforested 79.5% occurred in Brazil, followed by 8.2% in Peru, 5.3% in Bolivia, 3.4% in Colombia, 1.5% in Venezuela and 1% in Ecuador. The other countries contributed less than 1% of the total deforested area.

Furthermore, future scenarios are not very encouraging if the current land-use change trends continue. If the 2002-2003 deforestation rate (2.3 Mha yr^{-1}) in the Brazilian Amazonia continues, then 100 Mha of forest (about 25% of the original forest) will have disappeared by the year 2020 (Laurance *et al.*, 2001). Under business-as-usual scenario, 269.8 Mha will be deforested by 2050 (Moutinho and Schwartzman, 2005). Using a worst-case scenario, Soares-Filho *et al.* (2006) indicated that by 2050 the projected deforestation trend will eliminate 40% of the current 540 Mha of Amazon forests, releasing approximately 32 Pg (109 t ha^{-1}) of carbon to the atmosphere.

Land-use change studies and monitoring systems

There are increasing numbers of studies, especially since the late 1980's, which have completed multi-temporal assessments of land-use change for the entire Amazonia region (for further details see the Large-Scale Biosphere-Atmosphere Experiment in Amazonia - http://daac.ornl.gov/LBA/lba.shtml). Despite differences in methodology, which in some cases make it difficult to compare studies, the majority focus on the loss of forest cover and land-use change from activities such as agriculture, infrastructure constructions, and fire-induced events, among others. It is worth noting that in the last decade there has been an increase in land use change, mainly due to expanding agricultural activities resulting from the growing global demand for agricultural commodities (Aguiar et al., 2012; Uriostre, 2010).

Most land-use change initiatives at the local/regional level have addressed the Amazonian deforestation/land-use change processes, in particular through a number of major field studies such as the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) and the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).

On the other hand, online GIS tools allowing user-interaction and visualization are changing the way Amazon land-use information is presented. One example is MAPAZ (http://gismap.ciat.cgiar.org/IAViewer/v1.2), an online tool developed by the Amazon Initiative, compiling different sources of land-use (ESA Globcover project) as well as the distribution of the main crops according to official sources of each country.

Currently, Terra-i is the only land-cover change monitoring system available that provides data with consistent spatial (250m) and temporal resolution (16-days) for the entire of Amazonia. This tool has the distinct advantage of being able to provide a single objective measure of land-use change across multiple countries and time periods.

Terra-i data

In the Amazon, the Terra-i system detected an average annual deforestation rate of 1,769,989 million ha yr-1 between 2004 and 2011 for the nine Amazon countries, based on an analysis of 98% of the Amazonian area (Table 1). The remaining 2% corresponds to areas with significant cloud cover. This average, however, hides the more startling fact that between 2004 and 2011 the rate of annual natural habitat loss increased by 67% from 1,430,950 to 2,383,131 million ha (Figure 1).

According to these figures, it appears that the Brazilian Amazon has the highest habitat loss rate with an average of 1,431,755 ha yr^{-1} (0.3% of average rate per unit area) from 2004 to 2011. In Brazil, forest loss is advancing mainly in the "arc of deforestation", which spans the states of Acre, Rondônia, Southern Amazonas, Northern Mato Grosso, Southeast Pará, Central and Northern Tocantins, and Maranhão. However, it is important to note that habitat loss in the Amazon, despite being higher in Brazil, is not just a problem in this country but throughout the entire basin.

The Bolivian Amazon, though slightly less than the Brazilian rate, is well above the average rate of deforestation of the other Amazonian countries, and has an average deforestation rate of 203,459 ha yr^{-1} (0.29% of deforestation rate per unit area), measured during the same eight-year period (Table 1). However, it's important to highlight that Bolivia differs from the Brazilian Amazon by having a high deforestation rate despite a low population density (Uriostre, 2010). This fact highlights the need for an increase in the scientific research as well as management policies for the land-use change of the others countries in the Amazon besides Brazil.

The land-use change of the remaining Amazon countries is clarified when the Brazilian Amazon is excluded from the entire region. Thus, under this condition, the eight countries reached an average rate of habitat loss of 338,234 ha yr^{-1} for the eight-year period. Bolivia, followed by Colombia and Peru contributed around >50% of the total accumulated habitat loss of those countries (2,705,869 million ha) (Figure 2).

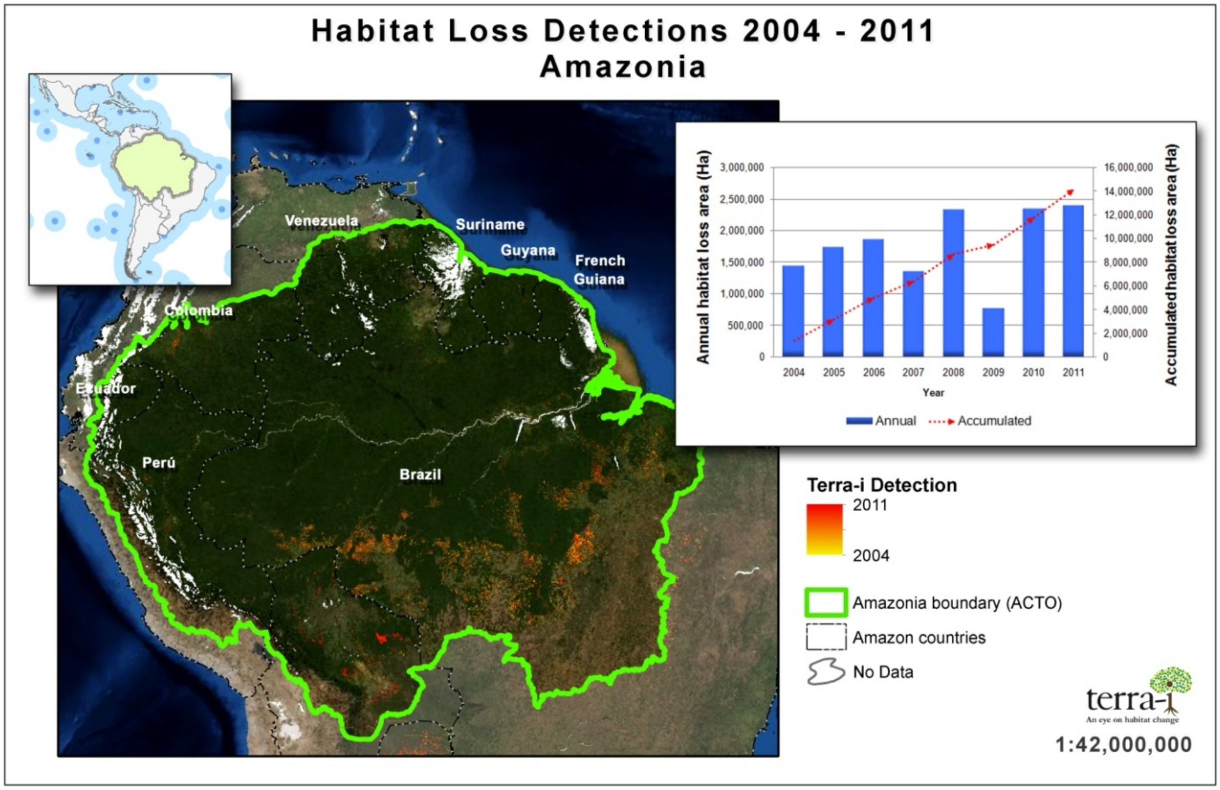

Figure 1: The Terra-i land use change detection map between 2004 to 2011, zoomed on deforestation hotspots (yellow to red spots) for the nine countries of Amazonia. Right: annual rate of habitat loss and accumulated loss, including Brazil.

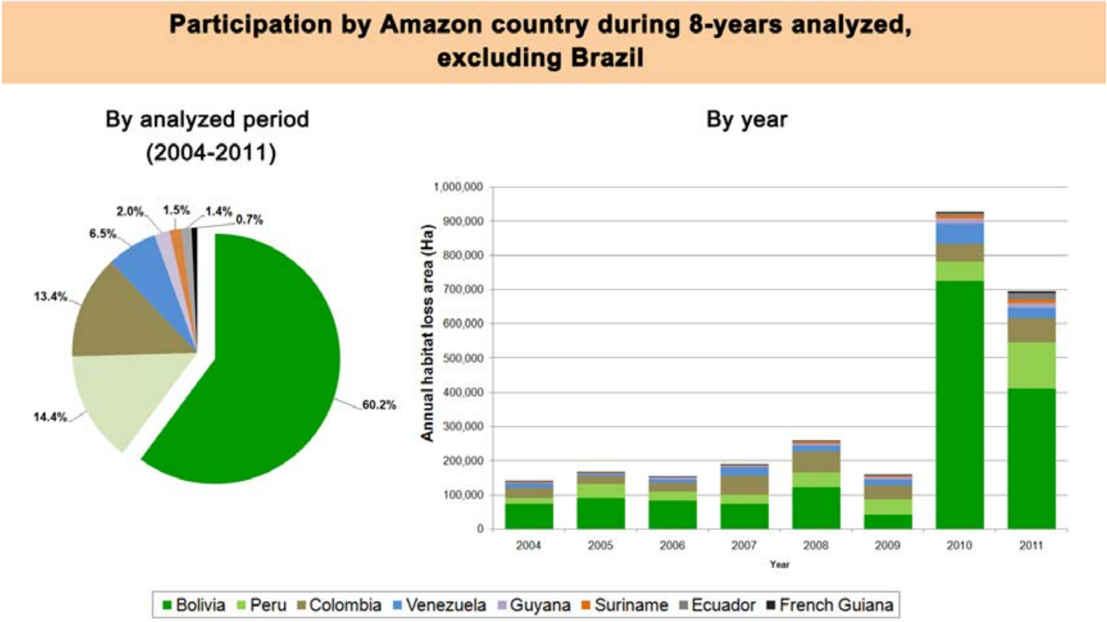

Figure 2: Participation of Amazon countries, excluding Brazil, by the total accumulated by year (right) and for the analyzed period 2004 to 2011 (left).

The Terra-i tool has identified a clear habitat loss pattern across the different Amazon countries. As seen above, habitat loss trends in Brazil and Bolivia are much higher than in the remaining Amazon countries. While Colombia, Ecuador and Peru show a prevalence of "slash-and-burn", with many small size plots scattered around rivers and roads, Brazil and Bolivia show extensive fields, with a more "geometric pattern", which is associated to the land tenure structure in the region, the vast majority for monoculture crops (soybean) and cattle ranching activities.

Table 1: Amazonia: Data for the nine countries, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-2011.

Habitat loss, per Amazon Country (ha), organize in terms of Avg. annual loss

Country	Analyzed Area	Not Analyzed	% NoData	% of total country analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Brazil	475,390,644	4,587,475	0.96%	99.04%	1,288,600	1,562,006	1,694,781	1,159,963	2,057,844	601,144	1,403,019	1,686,688	11,454,044	1,431,755	0.30%
Bolivia	69,977,250	289,269	0.41%	99.59%	74,619	90,638	82,706	75,469	124,275	41,756	726,269	411,938	1,627,669	203,459	0.29%
Peru	90,698,800	5,218,556	5.44%	94.56%	17,038	41,756	26,369	25,588	43,038	45,525	56,150	133,269	388,731	48,591	0.05%
Colombia	47,911,488	978,663	2.00%	98.00%	29,581	21,481	28,006	55,113	60,919	41,706	52,744	72,869	362,419	45,302	0.09%
Venezuela	43,233,875	979,713	2.22%	97.78%	13,288	7,669	9,656	24,694	15,275	17,300	59,881	28,969	176,731	22,091	0.05%
Guyana	16,324,238	4,603,644	22.00%	78.00%	963	1,906	2,988	3,806	6,750	5,881	15,800	15,306	53,400	6,675	0.04%
Suriname	14,525,419	21,544	0.15%	99.85%	2,650	2,394	2,656	2,450	5,550	5,556	8,413	10,575	40,244	5,030	0.03%
Ecuador	11,254,100	1,898,794	14.44%	85.56%	3,244	1,288	1,075	2,381	2,731	2,306	6,106	17,581	36,713	4,589	0.04%
French Guiana	8,092,375	201,738	2.43%	97.57%	969	1,288	2,313	2,044	3,000	1,213	3,200	5,938	19,963	2,495	0.03%
Total in Amazonia (n=8)	**777,408,188**	**18,779,394**	**2.36%**	**97.64%**	**1,430,950**	**1,730,425**	**1,850,550**	**1,351,506**	**2,319,381**	**762,388**	**2,331,581**	**2,383,131**	**14,159,913**	**1,769,989**	**0.23%**
Total in Amazonia, excluding Brazil (n=7)	**302,017,544**	**14,191,919**	**4.49%**	**95.51%**	**142,350**	**168,419**	**155,769**	**191,544**	**261,538**	**161,244**	**928,563**	**696,444**	**2,705,869**	**338,234**	**0.11%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Madeira-Tapajós moist forests	68,000,000	283,138	0.41%	99.59%	256,450	413,113	726,469	261,744	545,744	148,169	489,013	481,863	3,322,563	415,320	0.61%
Mato Grosso seasonal forests	38,800,000	6,625	0.02%	99.98%	468,025	406,931	239,750	248,219	433,238	44,444	260,469	271,350	2,372,425	296,553	0.76%
Xingu-Tocantins-Araguaia moist forests	24,600,000	48,581	0.20%	99.80%	134,069	244,325	192,350	218,413	412,906	63,550	246,756	331,163	1,843,531	230,441	0.94%
Southwest Amazon moist forests	73,000,000	650,263	0.88%	99.12%	47,931	104,044	92,538	59,925	117,125	52,569	281,044	242,219	997,394	124,674	0.17%
Tapajós-Xingu moist forests	32,000,000	493,313	1.52%	98.48%	102,050	89,044	128,906	63,606	234,238	83,075	75,463	189,169	965,550	120,694	0.38%
Tocantins/Pindare moist forests	18,300,000	266,388	1.43%	98.57%	79,456	106,369	122,750	86,169	108,800	61,275	96,794	88,138	749,750	93,719	0.51%
Chiquitano dry forests	15,000,000	2,325	0.02%	99.98%	62,900	25,044	36,906	33,825	65,975	12,819	306,863	201,288	745,619	93,202	0.62%
Cerrado	74,400,000	1,081	0.00%	100.00%	140,531	118,625	49,406	121,769	96,363	17,775	85,175	62,694	692,338	86,542	0.12%
Purus-Madeira moist forests	16,900,000	12,331	0.07%	99.93%	32,075	55,856	103,838	39,363	51,688	22,931	68,638	59,800	434,188	54,273	0.32%
Caqueta moist forests	18,100,000	2,900	0.02%	99.98%	16,081	13,481	16,925	38,538	44,144	25,494	31,631	43,306	229,600	28,700	0.16%
Sum of top 10	379,100,000.00	1,766,943.75	0.46%	99.54%	1,339,569	1,576,831	1,709,838	1,171,569	2,110,219	532,100	1,941,844	1,970,988	12,352,956	1,544,120	0.41%
Total in Ecoregions (n=54)	**777,408,188**	**18,779,394**	**2.36%**	**97.64%**	**1,430,950**	**1,730,425**	**1,850,550**	**1,351,506**	**2,319,381**	**762,388**	**2,331,581**	**2,383,131**	**14,159,913**	**1,769,989**	**0.23%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Triunfo do Xingu - Brazil (V)	1,427,713	0	0.00%	100.00%	24,719	28,275	38,081	20,300	62,631	13,856	14,856	45,581	248,300	31,038	2.17%
Rios Blanco y Negro - Bolivia (Ib)	1,199,725	100	0.01%	99.99%	1,325	1,319	863	1,931	3,775	69	166,744	22,713	198,738	24,842	2.07%
Bom Futuro - Brazil (VI)	187,400	0	0.00%	100.00%	4,088	9,206	18,475	11,431	13,544	2,594	14,731	12,488	86,556	10,820	5.77%
Jamanxim - Brazil (VI)	1,231,988	0	0.00%	100.00%	14,106	6,175	9,331	7,631	17,938	5,713	1,350	7,294	69,538	8,692	0.71%
Rio Jaciparana - Brazil (VI)	147,488	0	0.00%	100.00%	3,425	5,388	11,906	7,231	3,494	2,550	10,831	6,913	51,738	6,467	4.38%
Imataca - Venezuela (VI)	3,332,988	36,250	1.08%	98.92%	413	750	894	1,469	1,413	2,475	10,475	4,363	22,250	2,781	0.08%
Nascentes da Serra do Cachimbo - Brazil (Ia)	321,819	0	0.00%	100.00%	2,638	2,113	1,569	1,369	3,556	1,625	2,188	5,244	20,300	2,538	0.79%
Ilha do Bananal/Cantao - Brazil (V)	1,549,738	156	0.01%	99.99%	2,038	3,356	1,044	3,456	4,106	713	2,556	1,706	18,975	2,372	0.15%
Sur del Estado Bolivar - Venezuela (V)	4,914,625	130,863	2.59%	97.41%	1,700	1,175	1,731	1,569	1,969	1,450	3,350	5,088	18,031	2,254	0.05%
Terra do Meio - Brazil (Ia)	3,359,506	0	0.00%	100.00%	2,400	2,125	2,506	938	1,994	663	863	1,694	13,181	1,648	0.05%
Sum of top 10	17,672,987.50	167,368.75	0.94%	99.06%	56,850	59,881	86,400	57,325	114,419	31,706	227,944	113,081	747,606	93,451	0.53%
Total in PA (n=396)	**159,997,419**	**3,987,744**	**2.43%**	**97.57%**	**91,575**	**99,200**	**139,494**	**104,400**	**166,819**	**72,294**	**317,838**	**207,450**	**1,199,069**	**149,884**	**0.09%**

What is happening in terms of biome and ecoregions status?

For the eight-year period of analysis, the vast majority of land-use change has been experienced in the moist broadleaf forest (on average an 88% decrease) followed by dry broadleaf forest and then by the grasslands, savannas and shrublands biome (both average 12%). The remaining major habitats were less affected (average <1%) (Figure 3).

Six eco-regions of moist forest (Madeira-Tapajós, Xingu-Tocantins-Araguaia, Southwest Amazon, Tapajós-Xingu and Tocantins/Pindare moist forest and Mato Grosso seasonal forests) reported the highest rate of change (90,000 to 415,000 ha yr^{-1} over the analysis period). It's important to highlight their localization along the eastern and south-eastern part of the Amazon (Brazil) in the so-called *Arc of Deforestation*. Outside of this hotspot region, Caquetá moist forests in Colombia also showed considerable habitat loss with a rate of change of 28,700 ha yr^{-1}.

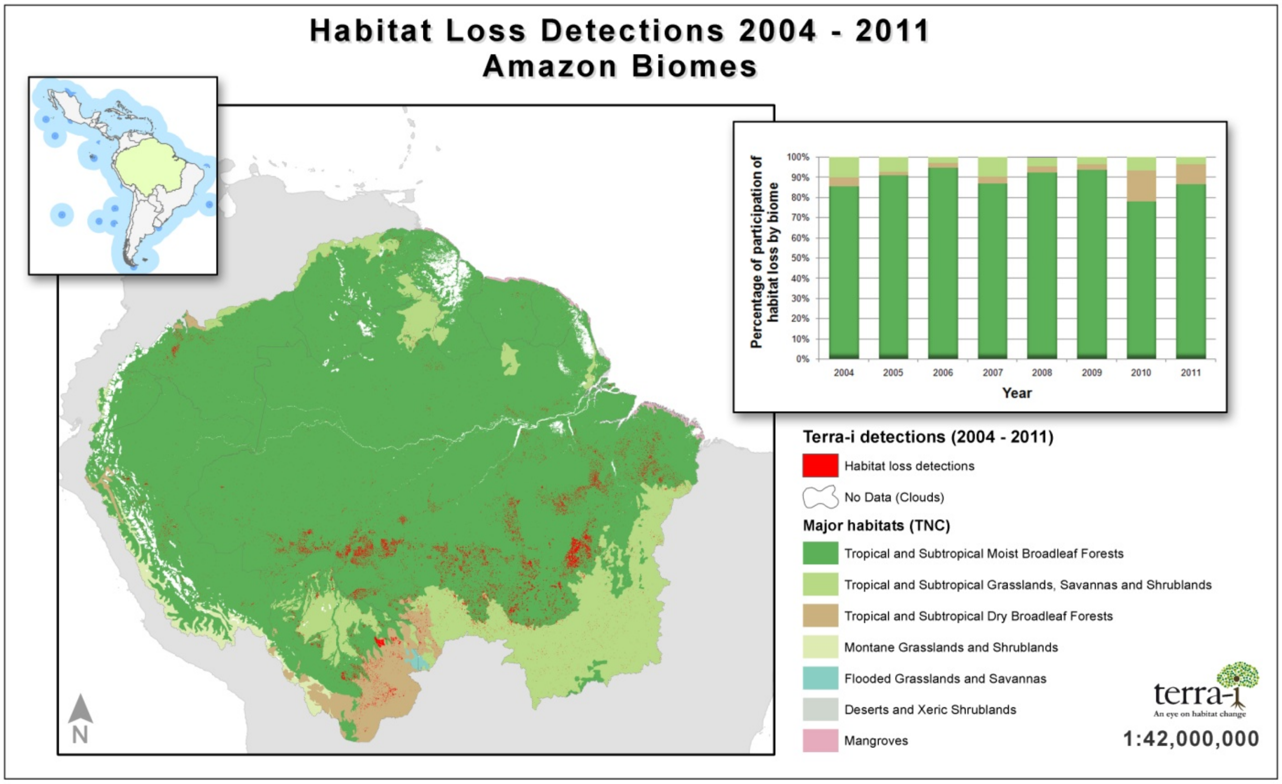

Figure 3: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) of Amazonia; habitat loss hotspots showed as red dots. Right, percentage of habitat loss for each biome.

For the others habitats, both Chiquitano dry forest and Cerrado savannas experienced a considerable cumulative area of habitat loss (749,750 and 745,619 ha, respectively) (Table 1).

What is the status of protected areas (PAs)?

Eight of the top ten PAs with the highest rate of change are located on the Brazilian side (Table 1). Triunfo do Xingu (Brazil) was the PA most affected during the eight-year period of analysis with an accumulated loss of around 248,300 ha, an area equivalent to the size of Luxemburg. Although the PA of Rios Blanco y Negro (Bolivia) obtained the second rate of change, this loss was due to fire events during 2010, and not due to human disturbances as has mainly occurred in Brazil.

Using the IUCN categories it is evident that PAs from categories V and VI were the most affected with a percentage contribution of 28% and 36% of the total area of land use change in PAs accumulated for the eight-year period, respectively (Table 2; Figure 4). This high contribution shows a trend of high vulnerability of the PAs of those categories, due to the nature of their management. According to IUCN and World Conservation Monitoring Centre both may contain a considerable proportion of their area devoted to some kind of agricultural or forest management.

Table 2: Habitat loss data by protected areas (IUCN categories) detected by Terra-i system for the period 2004-2011.

Habitat loss, per protected area IUCN Category (ha), organize in terms of Avg. annual loss															
IUCN Category	Analyzed Area	Not Analyzed	% NoData	% of total IUCN CAT analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accumulated	Avg. annual loss	% Annual rate of loss
Ia	16,207,831	4,738	0.03%	99.97%	6,700	7,575	9,150	6,869	9,763	5,219	8,763	11,106	65,144	8,143	0.05%
Ib	1,199,725	100	0.01%	99.99%	1,325	1,319	863	1,931	3,775	69	166,744	22,713	198,738	24,842	2.07%
II	16,207,831	4,738	0.03%	99.97%	8,704	9,580	11,156	8,876	11,771	7,228	10,773	13,117	65,144	18,293	0.11%
III	2,713,213	21,644	0.79%	99.21%	938	456	519	1,419	563	456	819	1,344	6,513	814	0.03%
IV	3,556,094	54,594	1.51%	98.49%	88	331	113	1,131	219	200	750	569	3,400	425	0.01%
V	21,737,856	483,481	2.18%	97.82%	33,906	37,706	48,000	32,425	76,631	22,338	27,581	62,131	340,719	42,590	0.20%
VI	67,711,500	1,771,256	2.55%	97.45%	31,375	39,625	63,888	46,288	57,719	32,606	79,000	78,513	429,013	53,627	0.08%
Total in Amazonia	**158,943,700**	**3,987,744**	**2.45%**	**97.55%**	**91,494**	**99,150**	**139,113**	**104,363**	**166,675**	**72,044**	**317,481**	**207,131**	**1,197,450**	**149,681**	**0.09%**

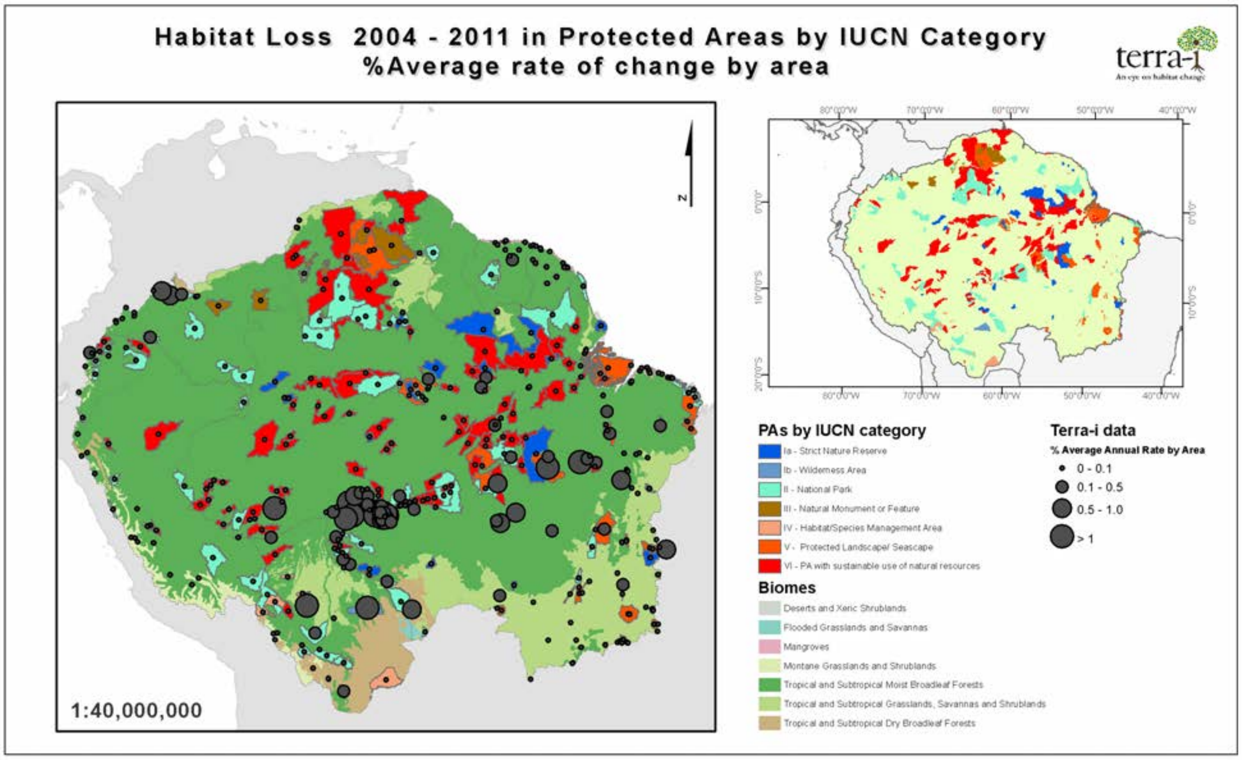

Figure 4: Left, map showing the percentage of average rate of land-use change by protected area for Amazonia between 2004 to 2011. Right, spatial distribution of the PAs by IUCN category.

An analysis of biomes, eco-regions and protected areas status by country using Terra-i detections will be discussed in more detail below.

Case Study
"Amazon forest threat is greater outside Brazil" (Killeen, 2012)

Recently, Timothy Killeen, a Bolivia-based ecologist and geographer, compiled data on the evolution of deforestation in the Amazon from 1990 to 2011 from environmental and forestry agencies (Figure 5). He concluded Amazon regions outside Brazil have been experiencing the most serious threat during the last decade, forming the so-called "*moon-shaped arc*" from Bolivia to Colombia and east to French Guiana and that the situation is more worrying with these countries having poorer and less stable governance, with less capacity to control the clear-cutting of trees than Brazil.

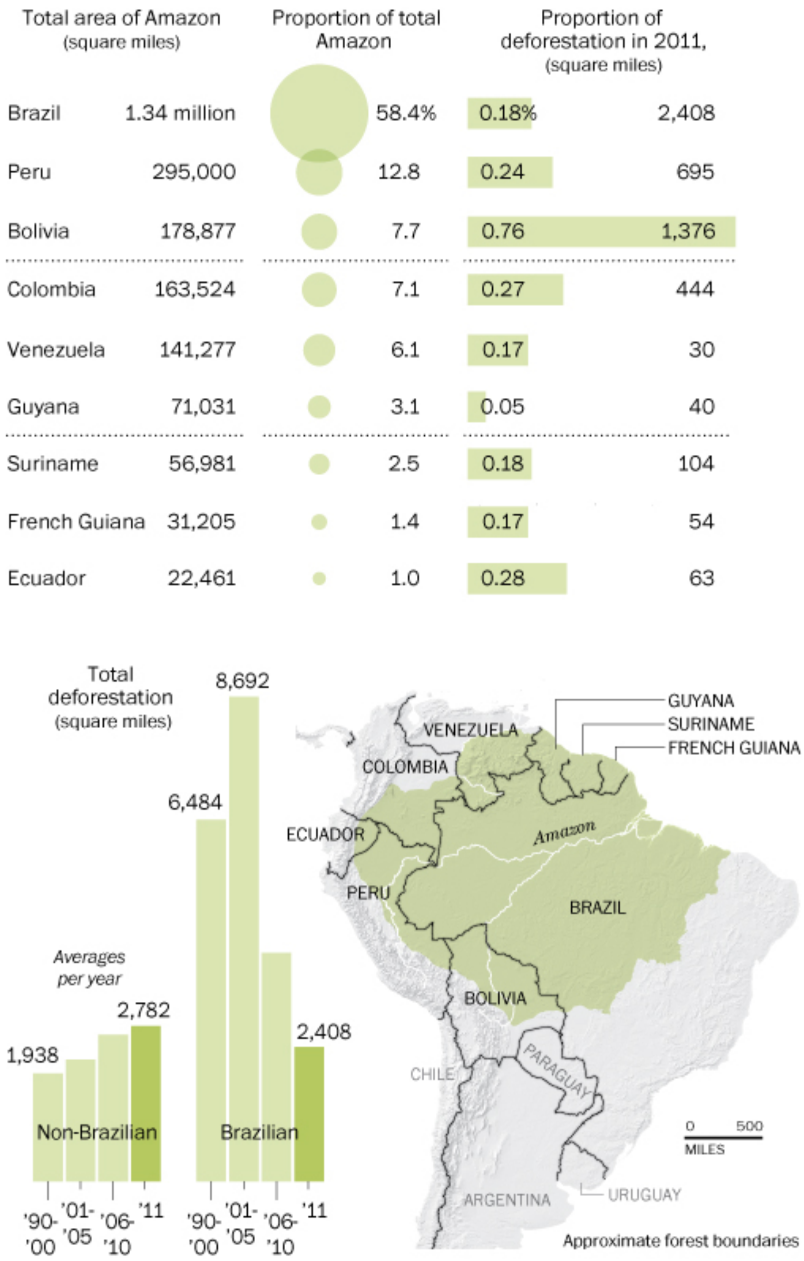

Figure 5: Contribution by country in terms of area in the Amazon, deforested data for 2011 and proportion of deforestation in 2011. Source: The Washington Post.

A preliminary comparison of the Terra-i data with Killeen's evidence shows both similarities and discrepancies between both sources (Table 3). Countries such as Guyana, French Guyana and Suriname had close values in terms of deforestation reported in 2011 (<20,000 ha) whereas Andean countries, with the exception of Ecuador, had higher differences in their deforestation areas (>40,000 ha) due to differences in the extent of the analyzed areas. Finally, in the case of

Brazil, Killeen's source of data (PRODES) only estimated the changes in the moist forest and not for grasslands and savannas as the Terra-i system is able to do. The Annex II is dedicated to compare the methodologies and output data from Terra-i and PRODES system for the Brazilian Legal Amazon.

Table 3: Comparison Killen and Terra-i data in terms of analyzed and deforested area in 2011. Values in hectares.

Country	**Killen data**			**Terra-i data**		
	Area	**Deforested area in 2011**	**% proport.**	**Area**	**Deforested area in 2011**	**% proport.**
Bolivia	46,328,930	356,382	0.77	69,977,250	411,938	0.59
Brazil	347,058,404	623,669	0.18	475,390,647	1,686,688	0.35
Colombia	42,352,521	114,995	0.27	47,911,488	72,869	0.15
Ecuador	5,817,372	16,317	0.28	11,254,100	17,581	0.16
French Guiana	8,082,058	13,986	0.17	8,092,375	5,938	0.07
Guyana	18,396,944	10,360	0.06	16,324,238	15,306	0.09
Peru	76,404,649	180,004	0.24	90,698,801	133,269	0.15
Suriname	14,758,011	26,936	0.18	14,525,419	10,575	0.07
Venezuela	36,590,575	7,770	0.02	43,233,875	28,969	0.07
Total	**595,789,465**	**1,350,420**	**0.23**	**777,408,192**	**2,383,131**	**0.31**

By country

Bolivia

Land-use change context

The Bolivian Amazon covers 66% of the country's territory of which roughly two-thirds is forested (52.8% of the entire country) (Uriostre, 2010; BBC, 2011).

Bolivia has experienced steadily increasing rates of land-cover change during the last three decades. Initially, the principal form of land-cover change was deforestation, as mechanized farmers, subsistence agriculturalists, and livestock producers all preferentially selected forest landscapes for conversion. However more recently, other types of land cover change have become more prevalent, including i) conversion of savanna and scrub vegetation to cultivated pasture; ii) conversion of wetlands to mechanized farming by modification of natural drainage patterns; iii) the conversion of wetlands to paddy rice farming; and iv) the conversion of inundated wetlands to native pasture. Despite the increase of these other types of land-cover change, deforestation continues to represent 77% of the total land-use change (Kaimowitz et al., 2002).

Up until 1975, 60% of Bolivia's territory was covered by forests. In comparison, that cover was reduced to 52.8% for 2010 (FAO, 2011). In the 1990s forest cutting began to grow steadily and since then the rate of deforestation has been steadily increasing. In three decades deforestation rates increased from about 168,000 ha yr^{-1} (between 1975 and 1993) to about 500,000 ha yr^{-1} by the end of the 1990s (Villegas, 2009). Increases in forest loss up to a rate of around 290,000ha yr^{-1} for the period 2000-2004 have also been reported in the Bolivian Amazon mainly due to the expansion of mechanized agriculture and cattle farms (Killeen et al., 2008). Furthermore, a study, led by the Economic Commission for Latin America and the Caribbean (ECLAC) for a deforestation scenario by 2100, found that the expansion of the agricultural frontier will be the main cause of deforestation, possibly accounting for 33 million hectares of lost forest in Bolivia (Canziani and Carbajal, 2012).

Land-use change studies and monitoring systems

Bolivia has a critical lack of information regarding its ecosystems and land cover. Non-profit organizations such as CIFOR and Conservation International have documents which review the temporal variation of land cover change between pre-1976 to the current decade. They concluded that the LUCC dynamics have a high correlation with the distinct economic production models by various social Bolivian groups (Pacheco and Mertens, 2004; Killeen et al., 2008).

Bolivia's Government does not yet use an official system for monitoring land cover change and the official deforestation data is based on FAO reports about the world's forests status (FAO, 2011). It is worth noting that non-profit organizations are playing a fundamental role in generating land cover change data; i.e. Friends of Nature Foundation has been monitoring and producing information about deforestation across the entire of Bolivia since 2010 using satellite imagery.

Terra-i data

According to Terra-i, the trends show that 74,619 ha were lost in 2004, reaching 411,938 ha in 2011 (an increase of 452%). During this eight-year period, a total of 1,627,669 million ha of natural vegetative cover were lost, with an average loss of 203,459 ha yr-1 (Table 4; Figure 6). The greatest annual loss was detected in the departments of Santa Cruz and Beni, where losses of 134,198 and 48,932 ha yr-1 were recorded, respectively. Figure 6 shows Bolivia had large habitat loss increases after 2009. According to Rodriguez (2011), this abrupt change was due to forest fire events, mainly in the department of Santa Cruz in 2010.

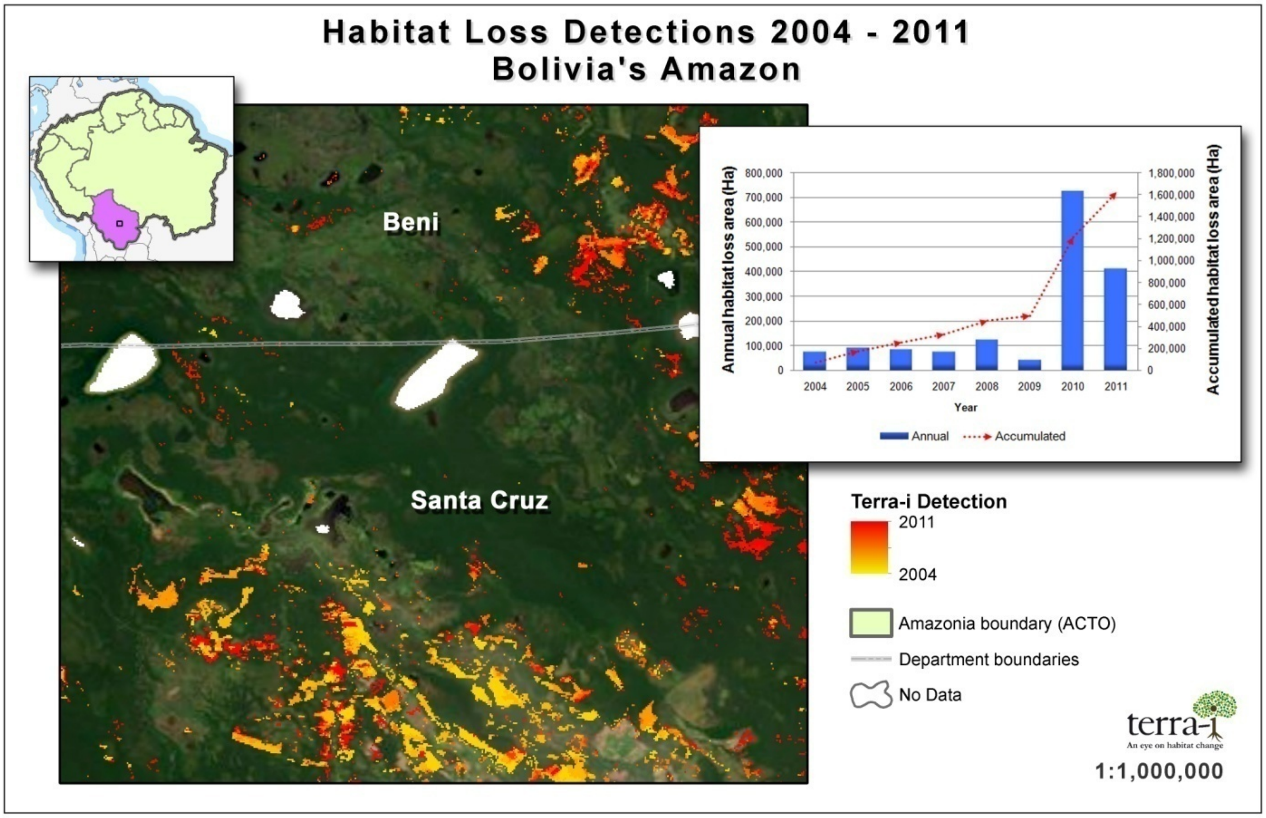

Figure 6: The Terra-i land use change detection map between 2004 to 2011, zoomed-in on deforestation hotspots (yellow to red spots) in the Bolivian Amazon. Right: annual rate of habitat loss and accumulated loss.

Habitat loss rates in Santa Cruz has been historically high in the entire country, having >70% of the total average of Bolivian habitat loss (Steininger et al., 2001). The main area of cover change has occurred in Tierras Bajas, east of Santa Cruz. This area was the focus of a World Bank development project, and forest there was cleared almost exclusively for industrial-scale soybean production, largely by Mennonites, and Brazilian and other foreign land owners (Pacheco and Mertens, 2004). CUMAT (1992) cited by Kaimowitz et al (2002) reported a deforestation rate of 38,000 ha yr^{-1} in this department. Between 1989 and 1992, this rose to around 78,000 ha yr^{-1}, and from 1992 to 1994 the yearly total reached 117,000 hectares (Morales, 1993; Morales, 1996). For the period of 1994 to 2000, the loss rate of forest cover was reported at around 204,000 ha yr^{-1} (Pacheco and Mertens, 2004).

What is happening in terms of biome and ecoregions status?

The highest land-use change has been experienced in both the moist broadleaf forest and the dry broadleaf forest which represented 50% and 44%, respectively of the total habitat loss (Table 4; Figure 7). Those values are mainly explained by the considerable land-use change in the eco-regions of Chiquitano dry forest (76,337 ha yr^{-1}) and Southwest Amazon moist forests (69,905 ha yr^{-1}).

There is evidence of high rates of habitat change in other ecoregions beside moist forest in Bolivia when it's compared with the remaining Amazon countries. Land-use change activities and logging impact the long-term conservation of the Chiquitano dry forest, characterized by a high vulnerability due to the very slow growth of tree species in comparison with the moist areas. Additionally, these land use change activities promote fire, as seen in the autumn of 2004 when an estimated 1.5 million hectares was affected by forest fires, most of which originated in forest being cleared for pasture, but spread into adjacent intact forest (Killeen *et al.*, 2005).

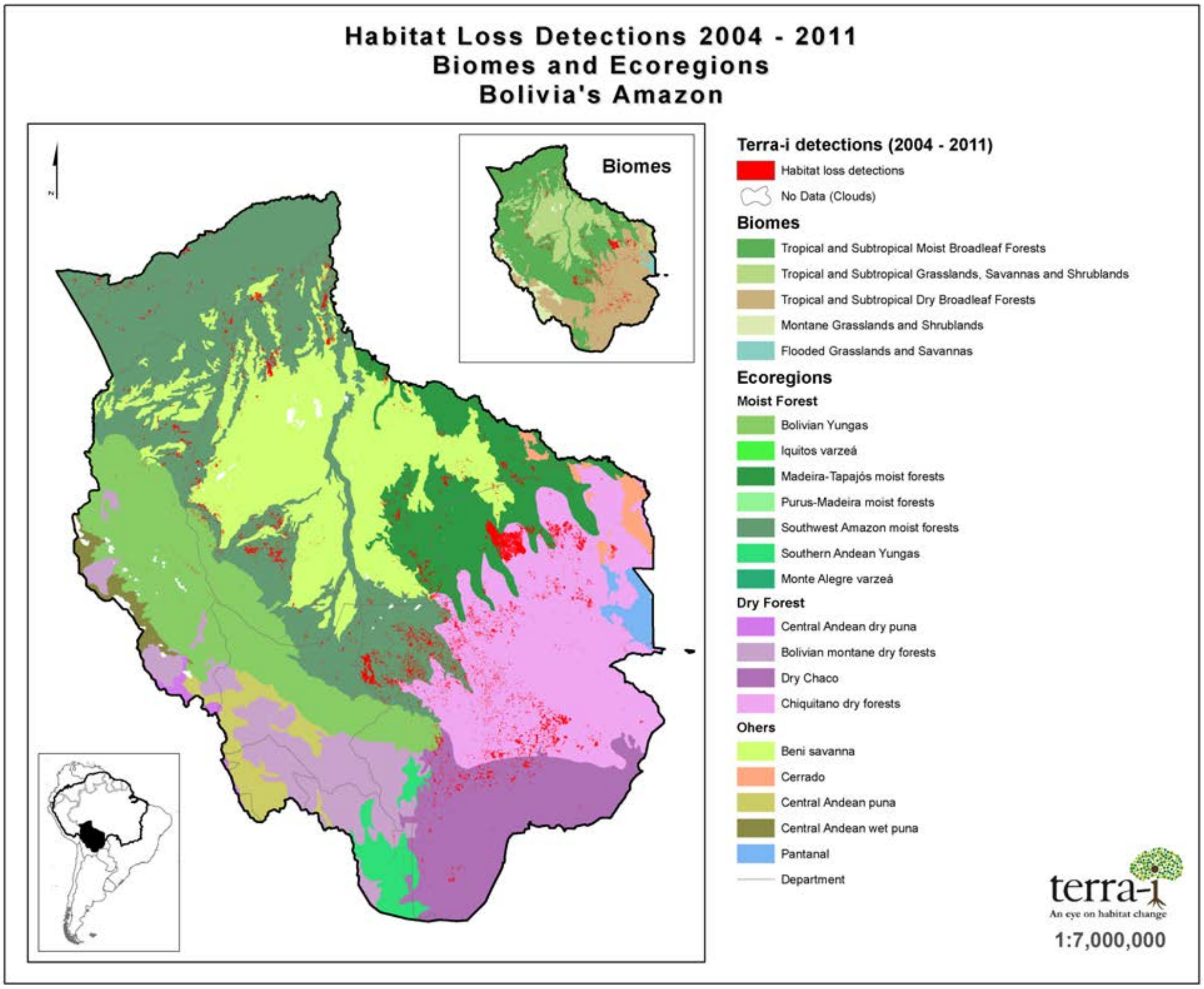

Figure 7: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) and ecoregions of the Bolivian Amazon.

For the Southwest Amazon moist forest, which is slowly receiving increased attention from the scientific community (Azevedo-Ramos, 2008), the habitat loss was located mainly in the department of Beni, followed by Pando. In Beni, intensive agricultural processes are the main driver of land cover-change. In the case of Pando, the situation is alarming as the department holds the most intact moist forest in the Bolivia Amazon. However, infrastructure developments such as highways projects, around the tri-frontier side shared with Brazil and Peru, has created incentives to clear cut this large proportion of forest as evidenced by Terra-i detections (Marsik et al., 2011).

What is the status of protected areas (PAs)?

Terra-i was able to detect habitat changes in 17 of the 25 protected areas in Bolivia. The top ten in terms of deforestation rates show that most habitat loss was located in PAs with IUCN category III and VI (Table 4; Figure 8). However, Rios Blanco y Negro Wildlife Reserve had the highest rate of change (24,842 ha yr^{-1}) for the eight-year period of analysis despite its IUCN category, Ia. Fire events occurred between 2010 and 2011 which explain the vast majority of this high habitat loss rate.

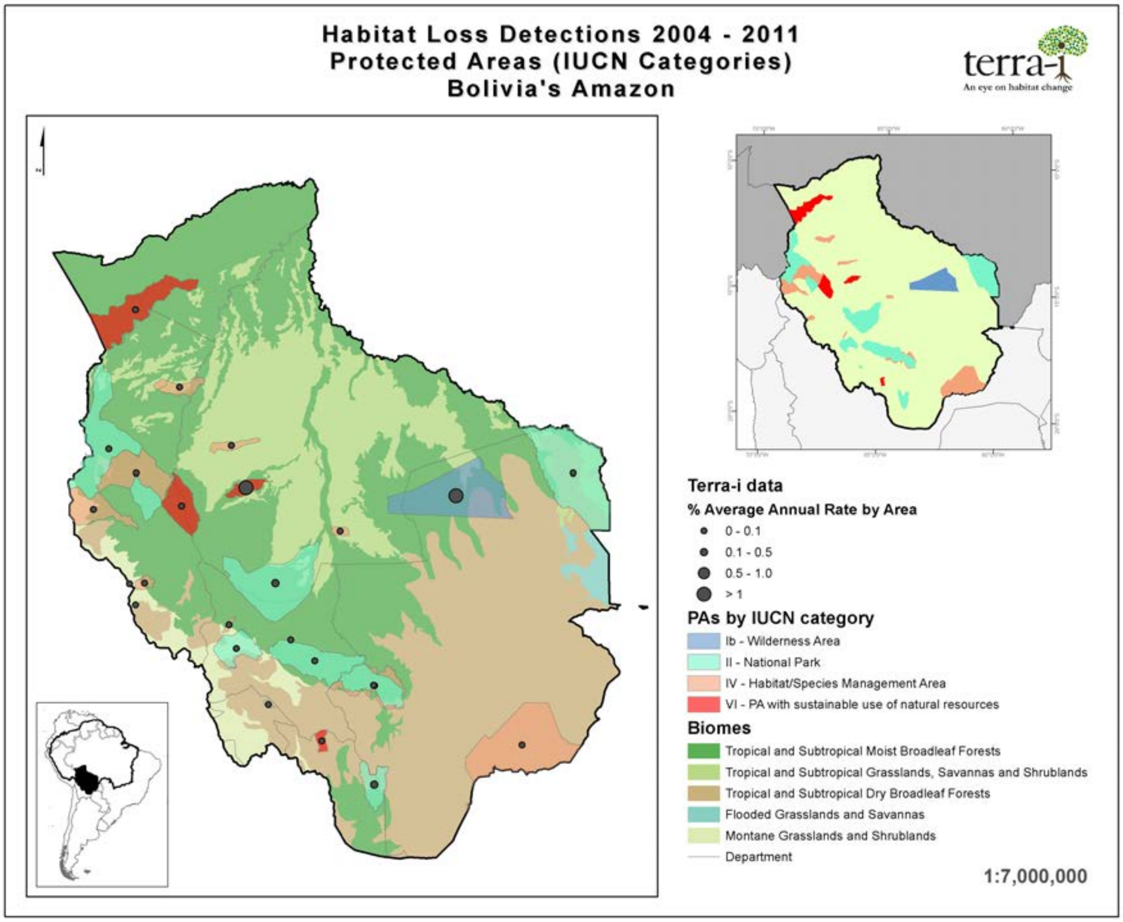

Figure 8: Left, map showing the percentage of average rate of land-use change by protected area for the Bolivian Amazon between 2004 to 2011. Right: spatial distribution of the PAs by IUCN category.

The Isiboro Sécure National Park and Indigenous Territory (TIPNIS) is one of the most interesting case studies by of the PAs with land-use change (average rate of 1614 ha yr^{-1}) in Bolivia during the last decade. According to the managers of the park, the TIPNIS faces two main threats: internal threats stemming from the non-rational and unplanned use of natural resources by the resident communities (e.g. agriculture, hunting, fishing, and forest extraction), and external threats resulting from political decisions at the departmental and national levels (e.g. building of new roads, oil concessions, etc.). Among the internal threats, activities such as agriculture and forest extraction are leading to a rapid loss of primary forest and also have disturbed the traditional life of the indigenous communities (Sanabria-Siles, 2009).

Table 4: Bolivian Amazon: Data by department, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-2011.

Habitat loss, per department (ha), organize in terms of Avg. annual loss

Department	Analyzed Area	Not Analyzed	% NoData	% of total department analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Santa Cruz	24,700,300	15,250	0.06%	99.94%	62,431	46,394	35,813	54,013	74,413	19,338	473,675	307,506	1,073,581	134,198	0.54%
Beni	20,650,700	123,244	0.59%	99.41%	9,144	29,606	26,363	13,119	35,150	15,044	190,663	72,369	391,456	48,932	0.24%
Pando	6,279,413	431	0.01%	99.99%	1,900	11,644	17,175	5,600	8,413	3,706	19,125	20,125	87,688	10,961	0.17%
La Paz	9,536,244	150,200	1.55%	98.45%	450	2,219	2,700	1,325	3,600	2,500	33,019	7,481	53,294	6,662	0.07%
Cochabamba	5,390,850	144	0.00%	100.00%	675	775	631	1,406	2,694	1,100	6,456	4,056	17,794	2,224	0.04%
Sum of top 5	66,557,506	289,269	0.43%	99.57%	74,600	90,638	82,681	75,463	124,269	41,688	722,938	411,538	1,623,813	202,977	0.30%
Total in Departments (n=8)	**69,977,250**	**289,269**	**0.41%**	**99.59%**	**74,619**	**90,638**	**82,706**	**75,469**	**124,275**	**41,756**	**726,269**	**411,938**	**1,627,669**	**203,459**	**0.29%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Chiquitano dry forest	11,502,800	2,325	0.02%	99.98%	44,056	15,769	22,569	21,106	46,325	7,369	272,688	180,813	610,694	76,337	0.66%
Southwest Amazon	16,382,400	24,850	0.15%	99.85%	20,794	46,350	41,019	35,481	49,313	19,469	210,006	136,806	559,238	69,905	0.43%
Madeira-Tapajós	5,694,900	619	0.01%	99.99%	6,650	19,069	11,738	6,394	14,825	3,119	117,000	31,488	210,281	26,285	0.46%
Beni savanna	12,347,600	109,394	0.88%	99.12%	938	5,031	5,075	3,125	7,406	3,081	53,100	22,906	100,663	12,583	0.10%
Dry Chaco	5,986,913	0	0.00%	100.00%	1,038	2,019	525	7,500	1,431	5,619	47,006	33,094	98,231	12,279	0.21%
Bolivian Yungas	8,477,588	47,813	0.56%	99.44%	925	2,244	1,500	1,794	4,369	2,713	14,894	5,400	33,838	4,230	0.05%
Cerrado	585,400	0	0.00%	100.00%	44	31	194	0	38	25	5,025	306	5,663	708	0.12%
Pantanal	560,156	1,806	0.32%	99.68%	94	0	6	38	531	38	2,400	538	3,644	455	0.08%
Bolivian montane	4,792,475	4,219	0.09%	99.91%	63	69	44	19	31	263	2,144	194	2,825	353	0.01%
Southern Andean	1,234,506	0	0.00%	100.00%	19	13	25	6	0	63	2,000	388	2,513	314	0.03%
Sum of top 10	67,564,738	191,025	0.28%	99.72%	74,619	90,594	82,694	75,463	124,269	41,756	726,263	411,931	1,627,588	203,448	0.30%
Total in Ecoregions (n=16)	**69,977,250**	**289,269**	**0.41%**	**99.59%**	**74,619**	**90,638**	**82,706**	**75,469**	**124,275**	**41,756**	**726,269**	**411,938**	**1,627,669**	**203,459**	**0.29%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Rios Blanco y Negro (Ib)	1,199,725	100	0.01%	99.99%	1,325	1,319	863	1,931	3,775	69	166,744	22,713	198,738	24,842	2.07%
Estación Biológica del Beni (VI)	121,763	19	0.02%	99.98%	225	444	306	250	44	106	10,356	1,181	12,913	1,614	1.33%
Isiboro Securé (II)	1,223,538	0	0.00%	100.00%	1,050	425	944	294	744	1,075	2,669	3,075	10,275	1,284	0.10%
Manuripi (VI)	769,394	19	0.00%	100.00%	0	2,263	1,425	44	400	144	119	50	4,444	555	0.07%
Iñao (II)	260,025	0	0.00%	100.00%	25	0	19	6	6	31	2,763	131	2,981	373	0.14%
Noel Kempff Mercado (II)	1,608,675	0	0.00%	100.00%	144	281	206	44	44	19	1,688	550	2,975	372	0.02%
Pilón Lajas (VI)	399,569	0	0.00%	100.00%	13	25	106	106	225	75	563	181	1,294	162	0.04%
Carrasco (II)	690,413	0	0.00%	100.00%	31	238	75	75	238	125	250	69	1,100	138	0.02%
Madidi (II)	1,270,744	10,363	0.81%	99.19%	6	25	181	138	50	44	425	194	1,063	133	0.01%
Amboró (IV)	158,856	0	0.00%	100.00%	69	56	25	169	69	38	456	138	1,019	127	0.08%
Sum of top 10	7,702,700	10,500	0.14%	99.86%	2,888	5,075	4,150	3,056	5,594	1,725	186,031	28,281	236,800	29,600	0.38%
Total in PAs (n=25)	**11,500,906**	**59,575**	**0.52%**	**99.48%**	**2,894**	**5,313**	**4,231**	**4,194**	**5,763**	**1,838**	**186,444**	**28,588**	**239,263**	**29,908**	**0.26%**

Brazil

Land-use change context

The Brazilian Legal Amazon covers 61% of the country's territory of which roughly more than two-thirds is forested (54.2% of the entire country) [14, 24]. Proportional to its size, the region is largely heterogeneous with respect to its biophysical characteristics, its occupation history and socioeconomic, political and institutional aspects (Aguiar, 2012).

In the Brazilian Amazon, land-use change has been caused mainly by ranches that convert native vegetation to pasture in order to raise cattle for national markets [25, 14]. In the last five decades, approximately 19% of the original rainforest has been removed (Aguiar, 2012). In the 1970's, land-use change started as a state-driven process, fuelled by large scale infrastructure and settlements projects as well as various fiscal incentives. From the 1980's, deforestation dynamics became more closely linked to market forces (Hargrave and Kis-Katos, 2012).

According to the Brazilian Institute of Geography and Statistics (IBGE), between 1996 and 2006, grazing areas in the Amazon region grew by approximately 10 million ha. Recently, the international demand for commodities has led to extensive conversion of the forest cover. Most of the expansion in monoculture crops has come from the conversion of pasture; however soybean around the margins of the Amazon is pushing pasture development further into the core of the Brazilian Amazon (MMA et al., 2007; Hargrave and Kis-Katos, 2012).

Based on data released by the Institute for Space Research (INPE), deforestation in Legal Amazonia underwent a period of decline, reaching its lowest point during the years 1990/1991, after which it accelerated and grew at an alarming rate to reach its highest historical value of 2,905,900 ha during the period 1994/1995. In subsequent years the annual deforestation rate slowed, gradually increased again until 2004, and since then has fallen sharply. The recent decline can be attributed largely to a combination of enforcement actions by the government and the global recession, which has reduced the demand for commodities (MMA et al., 2007).

However, in spite of this considerable reduction in deforestation rates and, consequently, in carbon emissions, there is still an enormous uncertainty about the fate of the forest. The Brazilian government is now committed (both under the UNFCCC framework and through its National Policy on Climate Change) to reducing the Brazilian Amazon deforestation by 80% from the historical rate of 1,900,500 million ha yr^{-1} by 2020 (Federal Law 12187/2009) (Aguiar, 2012).

Several studies about the future of Brazilian Amazon anticipate the Amazon Biome as an agricultural frontier. The expansion of unofficial roads, official projects for infrastructure upgrades, and the value trends of commodities in the international and national markets are identified as the main factors that will pose a significant threat to the Amazon biome (Pfaff et al., 2007).

Land-use change studies and monitoring systems

Most of the Amazon land-use change research has been focused on the Brazilian region due to the alarming land-use changes that it has been experiencing. Thus, several studies with single or multiple approaches (economic, social, geographic and/or among others) have been completed.

In 1973, Brazil was one of the first countries to have orbital observation data of the Earth. Since then, it has developed consolidated monitoring systems for land-cover change assessments at the regional level through the Project of Deforestation Estimation in the Amazon (PRODES) and the System of Deforestation Detection in Real Time (DETER), produced by the National Institute for Space Research (INPE). Furthermore, other institutions and NGO's such as The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and The Amazon Institute of People and the Environment (IMAZON) have developed strategies for ground-truthing deforestation events (Thiel and Viergever, 2007).

Terra-i data

According to Terra-i, the trends show that 1,288,600 million ha were lost in 2004, reaching 1,686,688 million ha in 2011 (an increase of 31%). During this eight-year period, a total of 11,454,044 million ha of natural vegetative cover was lost, with an average loss of 1,431,755 ha yr-1 (Table 5; Figure 9). The greatest annual loss was detected in the states of Pará and Mato Grosso, where losses of 478,038 and 457,055 ha yr^{-1} were recorded, respectively. Both states with Rondônia, average rate of deforestation of 253,018 ha yr^{-1}, shape the so-called *Deforestation Arc*. Additionally, they were colonized based on a latifundia model, differing with Trans-amazonian regions such as Rondônia or Acre where deforestation occurred by small-size plots (Soares, 2010; Pedlowski et al., 2005).

In the case of Pará, the higher values of deforestation are due to several factors, driven mainly by private large-scale entrepreneurs. Others factors such as localization of the main timber extraction hub and the trend of high population growth have further increased deforestation through land concessions and finance incentives. For Mato Grosso, only between 16–20% of forest clearance has been caused by cultivation; with the remaining >80% the result of pasture expansion for grazing (Aguiar, 2012).

What is happening in terms of biome and ecoregions status?

The highest land-use change has been experienced in the moist broadleaf forest, representing 88% of the total habitat loss of all biomes. These values are mainly explained by the considerable extent of area covered by moist broadleaf forest (>80%) in Amazonia. and 80% of the top ten eco-regions in terms of land use change belong to moist forest. Madeira-Tapajós, Mato Grosso seasonal forest and Xingu-Tocantins-Araguaia moist forest had the highest average rates of change (389,048; 296,498 and 230,491 ha yr^{-1}, respectively) (Table 5; Figure 10). The southern part of those eco-regions are located in the "arc of deforestation", traversed by the

Trans-Amazon Highway in the middle of the region east to west. Most of the forest along these roads has been felled, burned, and replaced by cattle ranches, municipal infrastructure, or agricultural fields. Most of the valuable timber has been removed from the remaining forest.

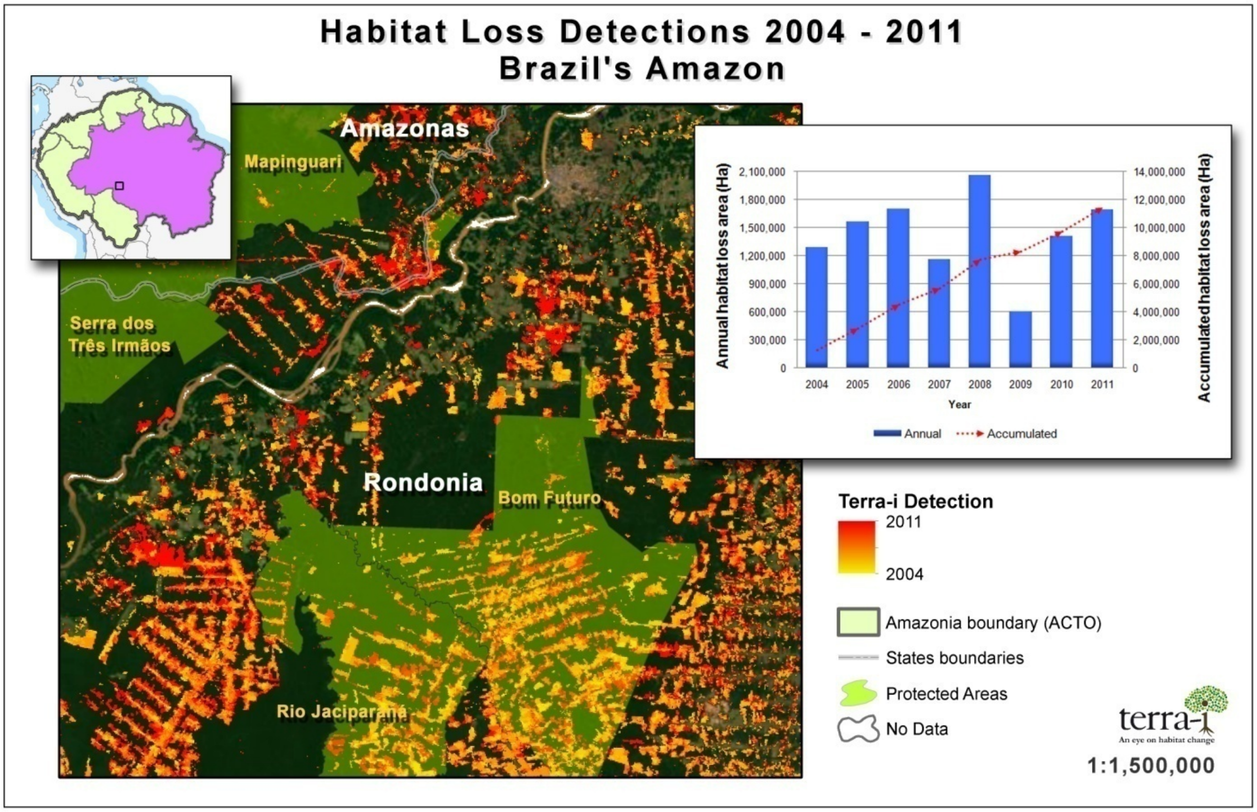

Figure 9: The Terra-i land use change detection map between 2004 to 2011, zoomed-in on deforestation hotspots (yellow to red spots) in Brazilian Amazon. Right: annual rate of habitat loss and accumulated loss.

What is the status of protected areas (PAs)?

Terra-i was able to detect habitat changes in 227 of 273 protected areas in Brazil. The top ten in terms of the highest average deforestation rate were in located PAs with IUCN category V and VI (Table 5; Figure 11). However, the Biologic Reserve of Nascentes da Serra do Cachimbo (BRNSC) and the Ecological Station of Terra do Meio (ESTM), both of category Ia and located in the state of Pará, are included in this top ten, indicating deforestation disturbances in areas classified as Strict Nature Reserve. These areas are located in the transition zone between Cerrado and the Amazon forest.

The State Environmental Protection Area Triunfo do Xingu (Pará) and Bom Futuro National Forest (Rondônia) were the two protected areas most affected by deforestation, with an average rate of 31,037 and 10,820 ha yr^{-1}, respectively. However, in terms of annual deforestation by percentage the area Bom Futuro is the most affected PA. Pedlowski et al. (2005) have documented the high pressure on this PA, observing an exponential increase in the amount of deforestation between 1992 and 2000. They concluded that this trend could lead to the total deforestation of the area in this PA by 2017.

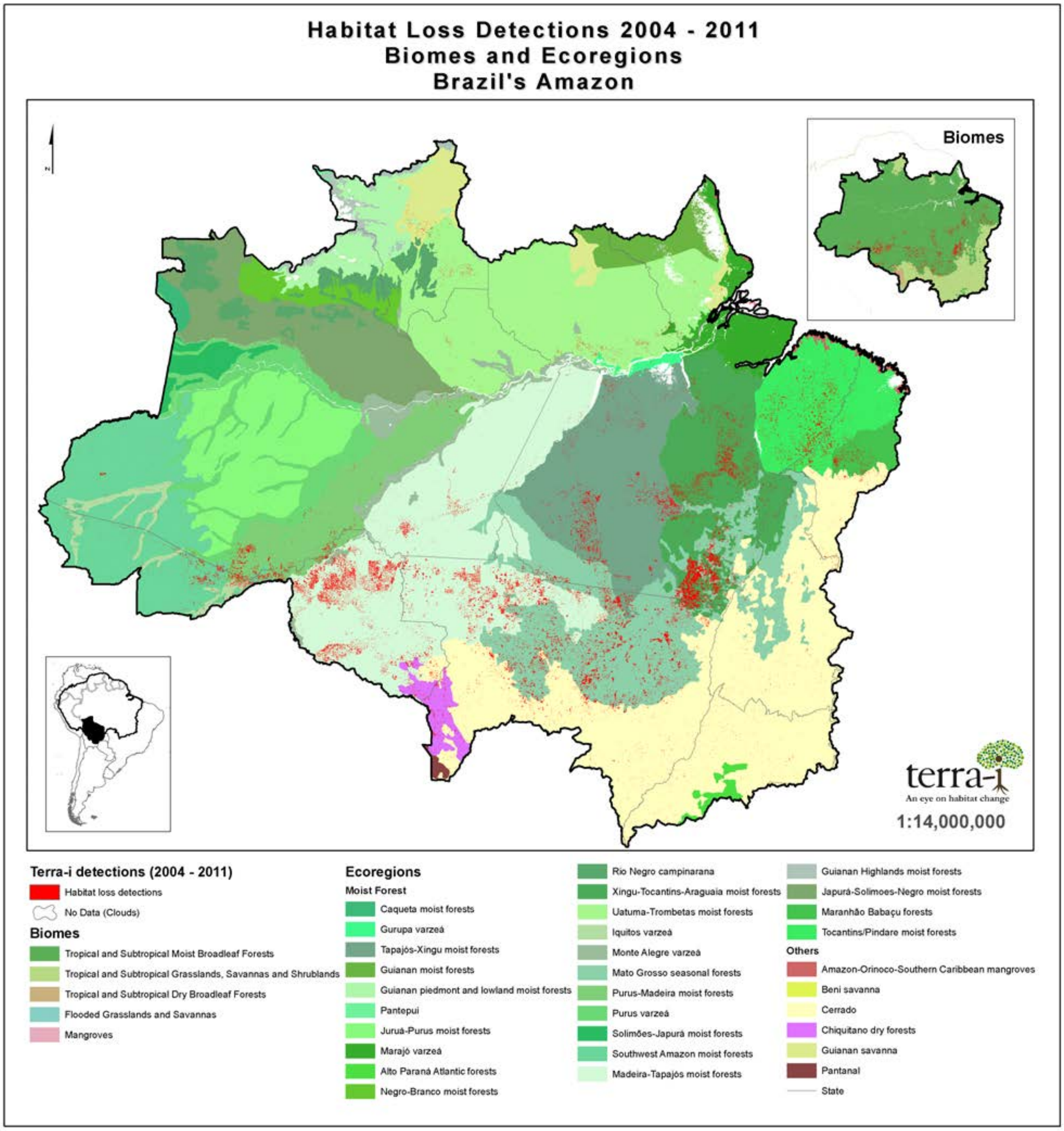

Figure 10: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) and ecoregions of Brazilian Amazon.

According to a recent publication by the Institute of Human and Environment in the Amazon (Imazon) and the Socio-Environmental Institute (ISA) (Veríssimo et al., 2011), half of all land clearing in protected areas occurred during the last decade. In addition, vast networks of illegal roads are located within and around the protected areas. For every 1,000 km2 of land under protection there are about 17.7 km of roads. Many of these pathways are associated with illegal logging, mainly in the states of Para and Mato Grosso.

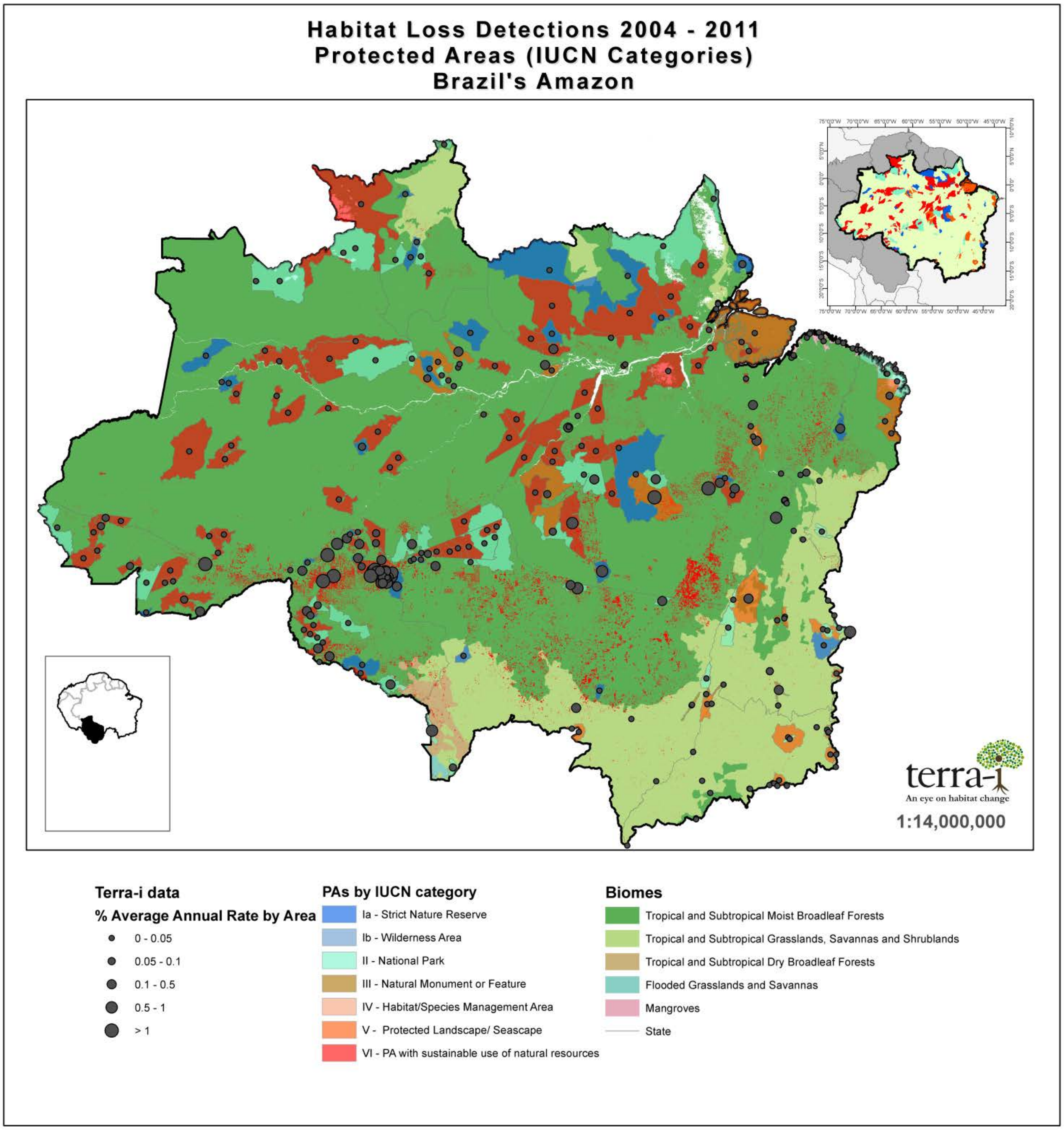

Figure 11: Left, map showing the percentage of average rate of land-use change by protected area for the Brazilian Amazon between 2004 to 2011. Right: spatial distribution of the PAs by IUCN category.

Table 5: *Brazilian Amazon: Data by state, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-2011.*

Habitat loss, per state (ha), organize in terms of Avg. annual loss

State	Analyzed Area	Not Analyzed	% NoData	% of total department analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Para	118,000,000	1,506,850	1.26%	98.74%	333,413	467,744	475,431	379,400	789,138	266,900	457,588	654,688	3,824,300	478,038	0.41%
Mato Grosso	69,108,600	2,606	0.00%	100.00%	683,650	618,375	443,488	352,625	671,963	99,269	374,919	412,156	3,656,444	457,055	0.66%
Rondonia	21,741,300	7,775	0.04%	99.96%	130,206	214,688	525,800	164,719	304,963	76,869	290,038	316,863	2,024,144	253,018	1.16%
Amazonas	155,000,000	747,150	0.48%	99.52%	64,794	91,406	137,525	62,838	109,631	91,819	147,238	161,500	866,750	108,344	0.07%
Maranhao	14,888,600	251,825	1.66%	98.34%	26,125	77,031	36,769	91,488	65,475	13,188	33,950	23,588	367,613	45,952	0.31%
Sum of top 5	378,738,500	2,516,206	0.66%	99.34%	1,238,188	1,469,244	1,619,013	1,051,069	1,941,169	548,044	1,303,731	1,568,794	10,739,250	1,342,406	0.35%
Total in States (n=14)	**475,390,644**	**4,587,475**	**0.96%**	**99.04%**	**1,288,600**	**1,562,006**	**1,694,781**	**1,159,963**	**2,057,844**	**601,144**	**1,403,019**	**1,686,688**	**11,454,044**	**1,431,755**	**0.30%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Madeira-Tapajós	62,346,100	282,556	0.45%	99.55%	249,794	394,019	714,738	255,388	530,925	145,081	372,088	450,356	3,112,388	389,048	0.62%
Mato Grosso seasonal forest	38,832,800	6,625	0.02%	99.98%	467,981	407,025	239,700	248,144	433,094	44,394	260,369	271,275	2,371,981	296,498	0.76%
Xingu-Tocantins-Araguaia moist forests	24,603,800	48,550	0.20%	99.80%	134,169	244,331	192,425	218,500	412,975	63,544	246,781	331,206	1,843,931	230,491	0.94%
Tapajós-Xingu moist forests	32,042,400	492,569	1.51%	98.49%	102,069	89,069	128,913	63,613	234,281	83,088	75,531	189,188	965,750	120,719	0.38%
Tocantins/Pindare moist forests	18,252,900	266,338	1.44%	98.56%	79,456	106,369	122,750	86,175	108,794	61,275	96,806	88,138	749,763	93,720	0.51%
Cerrado	73,841,000	1,081	0.00%	100.00%	140,413	118,469	49,163	121,700	96,313	17,744	80,206	62,381	686,388	85,798	0.12%
Purus-Madeira moist forests	16,874,400	12,188	0.07%	99.93%	32,081	55,900	103,888	39,375	51,738	22,913	68,675	59,825	434,394	54,299	0.32%
Southwest Amazon moist forests	31,279,800	7,144	0.02%	99.98%	24,031	44,706	47,681	19,775	57,788	22,088	56,144	80,200	352,413	44,052	0.14%
Uatuma-Trombetas moist forests	45,903,300	819,206	1.75%	98.25%	13,019	17,794	21,494	20,000	30,194	68,906	18,900	31,600	221,906	27,738	0.06%
Chiquitano dry forest	3,466,263	0	0.00%	100.00%	18,838	9,250	14,319	12,719	19,625	5,469	33,975	20,456	134,650	16,831	0.49%
Sum of top 10	347,442,763	1,936,256	0.55%	99.45%	1,261,850	1,486,931	1,635,069	1,085,388	1,975,725	534,500	1,309,475	1,584,625	10,873,563	1,359,195	0.39%
Total in Ecoregions (n=31)	**475,390,644**	**4,587,475**	**0.96%**	**99.04%**	**1,288,600**	**1,562,006**	**1,694,781**	**1,159,963**	**2,057,844**	**601,144**	**1,403,019**	**1,686,688**	**11,454,044**	**1,431,755**	**0.30%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Triunfo do Xingu (V)	1,427,713	0	0.00%	100.00%	24,719	28,275	38,081	20,300	62,631	13,856	14,856	45,581	248,300	31,038	2.17%
Bom Futuro (VI)	187,400	0	0.00%	100.00%	4,088	9,206	18,475	11,431	13,544	2,594	14,731	12,488	86,556	10,820	5.77%
Jamanxim (VI)	1,231,988	0	0.00%	100.00%	14,106	6,175	9,331	7,631	17,938	5,713	1,350	7,294	69,538	8,692	0.71%
Rio Jaciparaná (VI)	147,488	0	0.00%	100.00%	3,425	5,388	11,906	7,231	3,494	2,550	10,831	6,913	51,738	6,467	4.38%
Nascentes da Serra do Cachimbo (Ia)	321,819	0	0.00%	100.00%	2,638	2,113	1,569	1,369	3,556	1,625	2,188	5,244	20,300	2,538	0.79%
Ilha do Bananal/Cantao (V)	1,549,738	156	0.01%	99.99%	2,038	3,356	1,044	3,456	4,106	713	2,556	1,706	18,975	2,372	0.15%
Terra do Meio (Ia)	3,359,506	0	0.00%	100.00%	2,400	2,125	2,506	938	1,994	663	863	1,694	13,181	1,648	0.05%
Tapajós (V)	2,046,225	0	0.00%	100.00%	1,650	1,119	1,613	669	1,863	1,819	1,294	3,106	13,131	1,641	0.08%
Arquipélago do Marajó (V)	4,772,675	18,144	0.38%	99.62%	1,175	1,081	1,613	1,700	2,538	1,088	1,569	2,031	12,794	1,599	0.03%
Antimary (VI)	54,519	0	0.00%	100.00%	306	863	2,356	1,169	2,388	681	1,763	1,825	11,350	1,419	2.60%
Sum of top 10	15,099,069	18,300	0.12%	99.88%	56,544	59,700	88,494	55,894	114,050	31,300	52,000	87,881	545,863	68,233	0.45%
Total in PAs (n=273)	**103,778,119**	**1,441,631**	**1.37%**	**98.63%**	**76,638**	**86,006**	**125,013**	**81,506**	**147,825**	**57,725**	**96,263**	**144,869**	**815,844**	**101,980**	**0.10%**

Colombia

Land-use change context

The Colombian Amazon covers 42% of the country's territory of which roughly more than two-thirds is forested (54.5% of the entire country) (Etter et al., 2006a). The region can be clearly divided into two sub regions according to the transformation undergone by the environment as a result of human activities: the Northern Region, which corresponds to the area with greater human intervention and therefore evidence of greater pressure on ecosystems and the territory, and the Southern Region which is characterized by lower levels of transformation affecting its ecosystems because most of its population corresponds to indigenous peoples who have been settled there for centuries (COL R-PP, 2011)

In the case of the Colombian Amazon, logging for the cultivation of illegal crops, expansion of the agricultural frontier, new settlements and extensive cattle ranching are the main causes of deforestation. The annual deforestation rates vary from 0.97% to 3.73% in highly populated areas, and are about 0.23% in sparsely populated areas (Armenteras et al., 2006). However, during the last decade cattle ranching has been driven by Government incentives to meet rising domestic demand for meat and milk products (Etter et al., 2006a). Currently, more than 38.6 million ha in Colombia are dedicated to cattle raising, even though only 20 million ha are adequate for this type of activity. More recently, other drivers such as the expansion of mineral exploitation mining are also responsible for land use change (CONPES, 2011; MADS, 2011)).

Coca bush cultivation has also played an important role in Colombia's land-use change. UNODC's analysis of the 2009-2010 period concluded that 18% of the area planted with coca (61,813 ha) replaced primary forest, 26% was "stable" – coca crops were identified at the beginning of the period and were still cultivated when the observation period ended and 56% replaced other types of vegetation or bare soil, some of which had been planted with coca in previous years and had then been abandoned (UNODC, 2009)

According to a future modelling analysis between 2010 and 2030, Colombia will have little habitat loss under an optimistic scenario. In contrast, under a pessimistic scenario, the country will have a loss of around 8.6 million ha (González et al., 2011).

Land-use change studies and monitoring systems

The Colombian Amazon has been a focus area for several studies. However, the majority of them have focused at the landscape-level, with little known about the patterns and drivers of land cover changes at regional and national levels (Etter et al., 2006b). Deforestation data reported for Colombia range from 600,000 hectares per year reported by IGAC and ICA in 1987, 221,000 hectares in 2002 reported by IGAC, and 101,000 hectares reported by IDEAM in 2004 for the period 1986-2001. Meanwhile, international studies give radically different figures for Colombia. For example, the World Resources Institute (WRI) reported that in 1991 the deforestation in the country was 380,000 hectares per year (Hansen et al., 2008), and FAO in 1993 states that in the period from 1981 to 1990 the rate of deforestation amounted to 367,000 hectares per year (COL R-PP, 2011).

At the moment, Colombia lacks both an integrated monitoring system of land cover change and a deforestation tracking system. The Institute of Environmental Studies (IDEAM), a national government institution, has the official function of monitoring the land cover change. A 2010 study by IDEAM reported a loss of over 2 million ha of national forest over the period 2000-2007, an average deforestation rate of about 300,000 ha yr^{-1}, much higher than the deforestation rate produced by the Terra-i tool, 55,000 ha yr^{-1} for the period 2004-2007. While it is important to address such a large discrepancy, methodological differences between the two studies makes this very difficult. However, both tools coincide in the epicenters of deforestation and this data is still very relevant to help prioritize interventions. Ground-truthing of data in the future could improve data in regions where cloud cover impedes accurate satellite monitoring.

Terra-i data

According to Terra-i, the trends show that 29,581 ha were lost in 2004, reaching 72,869 ha in 2011 (an increase of 146%). During this eight-year period, a total of 362,419 ha of natural vegetative cover were lost, with an average loss of 45,302 ha yr^{-1} (Table 6; Figure 12). The greatest annual loss was detected in the departments of Caquetá and Meta, where losses of 18,266 and 10,105 ha yr^{-1} were recorded, respectively. Both departments visually display a prevalence of “slash-and-burn” pattern, with many small size plots, in comparison to countries like Brazil, which show scattered deforestation around rivers and roads.

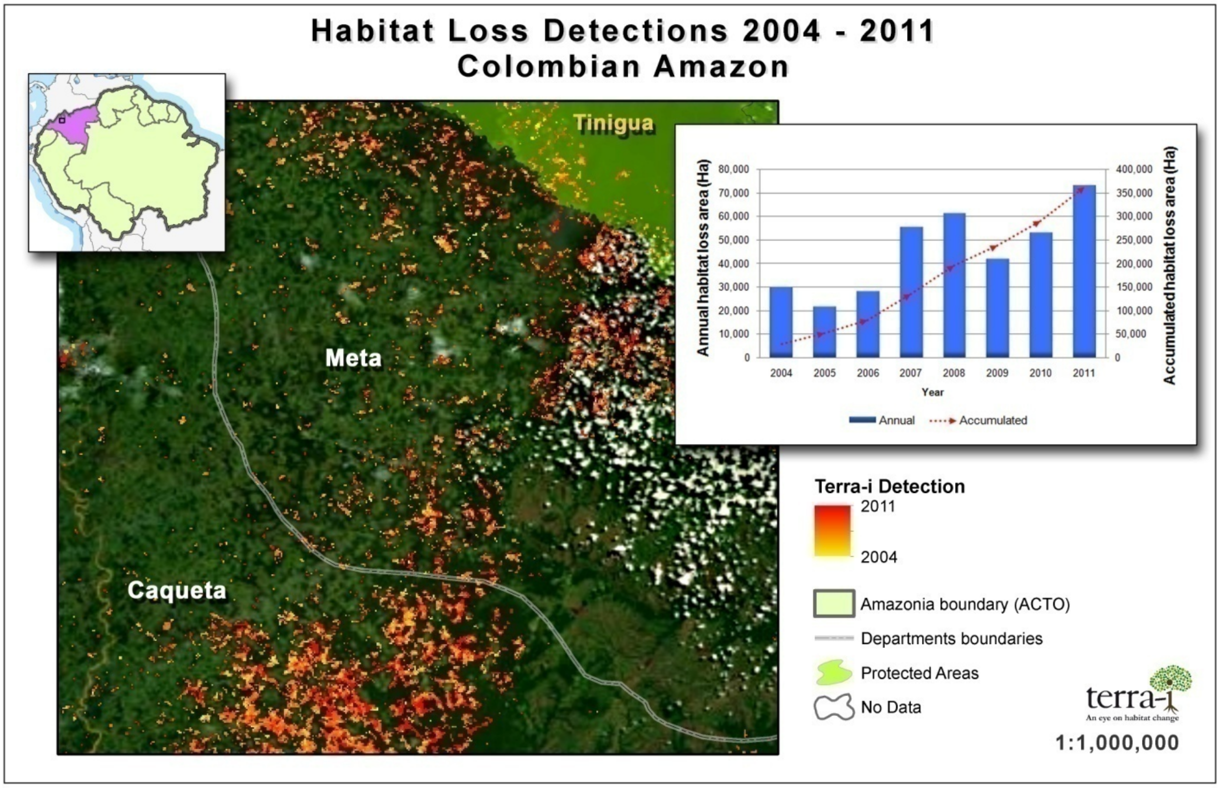

Figure 12: The Terra-i land use change detection map between 2004 to 2011, zoomed-in on deforestation hotspots (yellow to red spots) in Colombian Amazon. Right: annual rate of habitat loss and accumulated loss.

The Colombian agricultural/livestock frontier has expanded by 5-10% in the last 15 years, and today, the beef cattle industry is the primary contributor to the spatial footprint of national agricultural land use (Armenteras et al., 2006). Today, the department of Caquetá contains 5.3% of the national cattle herd (CONPES, 2011). Other factors have also fostered deforestation in the Colombian Amazon such as illicit crops which create a dynamic particularly harmful for forest conservation. Programs of crop eradication, development of trafficking routes, among other factors have displaced illegal crops to new other regions (the “balloon effect”) – often resulting in the clearance of forests and/or protected areas (Dávalos et al., 2010).

What is happening in terms of biome and ecoregions status?

The highest land-use change has been experienced in the moist broadleaf forest, representing 97% of the total habitat loss of all biomes. In terms of eco-regions, Caquetá moist forest, the largest eco-region in Colombia, is by far the eco-region most affected in the Colombian Amazon (Table 6; Figure 13). With an average rate of habitat loss of 28,487 ha yr^{-1}, these losses in the Caquetá moist forest are the result of small-scale subsistence agriculture (driven by rural-rural migration) and illicit crops, particularly in the Alto Caquetá within the Caquetá department (Sánchez-Cuervo et al., 2012).

On the other hand, Napo moist forest, the second most affected eco-region, is a tri-frontier shared by Ecuador, Colombia and Peru. Rodrigo Sierra, Assistant Professor of the University of Texas at Austin, analyzed the extent and rate of deforestation and the level of forest fragmentation in this ecoregion for the period 1986-1996 (Sierra, 2000). He concluded that deforestation was advancing faster on the Colombian side (0.9% yr^{-1}) due to population growth from the foot of the Andes towards the Amazon.

What is the status of protected areas (PAs)?

Terra-i was able to detect habitat changes in 14 of 19 protected areas in the Colombian Amazon. The top ten with the highest average loss rates shows most habitat loss was located in PAs with IUCN category II and III (Table 6; Figure 14). This situation is alarming due to the restricted use for anthropogenic disturbance activities in the areas of those categories.

The biological corridor complex, composed the National Parks of Tinigua, Cordillera de los Picachos and Sierra de la Macarena and located in the department of Meta, was the protected region most affected with 20,675 ha of accumulated loss for entire region and an average loss rate of 1,357; 681 and 541 ha yr^{-1} for each PA, respectively. The importance of this region is that it is the only remaining significant corridor between Andes and the Amazon lowlands (Steinfeld et al., 2006). Dávalos et al (Dávalos and Bejarano, 2008) reported for 2005 that the clearings carved out of the forest add up to more than 13,000 ha of coca planted across the Sierra de la Macarena national park and its buffer zone.

Other PAs such as the NP La Paya (II), NNR Nukak (III) and NP Chiribiquete (II), located in the departments of Caquetá and Guaviare, have been experiencing considerable changes in their habitats in accordance with Terra-i detections.

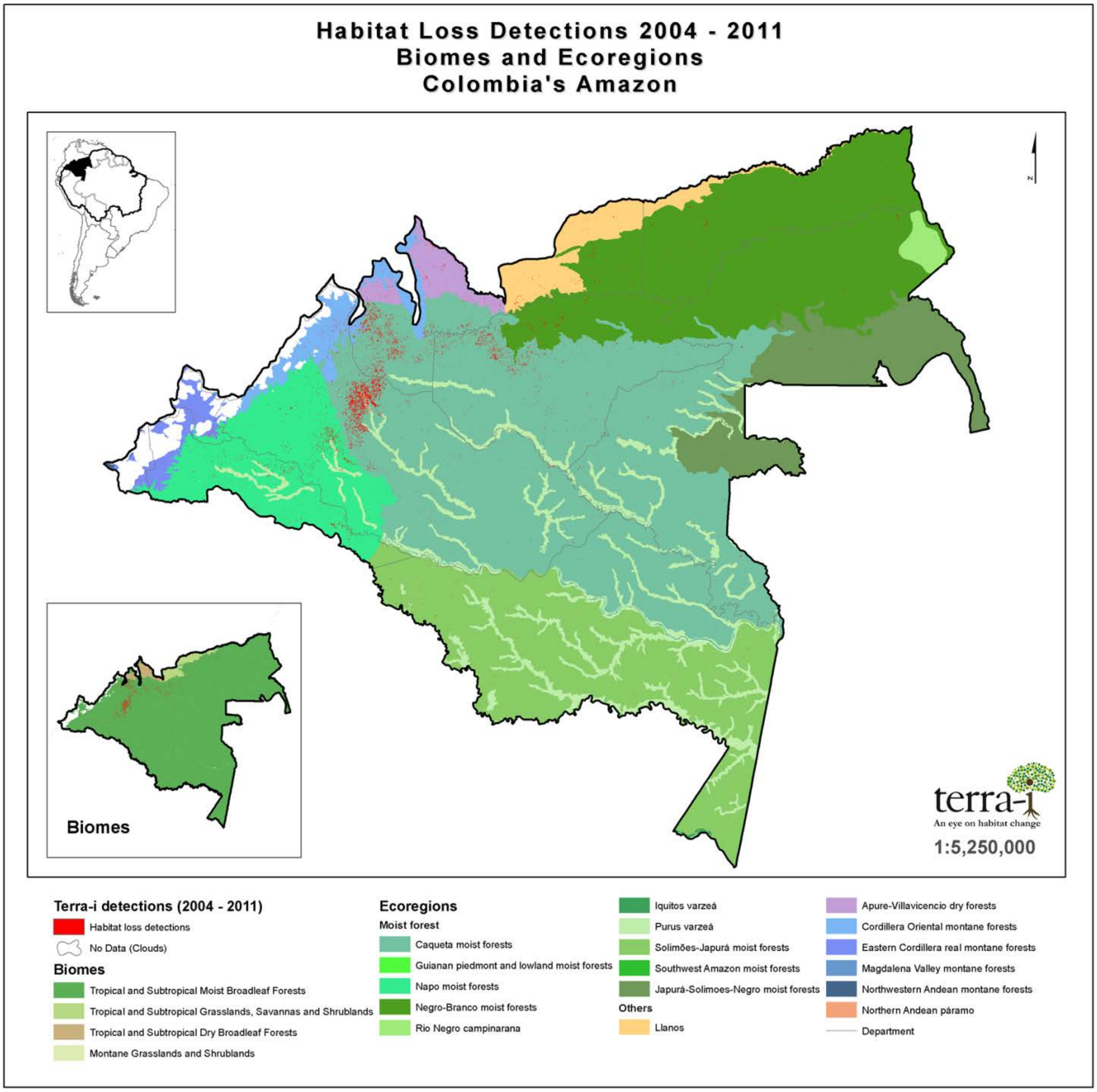

Figure 13: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) and ecoregions of Colombian Amazon.

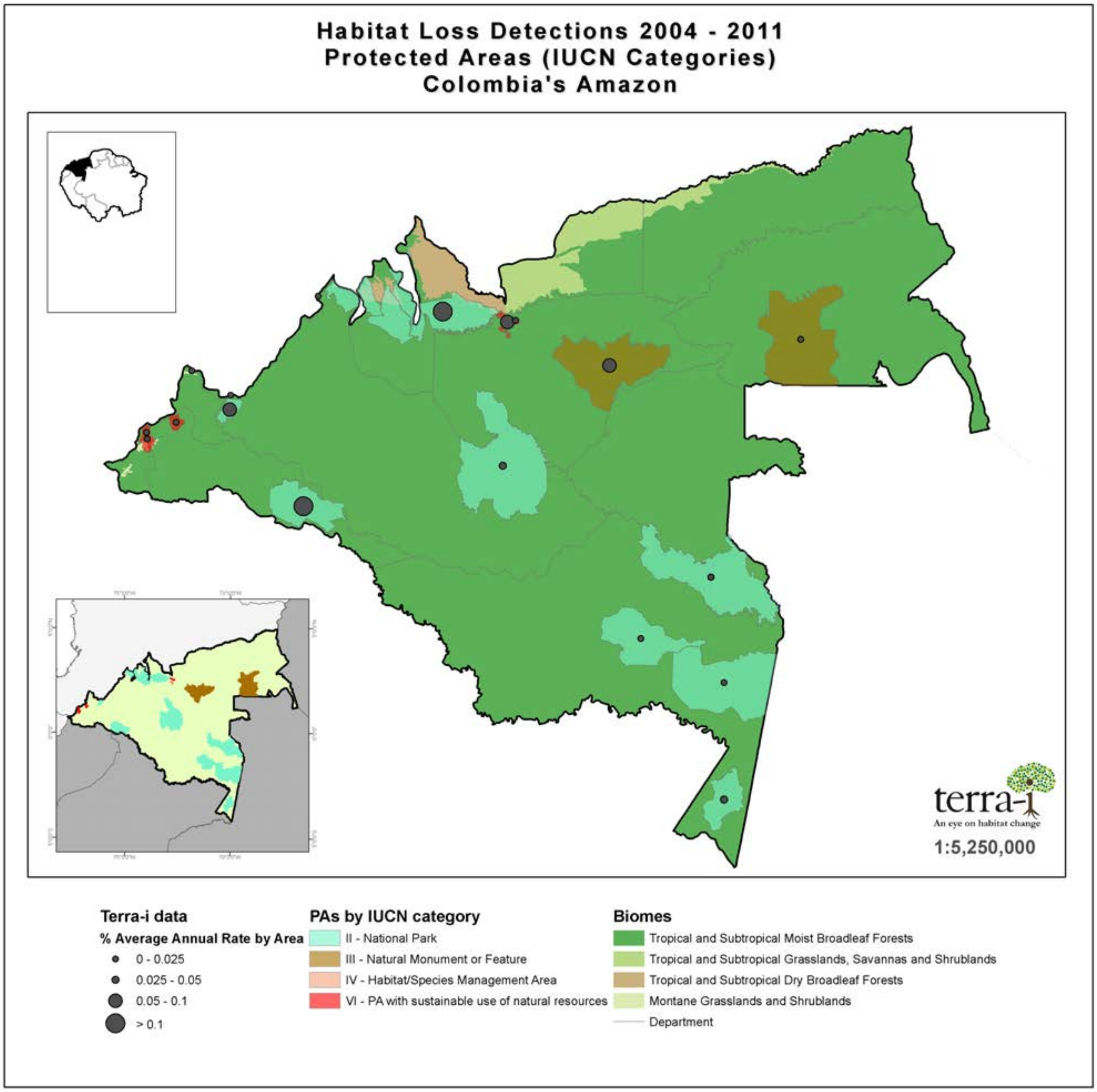

Figure 14: Left, map showing the percentage of average rate of land-use change by protected area for the Colombian Amazon between 2004 to 2011. Right: spatial distribution of the PAs by IUCN category.

Table 6. Colombian Amazon: Data by department, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-2011.

Habitat loss, per department (ha), organize in terms of Avg. annual loss

Department	Analyzed Area	Not Analyzed	% NoData	% of total department analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Caqueta	8,540,825	306,513	3.46%	96.54%	7,550	8,194	10,638	24,656	30,600	18,681	23,306	22,506	146,131	18,266	0.21%
Meta	4,221,481	18,263	0.43%	99.57%	4,431	5,281	6,563	14,356	15,319	9,638	10,531	14,725	80,844	10,105	0.24%
Guaviare	5,495,038	0	0.00%	100.00%	6,644	2,700	3,219	9,100	7,606	7,325	8,950	15,513	61,056	7,632	0.14%
Putumayo	2,179,300	180,081	7.63%	92.37%	1,838	1,394	2,231	1,544	1,969	1,888	3,406	6,294	20,563	2,570	0.12%
Vaupes	5,308,006	206	0.00%	100.00%	2,700	1,031	1,631	1,525	2,075	1,419	1,938	2,706	15,025	1,878	0.04%
Sum of top 5	25,744,650	505,063	1.92%	98.08%	23,163	18,600	24,281	51,181	57,569	38,950	48,131	61,744	323,619	40,452	0.16%
Total in Departments (n=11)	**47,911,488**	**978,663**	**2.00%**	**98.00%**	**29,581**	**21,481**	**28,006**	**55,113**	**60,919**	**41,706**	**52,744**	**72,869**	**362,419**	**45,302**	**0.09%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Caqueta moist forest	16,837,200	3,063	0.02%	99.98%	15,975	13,463	16,763	38,388	43,813	25,281	31,375	42,838	227,894	28,487	0.17%
Napo moist forest	3,895,950	8,669	0.22%	99.78%	2,988	2,663	3,938	3,631	6,100	6,475	9,306	10,606	45,706	5,713	0.15%
Negro-Branco moist forest	9,660,806	94	0.00%	100.00%	6,744	2,581	3,150	6,194	2,819	2,906	3,581	4,319	32,294	4,037	0.04%
Purus varzeá	2,984,044	10,013	0.33%	99.67%	1,256	681	1,238	1,456	2,525	1,169	1,775	3,525	13,625	1,703	0.06%
Cordillera Oriental montane forests	941,081	266,663	22.08%	77.92%	419	675	888	1,925	2,194	1,494	2,306	2,063	11,963	1,495	0.16%
Solimóes-Japurá moist forests	7,239,481	5,438	0.08%	99.92%	1,250	263	325	394	800	794	1,175	6,163	11,163	1,395	0.02%
Apure-Villavicencio dry forests	698,206	0	0.00%	100.00%	344	406	525	1,444	850	1,694	1,163	994	7,419	927	0.13%
Japurá-Solimoes-Negro moist forests	3,456,288	225	0.01%	99.99%	350	463	806	625	625	400	913	1,038	5,219	652	0.02%
Llanos	1,375,888	0	0.00%	100.00%	31	56	81	738	756	838	644	700	3,844	480	0.03%
Eastern Cordillera real montane forests	466,019	564,719	54.79%	45.21%	119	144	288	250	369	650	456	575	2,850	356	0.08%
Sum of top 10	47,554,963	858,881	1.77%	98.23%	29,475	21,394	28,000	55,044	60,850	41,700	52,694	72,819	361,975	45,247	0.10%
Total in Ecoregions (n=17)	**47,911,488**	**978,663**	**2.00%**	**98.00%**	**29,581**	**21,481**	**28,006**	**55,113**	**60,919**	**41,706**	**52,744**	**72,869**	**362,419**	**45,302**	**0.09%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Tinigua (II)	212,919	0	0.00%	100.00%	381	713	931	1,744	1,556	1,519	1,500	2,513	10,856	1,357	0.64%
Cordillera de los Picachos (II)	135,025	53,819	28.50%	71.50%	238	288	444	1,006	919	856	1,263	481	5,494	687	0.51%
Sierra de la Macarena (II)	500,919	0	0.00%	100.00%	600	644	300	463	450	219	781	869	4,325	541	0.11%
La Paya (II)	428,706	19	0.00%	100.00%	569	144	838	394	450	294	538	550	3,775	472	0.11%
Nukak (III)	854,769	0	0.00%	100.00%	750	331	281	888	194	194	275	588	3,500	438	0.05%
Chiribiquete (II)	1,316,244	0	0.00%	100.00%	1,000	63	44	100	375	225	375	488	2,669	334	0.03%
Rio Pure (II)	1,015,119	0	0.00%	100.00%	106	38	138	44	100	50	113	938	1,525	191	0.02%
Puinawai (III)	1,099,931	0	0.00%	100.00%	163	81	75	119	150	6	213	375	1,181	148	0.01%
Cahuinarí (II)	554,431	3,613	0.65%	99.35%	219	6	44	6	31	88	106	425	925	116	0.02%
Amacayacu (II)	272,244	0	0.00%	100.00%	25	0	31	0	63	50	156	400	725	91	0.03%
Sum of top 10	6,390,306	57,450	0.89%	99.11%	4,050	2,306	3,125	4,763	4,288	3,500	5,319	7,625	34,975	4,372	0.07%
Total in PAs (n=19)	**7,500,800**	**197,781**	**2.57%**	**97.43%**	**4,131**	**2,369**	**3,544**	**4,844**	**4,438**	**3,813**	**5,694**	**8,000**	**36,831**	**9,208**	**0.12%**

Ecuador

Land-use change context

The Ecuadorian Amazon covers 40% of the country's territory of which roughly more than two-thirds is forested (39.1% of the entire country) (Napo Wildlife Centre, 2010; FAO, 2011).

Land-use changes are particularly dynamic in the Ecuadorian Amazon, a biodiversity hotspot that was opened to active colonization in the 1970s through the construction of roads used for oil exploitation by foreign petroleum companies. Additionally, several researchers agree on a high destruction rate in the Andean and Coastal biomes, which are near and therefore exert pressure on the Amazon natural vegetation. Since the first colonial settlements, both biomes have been replaced by crops, pasture, towns and cities, and exotic tree (eucalyptus and pine) plantations (Mena et al., 2006).

The Ecuadorian Amazon has historically experienced less land-use change than the other Amazon countries analyzed. It is worth noting that Ecuador has the largest percentage of indigenous lands in the Amazon, with 65%, followed by Colombia, with 50.6%, Bolivia, with 25.7%, and Brazil, with 13% (Hargrave and Kis-Katos, 2012). This, alongside a "less bureaucratic process of officially recognizing Indian territories in Amazonia" (mentioned by anthropologist Beto Ricardo, RAISG project), has allowed a lower rate of land-use change for agricultural activities in Ecuador (Mecham, 2001).

According to Ecuadorian studies in the lowlands of the Ecuadorian Amazon basin, small agricultural activities take place (Pichon, 1997; Rudel et al., 2002; Latin American Herald Tribune, 2009) with settlers' farms averaging 40-50 hectares, 5-15 ha of which may be pastures,1-5 ha coffee and/or cocoa plantations, with the rest being forested. However, this situation is changing with the increasing scope and magnitude of planned oil and gas extraction. In Ecuador and Peru, oil and gas blocks now cover more than two-thirds of the Amazon (Walsh et al., 2002). Since the early 1970's about 30% of the Ecuadorian Amazon has been deforested and/or polluted. Entire indigenous cultures, such as the Cofan and Huaorani, have been placed in danger of extinction as a result of the oil industry and accelerated colonization facilitated by the roads of the oil industry (Finer et al., 2008).

Land-use change studies and monitoring systems

A recent study on the forest status has been conducted by The Ministry of the Environment of Ecuador with the support of FAO (Aguirre et al., 2011). Additionally, some models of Land-Use and Land Cover Change (LULCC) have been developed for Ecuador's Amazon (Messin and Walsh, 2001, Mena, 2008). Economic and social models have also studied the rate of land cover conversion (Mena et al., 2006).

As is the case in most Latin American countries, Ecuador has neither updated nor validated data of its forest status, and only has values calculated from estimated rates of deforestation (FAO, 2011).

Terra-i data

According to Terra-i, the trends show that 3,244 ha were lost in 2004, reaching 17,581 ha in 2011 (an increase of 442%). During this eight-year period, a total of 36,713 ha of natural vegetative cover were lost, with an average loss of 4,589 ha yr^{-1} (Table 7; Figure 15). The greatest annual loss was detected in the provinces of Sucumbios and Orellana, where losses of 1,582 and 1,277 ha yr^{-1} were recorded, respectively.

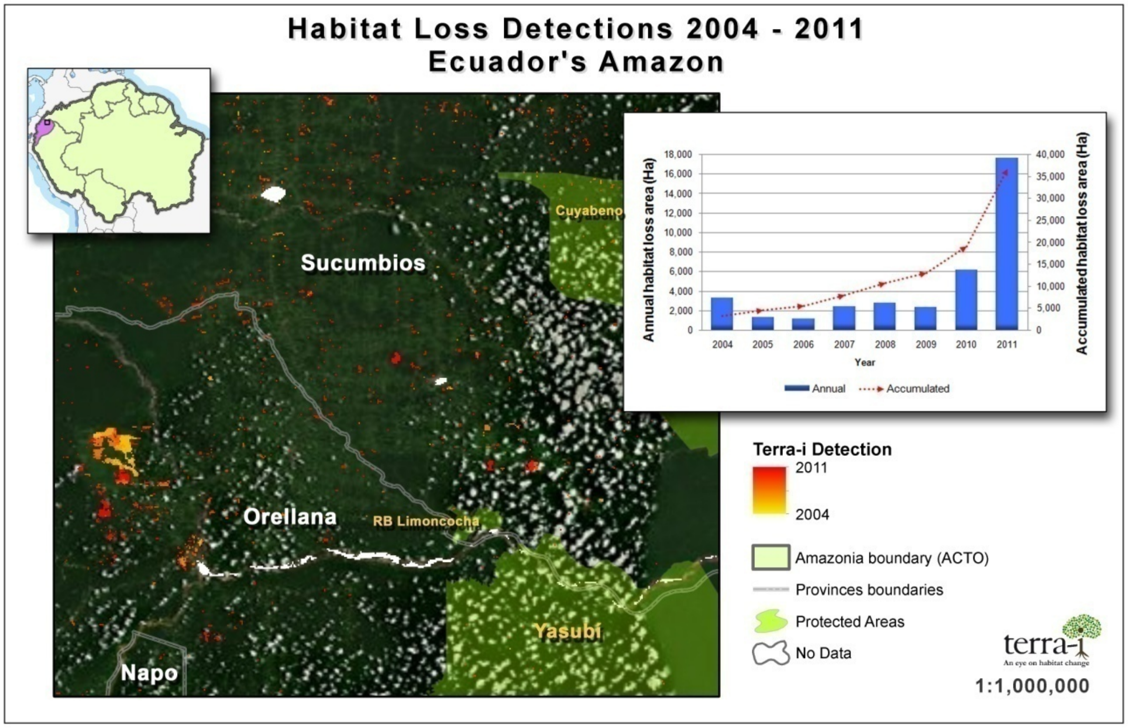

Figure 15: The Terra-i land use change detection map between 2004 to 2011, zoomed-in on deforestation hotspots (yellow to red spots) in Ecuador's Amazon. Right: annual rate of habitat loss and accumulated loss.

Although Ecuador has less habitat loss, with an average annual rate of 4589 ha yr^{-1} or 0.04% of habitat loss rate per unit area, in comparison with the other four countries analyzed, it has a trend of habitat loss by mineral exploration and oil exploitation. The province of Sucumbíos has, among the three provinces (Napo and Orellana), the highest proportion of deforested land (Mena et al., 2006). Between 1973 and 1996, approximately 22 percent of the overall forest cover was lost from within the state of Sucumbíos (Viña et al., 2004).

What is happening in terms of biome and ecoregions status?

The highest land-use change has been experienced in the moist broadleaf forest (average rate of 4,586 ha yr^{-1}) representing 99% of the total habitat loss of this biome and Montane Grasslands and Shrublands habitat (Table 7; Figure 16). In terms of ecoregions, this behavior is mainly distributed in the Napo moist forest (average rate of 30,019 ha yr-1). Mena et al., (2006) report that more than 85% of the land cleared in this region is dedicated to pasture.

What is the status of protected areas (PAs)?

Terra-i was able to detect habitat changes in 9 of 14 protected areas in the Ecuadorian Amazon. The top nine in terms of the highest average deforestation rate show that the highest deforestation was located in two PAs, Yasuní National Park and Cuyabeno Reserve (IUCN category II and VI, respectively) with an average rate of habitat loss of 355 and 216 ha yr^{-1}, respectively (Table 7; Figure 17). For Yasuni NP, Azqueta and Delacámara (Azqueta and Delacámara, 2008) reported a serious threat by new oil fields, wells and roads that have been constructed since the 1990s. Additionally, the same authors added that the expected growth of colonist and indigenous populations, the arrival of further refugees from Colombia due to Plan Colombia, and the utter lack of financial resources for protection of the Cuyabeno Reserve mean that threats to its biodiversity will continue and, therefore, need to be closely monitored and regulated.

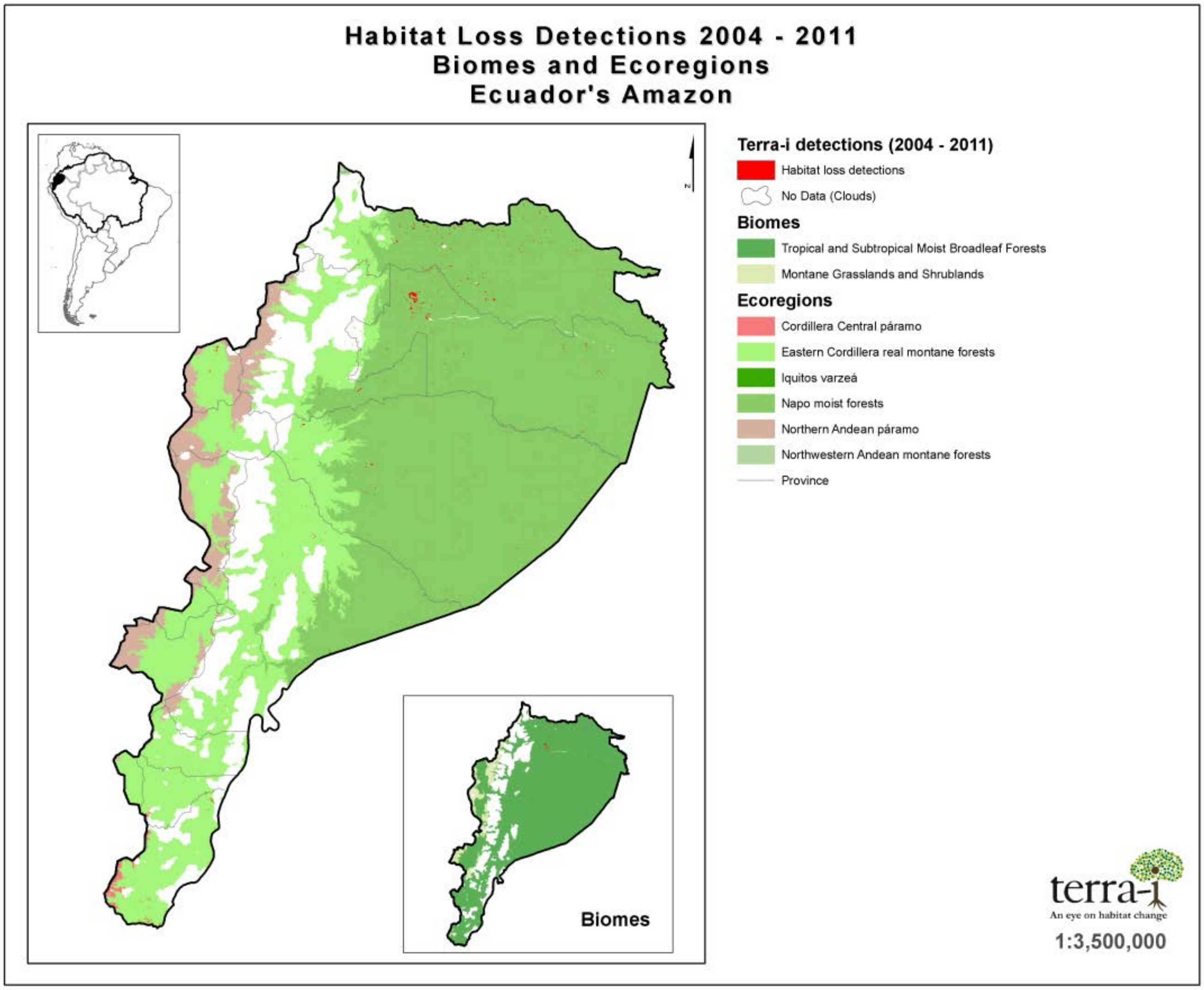

Figure 16: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) and ecoregions of Ecuadorian Amazon.

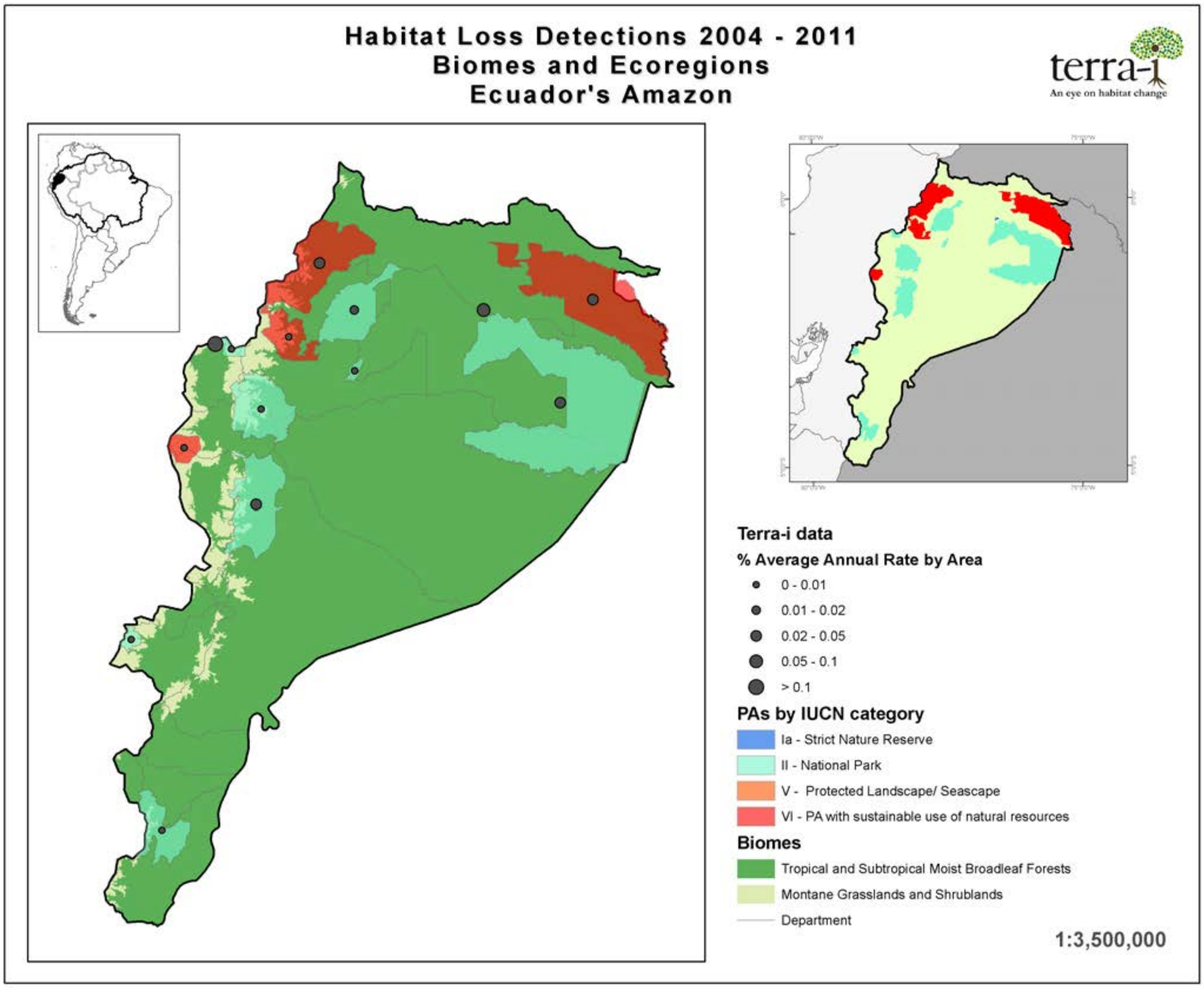

Figure 17: Left, map showing the percentage of average rate of land-use change by protected area for the Ecuadorian Amazon between 2004 to 2011. Right: spatial distribution of the PAs by IUCN category.

Table 7: Ecuadorian Amazon: Data by province, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-2011.

Habitat loss, per department (ha), organize in terms of Avg. annual loss

Province	Analyzed Area	Not Analyzed	% NoData	% of total department analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Sucumbios	1,596,225	193,413	10.81%	89.19%	369	200	325	588	1,094	863	2,181	7,038	12,656	1,582	0.10%
Orellana	1,971,094	31,988	1.60%	98.40%	1,263	581	375	850	656	625	694	5,169	10,213	1,277	0.06%
Pastaza	3,012,963	35,175	1.15%	98.85%	1,494	44	138	269	381	181	575	3,481	6,563	820	0.03%
Morona Santiago	1,849,913	777,000	29.58%	70.42%	69	100	100	400	238	188	544	1,050	2,688	336	0.02%
Zamora Chinchipe	645,900	196,013	23.28%	76.72%	0	56	31	38	31	50	1,719	363	2,288	286	0.04%
Sum of top 5	9,076,094	1,233,588	11.97%	88.03%	3,194	981	969	2,144	2,400	1,906	5,713	17,100	34,406	4,301	0.05%
Total in Provinces (n=15)	**11,254,100**	**1,898,794**	**14.44%**	**85.56%**	**3,244**	**1,288**	**1,075**	**2,381**	**2,731**	**2,306**	**6,106**	**17,581**	**36,713**	**4,589**	**0.04%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Napo moist forest	7,042,056	5,375	0.08%	99.92%	3,150	813	769	1,806	2,344	1,725	3,363	16,050	30,019	3,752	0.05%
Eastern Cordillera real montane forests	3,514,044	1,618,406	31.53%	68.47%	94	475	300	575	388	563	2,744	1,531	6,669	834	0.02%
Northern Andean páramo	660,588	265,356	28.66%	71.34%	0	0	0	0	0	19	0	0	19	2	0.00%
Cordillera Central páramo	28,056	8,625	23.51%	76.49%	0	0	6	0	0	0	0	0	6	1	0.00%
Sum of top 4	11,244,744	1,897,763	14.44%	85.56%	3,244	1,288	1,075	2,381	2,731	2,306	6,106	17,581	36,713	4,589	0.04%
Total in Ecoregions (n=6)	**11,254,100**	**1,898,794**	**14.44%**	**85.56%**	**3,244**	**1,288**	**1,075**	**2,381**	**2,731**	**2,306**	**6,106**	**17,581**	**36,713**	**4,589**	**0.04%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Yasuní (II)	1,029,050	338	0.03%	99.97%	1,000	25	6	94	63	106	38	1,506	2,838	355	0.03%
Cuyabeno (VI)	583,831	0	0.00%	100.00%	131	0	6	19	138	119	275	1,044	1,731	216	0.04%
Cayambe-Coca (VI)	132,606	186,100	58.39%	41.61%	0	25	25	0	6	0	150	38	244	30	0.02%
Sangay (II)	62,813	208,438	76.84%	23.16%	0	6	0	44	19	19	6	31	125	16	0.02%
Sumaco Napo Galeras (II)	59,238	135,063	69.51%	30.49%	13	19	0	6	0	6	19	25	88	11	0.02%
El Boliche (V)	938	0	0.00%	100.00%	6	0	0	13	0	0	0	0	19	2	0.25%
Limoncocha (Ia)	2,788	0	0.00%	100.00%	0	0	0	0	0	0	0	19	19	2	0.08%
Antisana (VI)	24,700	93,338	79.07%	20.93%	0	0	0	0	0	0	6	0	6	1	0.00%
Llanganates (II)	87,831	131,806	60.01%	39.99%	0	0	0	0	0	0	0	6	6	1	0.00%
Sum of top 9	1,983,794	755,081	27.57%	72.43%	1,150	75	38	175	225	250	494	2,669	5,075	634	0.03%
Total in PAs (n=14)	**2,155,119**	**819,581**	**27.55%**	**72.45%**	**1,150**	**75**	**38**	**175**	**225**	**250**	**494**	**2,669**	**5,075**	**634**	**0.03%**

Peru

Land-use change context

The Peruvian Amazon covers 60% of the territory of which roughly more than two-thirds is forested (53.1% of entire country) (FAO, 2011).

Studies by the Ministry of Environment of Peru identify agricultural expansion as the main direct cause of deforestation in Peru (MINAM, 2009). Agriculture in the country is based on slash-and-burn systems used by settlers for subsistence purposes. However, this system results in the expansion of agricultural impact; soil fertility eventually declines and settlers must move to another place to start again with the same method (MINAM, 2009).

Among the direct drivers of deforestation in the Peruvian Amazon, shifting cultivation is a key driver along with infrastructure operations like road construction, hydropower projects and hydrocarbon exploration and exploitation. Selective logging is a major cause of degradation. Among the underlying drivers, government policies, such as the requirements for granting property titles and the promotion of biofuels have led to perverse incentives (Velarde et al., 2010).

Historically, deforestation had been concentrated in the departments at the foothills of the Andean mountains. INEA reported for the period of 1985-1990 a total deforestation of 281,158 ha, of which 54,712 ha was located in the department of Loreto (CEPAL, 2007). Rodríguez (2010) stated that the total Peruvian deforested area in 2004 was 7.3 million hectares. The Peruvian regions with the highest deforestation rates were San Martin (1.62 million ha), Loreto (1.1 million ha), and Ucayalí (964 thousand ha)

A study of Velarde et al. (2010) estimated the deforestation for the year 2010, 2020 and 2030 in Loreto, Ucayali, Madre de Dios and San Martin. In 2010 almost 5% of forest cover has been removed. According to the model, an equivalent amount of deforestation will occur in just 20 years, and by 2030 the Peruvian Amazon would lose 10% of its forests.

Land-use change studies and monitoring systems

Before 2010, Peru had neither updated nor validated data of forest status, apart from estimated rates of deforestation (FAO, 2011). However The Ministry of the Environment of Peru (MINAM) now employs CLASlite for their System to Monitor Land Cover, Deforestation and Forest Degradation, a critical element for the management of Peruvian forests at the national level.

A summary of preliminary outcomes of MINAM's forest monitoring system is included in "El Peru de los bosques", an inter-ministerial publication focusing on sustainable management and conservation of the country's forests (MINAM Peru, 2011).

Terra-i data

According to Terra-i, the trends show that 17,038 ha were lost in 2004, reaching 133.269 ha in 2011 (an increase of 682%). During this eight-year period, a total of 388,731 ha of natural vegetative cover were lost, with an average loss of 48,591 ha yr^{-1} (Table 8; Figure 18). The greatest annual loss was detected in the departments of Loreto and Ucayali, where average losses of 12,218 and 9,830 ha yr^{-1} were recorded, respectively.

Deforestation affects 9% of the 10.4 million hectares of forests in Ucayali (Arce and Porro, 2010). The situation is worse than in Loreto and Madre de Dios regions altogether. Deforestation results from both shifting cultivation and roads opened for logging, which enables the arrival of farmers.

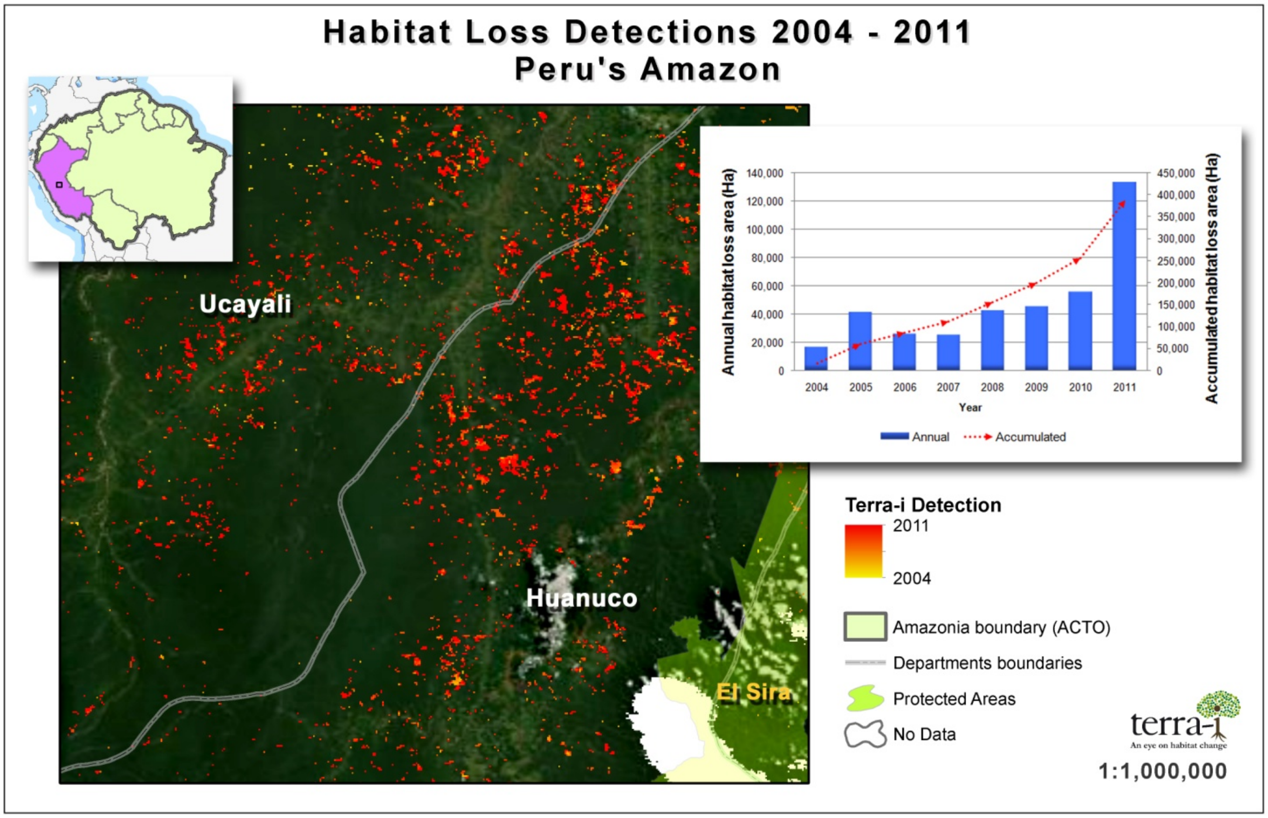

Figure 18: The Terra-i land use change detection map between 2004 and 2011, zoomed-in on deforestation hotspots (yellow to red spots) in Peruvian Amazon. Right: annual rate of habitat loss and accumulated loss.

What is happening in terms of biome and ecoregions status?

The highest land-use change has been in the moist broadleaf forest (average rate of 47,878 ha yr^{-1}) representing 99% of the total habitat loss. In terms of ecoregions, areas of deforestation are mainly distributed in the Ucayali moist forest, Southwest Amazon moist forests and Iquitos varzeá (average rate of 168,562; 85,887 and 74,706 ha yr-1, respectively) (Table 8; Figure 19). These eco-regions are located across the departments of Ucayali, Loreto and San Martin where drivers explained above are constantly causing land-use change. Additionally, road construction has increased the incentives for disturbances by the direct drivers (Mäki et al., 2001).

What is the status of protected areas (PAs)?

Terra-i was able to detect habitat changes in 11 of 22 protected areas in the Peruvian Amazon. The top ten in terms of the highest average deforestation rate were located in PAs with IUCN category II and VI (Table 8; Figure 20). By far, Pacaya Samiria Natural Reserve, IUCN category VI, was the most affected PA during the period analyzed. WWF (WWF, 2012) reports that due to the high degree of connectivity in the Abanico del Pastaza, unsustainable natural resource extraction activities have had a profound and widespread impact on freshwater habitats in this protected region, affecting wildlife populations, migration processes, and ecosystem health. Two major threats to both the biological and cultural diversity of the Complex are petroleum extraction and commercial over-fishing.

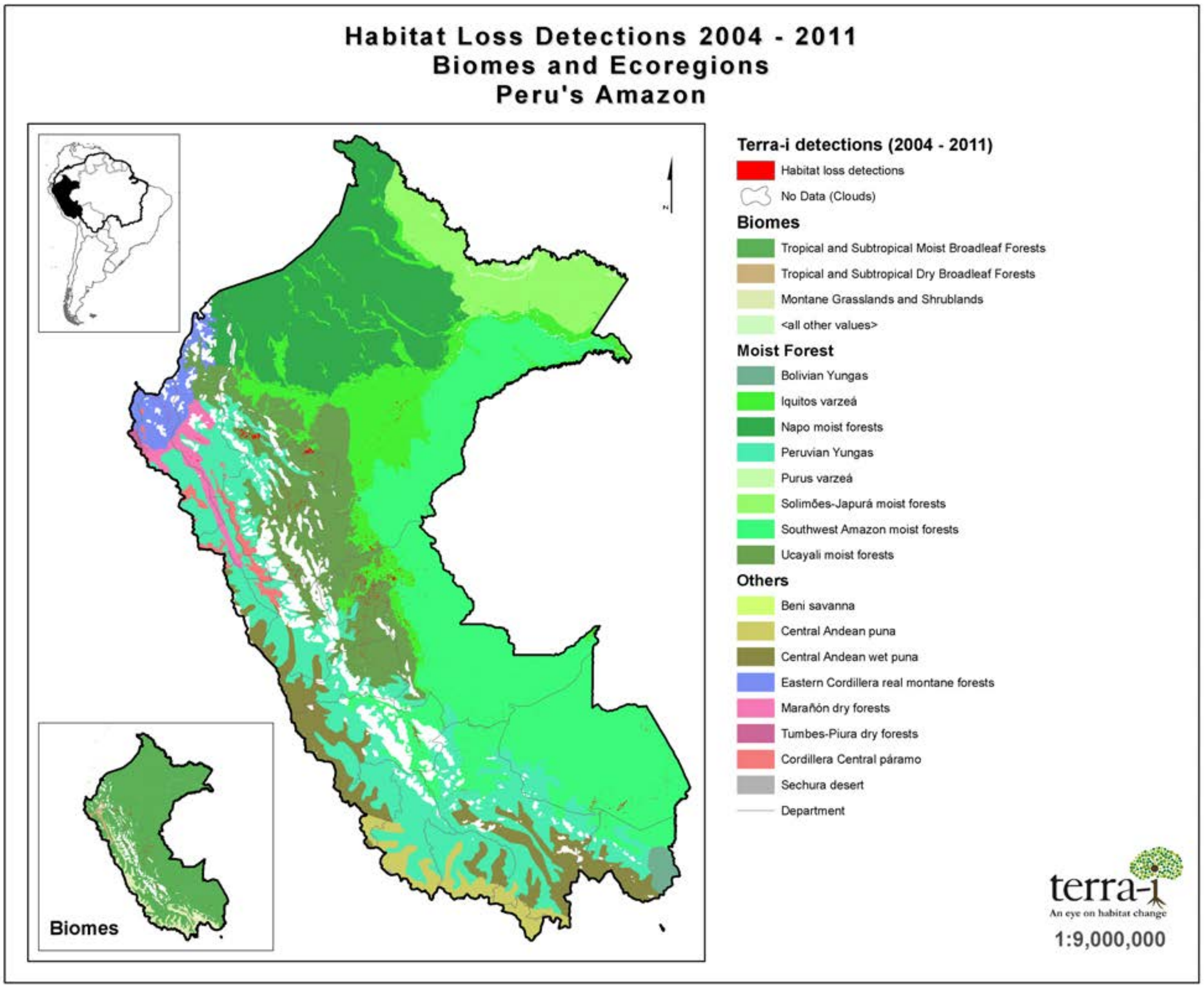

Figure 19: The Terra-i land use change detection map between 2004 to 2011 for the major habitats (biomes) and ecoregions of Peruvian Amazon.

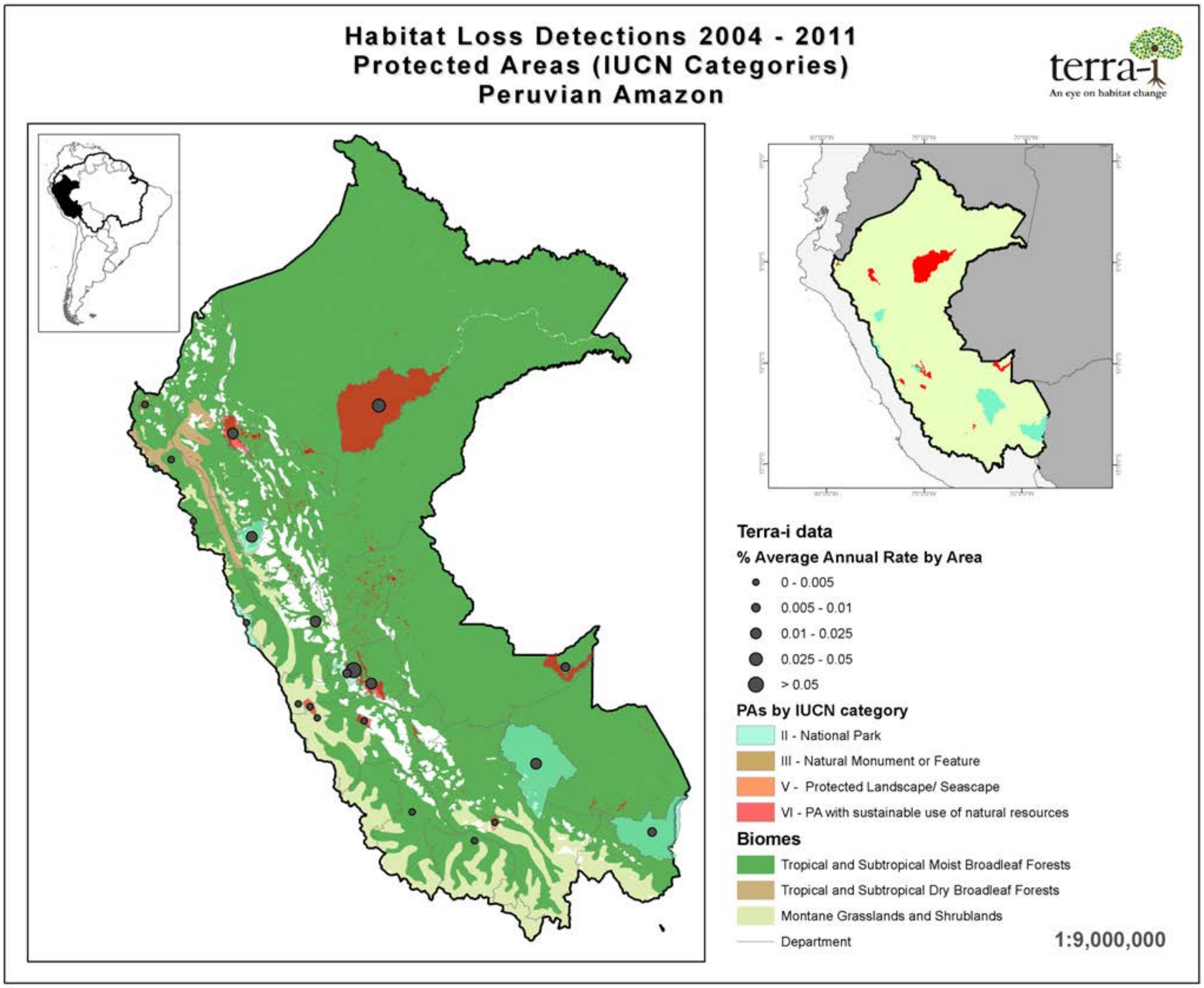

Figure 20: Left, map showing the percentage of average rate of land-use change by protected area for the Peruvian Amazon between 2004 to 2011. Right: spatial distribution of the PAs by IUCN category.

*Table 8: Peruvian Amazon: Data by department, and top 10 ecoregions and protected areas with the highest habitat loss, as detected by Terra-i system for the period 2004-*2011.

Habitat loss, per department (ha), organize in terms of Avg. annual loss

Department	Analyzed Area	Not Analyzed	% NoData	% of total department analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Loreto	37,444,200	360,331	0.95%	99.05%	8,575	7,213	6,638	7,313	9,188	8,488	12,094	38,238	97,744	12,218	0.03%
Ucayali	9,919,150	224,550	2.21%	97.79%	3,588	10,725	6,200	5,775	9,075	9,388	6,994	26,900	78,644	9,830	0.10%
San Martin	3,951,056	1,203,056	23.34%	76.66%	2,550	5,638	4,850	6,025	7,800	11,938	11,713	27,688	78,200	9,775	0.25%
Huanuco	2,984,919	722,469	19.49%	80.51%	238	3,213	3,650	1,569	6,525	5,975	3,175	20,894	45,238	5,655	0.19%
Madre De Dios	8,325,694	15,781	0.19%	99.81%	469	2,544	1,200	1,938	3,706	3,394	7,231	7,888	28,369	3,546	0.04%
Sum of top 5	62,625,019	2,526,188	3.88%	96.12%	15,419	29,331	22,538	22,619	36,294	39,181	41,206	121,606	328,194	41,024	0.07%
Total in Departments (n=11)	**90,698,800**	**5,218,556**	**5.44%**	**94.56%**	**17,038**	**41,756**	**26,369**	**25,588**	**43,038**	**45,525**	**56,150**	**133,269**	**388,731**	**48,591**	**0.05%**

Habitat loss, per Ecoregion (ha), organize in terms of Avg. annual loss

Ecoregion	Analyzed Area	Not Analyzed	% NoData	% of total ecoregion analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Ucayali moist forest	9,987,888	1,279,244	11.35%	88.65%	5,919	10,056	9,506	11,531	21,525	24,038	20,156	65,831	168,563	21,070	0.21%
Southwest Amazon moist forests	25,313,600	616,888	2.38%	97.62%	3,088	13,000	3,825	4,669	10,050	10,988	14,975	25,294	85,888	10,736	0.04%
Iquitos varzeá	8,179,950	49,963	0.61%	99.39%	3,288	13,906	9,844	5,950	6,813	5,381	7,563	21,963	74,706	9,338	0.11%
Peruvian Yungas	15,634,800	2,407,263	13.34%	86.66%	344	1,131	1,275	1,356	3,119	2,731	4,100	7,563	21,619	2,702	0.02%
Napo moist forest	13,897,200	98,663	0.70%	99.30%	1,888	900	475	1,100	938	1,269	1,438	7,188	15,194	1,899	0.01%
Solimões-Japurá	5,828,456	8,419	0.14%	99.86%	1,844	150	219	481	413	413	394	4,363	8,275	1,034	0.02%
Eastern Cordillera real montane forests	1,585,188	389,438	19.72%	80.28%	563	181	875	188	94	200	5,394	681	8,175	1,022	0.06%
Marañón dry forest	1,096,231	28,100	2.50%	97.50%	50	2,394	269	25	81	463	1,788	156	5,225	653	0.06%
Purus varzeá	289,631	1,631	0.56%	99.44%	50	0	0	19	0	13	63	169	313	39	0.01%
Bolivian Yungas	462,856	0	0.00%	100.00%	0	0	0	0	6	6	238	44	294	37	0.01%
Sum of top 10	82,275,800	4,879,606	5.60%	94.40%	17,031	41,719	26,288	25,319	43,038	45,500	56,106	133,250	388,250	48,531	0.06%
Total in Ecoregions (n=15)	**90,698,800**	**5,218,556**	**5.44%**	**94.56%**	**17,038**	**41,756**	**26,369**	**25,588**	**43,038**	**45,525**	**56,150**	**133,269**	**388,731**	**48,591**	**0.05%**

Habitat loss, per Protected Area (ha), organize in terms of % Annual rate of loss

Protected Area (PA)	Analyzed Area	Not Analyzed	% NoData	% of total PA analyzed	2004	2005	2006	2007	2008	2009	2010	2011	Accum.	Avg. annual loss	% Annual rate of loss
Pacaya Samiria (VI)	2,161,869	438	0.02%	99.98%	406	1,219	1,281	506	663	775	756	2,106	7,713	964	0.04%
Manú (II)	1,654,213	38,613	2.28%	97.72%	150	38	44	194	138	181	288	356	1,388	173	0.01%
Bahuaja Sonene (II)	1,086,581	0	0.00%	100.00%	25	25	19	138	81	94	350	106	838	105	0.01%
Alto Mayo (VI)	114,081	90,456	44.22%	55.78%	0	13	19	31	0	6	75	56	200	25	0.02%
Río Abiseo (II)	215,688	56,344	20.71%	79.29%	0	0	0	13	13	0	94	63	181	23	0.01%
San Matias San Carlos (VI)	103,681	45,394	30.45%	69.55%	31	19	56	6	25	0	6	6	150	19	0.02%
Yánesha (VI)	30,250	1,275	4.04%	95.96%	6	6	0	0	13	19	44	50	138	17	0.06%
Purus (VI)	201,713	0	0.00%	100.00%	0	13	0	0	6	25	13	50	106	13	0.01%
Yanachaga-Chemillen (II)	34,219	76,206	69.01%	30.99%	0	0	0	0	13	6	0	0	19	2	0.01%
Tabaconas Namballe (III)	30,838	2,894	8.58%	91.42%	0	0	0	0	6	0	0	0	6	1	0.00%
Sum of top 10	5,633,131	311,619	5.24%	94.76%	619	1,331	1,419	888	956	1,106	1,625	2,794	10,738	1,342	0.02%
Total in PAs (n=22)	**5,847,656**	**426,063**	**6.79%**	**93.21%**	**625**	**1,331**	**1,419**	**888**	**956**	**1,106**	**1,625**	**2,794**	**10,744**	**1,343**	**0.02%**

Summary

This report mainly focuses on a description of the land-use change in Amazonia. Firstly, it describes the context of land-use change. Secondly, it discusses some of the available literature. Thirdly, data produced by the tool Terra-i are explored taking advantage of the fact that it serves as the only land-cover change monitoring system available which provides data with good spatial (250m) and temporal resolution (16-days) for the entire of Amazonia.

This report also includes a short presentation of the five studied Amazon countries including analysis of land cover change by departments or provinces, biomes, ecoregions and protected areas.

A clear deforestation pattern has been identified between the Amazon countries, with agricultural activities being the key driver. Stakeholders have undertaken activities at different scales depending mainly on their economic production and political models which vary by country.

References

Aguiar, A.P.D., J.P. Ometto, C. Nobre, D.M. Lapola, C. Almeida, I.C. Vieira, J.V. Soares, R. Alvala, S. Saatchi, D. Valeriano and J.C. Castilla-Rubio. 2012. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon. Global Change Biology. doi: 10.1111/j.1365-2486.2012.02782.x

Aguirre, N., M. Añazco, K. Cueva, L. Ordoñez, A. Pekkarinen, C. Ramirez, R. Roman, G. Sanchez and C. Velasco. 2011. Evaluación Nacional Forestal - Metodología para desarrollar el estudio piloto de la ENF en conformidad con el mecanismo REDD+. Quito: MAE, FAO y Programa UN-REDD. 58 p.

Arce, R. and R. Porro. 2010. Energy Policies, Forests and Local Communities in the Ucayali Region, Peruvian Amazon. ICRAF Working Paper no. 117. Nairobi, Kenya: World Agroforestry Centre. Available online: http://www.worldagroforestry.org/downloads/publications/PDFs/WP16793.PDF

Armenteras, D., N. Rudas, S. Rodriguez, S. Sua and M. Romero. 2006. Patterns and causes of deforestation in the Colombia Amazon. Ecological Indicators, 353-368.

Azevedo-Ramos, C. 2008. Sustainable development and challenging deforestation in the Brazilian Amazon: the good, the bad and the ugly. Unasylva 59(230), 12-16.

Azqueta, D. and G. Delacámara. 2008. Oil extraction and deforestation: a simulation exercise. pp. 57-70. In: CEPAL review. New York, NY: Comm., 94, p. Available online: http://www.eclac.cl/publicaciones/xml/0/33820/RVI94AzquetaDelacamara.pdf

Barona, E., N. Ramankutty, G. Hyman and O. Coomes. 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environmental Research Letters. 5 (April-June 2010). Available online: http://iopscience.iop.org/1748-9326/5/2/024002/fulltext.

BBC World Service. 2011. Amazon by Country. Available online: http://www.bbc.co.uk/worldservice/specials/1533_amazon/page2.shtml

Canziani, P.O. and G. Carbajal. 2012. Climate Impacts of Deforestation/Land-Use Changes in Central South America in the PRECIS. The Scientific World Journal 972672.

CEPAL. 2007. Experiencia comunitaria para el desarrollo sostenible y la conservación del medio ambiente en la Reserva Nacional Pacaya-Samiria (Loreto, Perú). 38 p. Available online: http://www.cepal.org/dds/innovacionsocial/e/proyectos/doc/Proyecto.ProNaturaleza.Peru.esp.pdf

COL R-PP. 2011. Readiness preparation proposal for REDD+ (R-PP). Available online: http://forestcarbonpartnership.org/fcp/sites/forestcarbonpartnership.org/files/Documents/PDF/Oct2011/Colombia_R-PP_Revised-%20English-%20September%2029%2C%202011.pdf

Consejo Nacional de Política Económica y Social-CONPES. 2011. Estrategia Institucional para la articulación de políticas y acciones en materia de cambio climático en Colombia. Documento CONPES 3700. Consejo Nacional de Política Económica y Social. Departamento Nacional de Planeación. Colombia.

Dávalos, L. M. and A.C. Bejarano. 2008. Conservation in conflict: Illegal drugs versus habitat in the Americas. In: Not Set ed. State of the Wild 2008-2009: A global portrait of wildlife, wildlands, and oceans. State of the Wild (2). Washington, DC: Island Press, pp. 218–225. Available online: http://oro.open.ac.uk/10633/1/Davalos&Bejarano_proof.pdf

Dávalos, L.M., A.C. Bejarano, M.A. Hall, H.L. Correa, A. Corthals and O.J. Espejo. 2010. Forests and Drugs: Coca-Driven Deforestation in Tropical Biodiversity Hotspots. Environmental Science & Technology. 45 (4), 1219-1227.

Etter, A., C. McAlpine, D. Pullar and H. Possingham. 2006a. Modelling the conversion of Colombian lowland ecosystems since 1940: Drivers, patterns and rates. Journal of Environmental Management 79, 74-87

Etter, A., C. McAlpine, K. Wilson, S. Phinn and H. Possingham. 2006b. Regional patterns of agricultural land use and deforestation in Colombia. Agriculture, Ecosystems and Environment 114, 369-386.

Finer, M., C.N. Jenkins, S.L. Pimm, B. Keane and C. Ross. 2008. Oil and Gas Projects in the Western Amazon: Threats to Wilderness, Biodiversity, and Indigenous Peoples. PLoS One 3(8), e2932.

Food and Agriculture Organization- FAO (2011). State of the World's Forests. http://www.fao.org/docrep/013/i2000e/i2000e00.

González J.J., A.A. Etter, A.H. Sarmiento, S.A. Orrego, C. Ramírez, E. Cabrera, D. Vargas, G. Galindo, M.C. García and M.F. Ordoñez. 2011. Análisis de tendencias y patrones espaciales de deforestación en Colombia. IDEAM, Bogotá D.C., Colombia. 64 p.

Hargrave, J. and K. Kis-Katos. 2012. Economic Causes of Deforestation in the Brazilian Amazon: A Panel Data Analysis for the 2000s. 32 p. Available online: http://www.eea-esem.com/files/papers/eea-esem/2012/747/Submit_EEA.pdf

Kaimowitz, D., P. Mendez, A. Puntodewo and J. Vanclay, 2002. Spatial regression analysis of deforestation in Santa Cruz, Bolivia. In: C.H. Wood and R. Porro (eds) Land Use and Deforestation in the Amazon. University Press of Florida, p. 41-65. ISBN 0-8130-2464-1.

Killeen, T. 2012. In the Amazon, threats to an arc of wilderness. The Washington Post. Available online: http://www.washingtonpost.com/world/in-the-amazon-threats-to-an-arc-of-wilderness/2012/08/30/44354750-f309-11e1-adc6-87dfa8eff430_graphic.html

Killeen, T., J.E. Chávez, M. Peña-Claros, M. Toledo, L. Arroyo, J. Caballero, L. Correa, R. Guillén, R. Quevedo, M. Saldias, L. Soria, Y. Uslar, I. Vargas and M. Steininger. 2005. The Chiquitano dry forest, the transition between humid and dry forest in Eastern lowland Bolivia. In: Neotropical savannas and dry forests: Diversity, Biogeography, and Conservation. Taylor and Francis, LLC. (in press).

Killeen, T.J., A. Guerra, M. Calzadilla, L. Correa, V. Calderón, L. Soria, B. Quezada and M. K. Steininger. 2008. Total historical land-use change in eastern Bolivia: who, where, when, and how much? Ecology and Society 13(1), 36.

Latin American Herald Tribune. 2009. Venezuela, Ecuador Protect More of Amazon, Study Says. Available online: http://www.laht.com/article.asp?ArticleId=330735&CategoryId=10717

Laurance, W.F., M.A. Cochrane, S. Bergen, P.M. Fearnside, P. Delamonica, C. Barber, S. D'Angelo, and T. Fernandes. 2001. The future of the Brazilian Amazon. Science 291, 438-439. Available online: http://si-pddr.si.edu/dspace/bitstream/10088/1467/1/Laurance_Science.pdf
Mäki, S., K. Risto and K. Vuorinen. 2001. Road construction in the Peruvian Amazon: process, causes and consequences. Environmental Conservation 28(3), 199-214.

Marsik, M., F.R. Stevens and J. Southworth. 2011. Amazon deforestation: Rates and patterns of land cover change and fragmentation in Pando, northern Bolivia, 1986 to 2005. Progress in Physical Geography 35(3), 353-374.

Mecham, J. 2001. Causes and consequences of deforestation in Ecuador. Available online: http://www.rainforestinfo.org.au/projects/jefferson.htm

Mena, C. 2008. Trajectories of Land-use and Land-cover in the Northern Ecuadorian Amazon: Temporal Composition, Spatial Configuration, and Probability of Change. PhEngRS 74(6), 737-752.

Mena, C.F., R.E. Bilsborrow and M.E. McClain. 2006. Socioeconomic drivers of deforestation in the Northern Ecuadorian Amazon. Environmental Management 37(6), 802-815.

Messina, J.P., and S.J. Walsh. 2001. Simulating Land Use and Land Cover Dynamics in the Ecuadorian Amazon Through Cellular Automata Approaches and an Integrated GIS.

Proceedings, Open Meetings of the Human Dimensions of Global Environmental Change Research Community, Rio de Janeiro, Brazil.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and human well-being: Scenarios. Findings of the scenarios working group. Island Press: Washington D.C.

MINAM Peru. 2009. Mapa de Deforestación de la Amazonía Peruana 2000. Lima, Peru: Ministerio del Medio ambiente del Perú.

MINAM Peru. 2011. El Peru de los bosques. 73 p. Available online: http://cdam.minam.gob.pe/novedades/elperudelosbosques2011.pdf

Ministerio de Agricultura y Desarrollo Rural- MADS (2011). Proyecto de Ley General de Tierras y Desarrollo Rural. Marzo 2011.

MMA, PNUMA and UNESCO. 2007. Iniciativa Latinoamericana y Caribeña para el Desarrollo Sostenible -ILAC. Brasilia: Ministerio del Medio Ambiente (MMA). 171p.

Morales, I. 1993. Monitoreo del bosque en el Departamento de Santa Cruz, Periodo 1988/89 - 1992/93. CORDECRUZ, Santa Cruz.

Morales, I. 1996. Memoria explicativa del monitoreo preliminar del desbosque en el Departamento de Santa Cruz, 1994. CORDECRUZ, Santa Cruz.

Moutinho, P. and S. Schwartzman. 2005. Compensated reduction of deforestation. Amazon Intitute of Environmental Research. Available online: http://www.ipam.org.br/web/index.php

Napo Wildlife Centre. 2010. Birding in the Amazon Rainforest. Available online: http://www.thinkbirding.com/amazon-rainforest.html

Pacheco, P. and B. Mertens. 2004. Land use change and agriculture development in Santa Cruz, Bolivia . Bois et Forets des Tropiques 280, 29-40.

Pedlowski, M.A., E. Matricardi, D.L. Skole, S. Cameron, W. Chomentowski, C. Fernandes and A. Lisboa. 2005. Conservation Units: A New Deforestation Frontier in the Amazonian State of Rondônia, Brazil. Environmental Conservation. 32(2), 1- 7.

Pfaff, A., J. Robalino, R. Walker, S. Aldrich, M. Caldas, E. Reis, S. Perz, C. Bohrer, E. Arima, W. Laurance and K. Kirby. 2007. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. Journal of Regional Science, 47(1), 109–123.

Pichon F.J. 1997. Settler households and land-use patterns in the Amazon frontier: farm-level evidence from Ecuador. World Dev. 25(1), 67–91.

Rodriguez, A. 2011. Cartografía multitemporal de quemas e incendios forestales en Bolivia: Detección y validación post-incendio. Ecología en Bolivia 47(1), 53-71. Available online: http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S1605-25282012000100004&lng=es&nrm=iso

Rodríguez, S.C. 2010. Impacts of Deforestation on Poverty: Case Study of the Region San Martin in Peru. Master these for Institute of Social Studies, The Hague, The Netherlands. Available online: http://oaithesis.eur.nl/ir/repub/asset/8628/ISS_RP_Rodriguez.pdf

Rudel T.K., D.Bates and R. Machinguiashi. 2002. A tropical forest transition? Agricultural change, out-migration, and secondary forests in the Ecuadorian Amazon. Ann. Assoc. Am. Geogr. 92(1), 87–102.

Sanabria-Siles, N.J. 2009. Spatial modelling and prediction of tropical forest conversion in the Isiboro sécure national park and indigenous territory TIPNIS, Bolivia. Master These in Natural Resources Management (NRM). Enschede, ITC. Available online: http://www.itc.nl/library/papers_2009/msc/nrm/siles.pdf

Sánchez-Cuervo, A.M, T.M. Aide, M.L Clark and A. Etter. 2012. Land Cover Change in Colombia: Surprising Forest Recovery Trends between 2001 and 2010. PLoS ONE 7(8), e43943. doi:10.1371/journal.pone.

Sanderson, E.W., M. Jaiteh, M.A. Levy, K.H. Redford, A.V. Wannebo and G. Woolner. 2002. The human footprint and the last of the wild. BioScience 52(10), 891-904.

Sierra, R. 2000. Dynamics and patterns of the deforestation in the western Amazon: the Napo deforestation front, 1986-1996. Applied Geography 20, 1-16.

Soares, R. 2010. Pará Case: “One Billion Trees for the Amazon”. 127 p. Available online: http://www.erb.umich.edu/Research/Student-Research/Para_Case-One_Billion_Trees_for_the_Amazon.pdf

Soares-Filho, B.S., D.C. Nepstad, L.M. Curran, G.C. Cerqueira, R.A. Garcia, C. Azevedo Ramos, E. Voll, A. Macdonald, P. Lefebvre and P. Schlesinger. 2006. Modelling conservation in the Amazon basin. Nature, 440, 520–523.

Sombroek, W.G. and N. Higuchi. 2003. (In Press). Deforestation in the Amazon; past, present and future. Encyclopedia of Life Support Systems (EOLSS). Chapter 1.5.5.1 Unesco, Paris. Available online: http://www.eolss.net/Sample-Chapters/C12/E1-05-05-01.pdf.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales and C. De Haan. 2006. Livestock's Long Shadow: Environmental Issues and Options. FAO, Rome, Italy, 978-92-5- 105571-7.

Steininger, M.K., C.J. Tucker, J.R.G. Townshend, T. J. Killeen, A. Desch, V. Bell, and P. Ersts. 2001. Tropical deforestation in the Bolivian Amazon. Environmental Conservation 28,127-134.

Thiel, H. and M. Viergever. 2007. Giants Don't Leap: Verification in Brazil's Process towards Sustainable Forestry. Verifor Country Case Study 5. 16 p. Available online: http://www.catie.ac.cr/BancoMedios/Documentos%20PDF/brazil.pdf

UNODC. 2009. World Drug Report. Available online: http://www.unodc.org/documents/crop-monitoring/Colombia/Colombia-cocasurvey2010_es.pdf

Uriostre, A. 2010. Deforestación en Bolivia: Una Amenaza mayor al cambio climático. Bolivia: Fundación Friedrich Ebert. Available online: http://library.fes.de/pdf-files/bueros/bolivien/07570.pdf

Velarde, S.J., J. Ugarte-Guerra, M.R. Tito, J.L Capella, M. Sandoval, G. Hyman, A. Castro, J.A. Marín and E. Barona. 2010. Reducing Emissions from All Land Uses in Peru. Final National Report.. 2010. ASB Partnership for the Tropical Forest Margins. Nairobi, Kenya. 142 p. Available online: http://www.asb.cgiar.org/PDFwebdocs/REALU%20I-Peru%20Report-.pdf

Veríssimo, A., A. Rolla, M. Vedoveto and S. De M. Futada. 2011. Protected Areas in the Brazilian Amazon: Challenges & Opportunities. Imazon, Belém. 96 p. Available online: http://www.socioambiental.org/banco_imagens/pdfs/10381.pdf

Villegas, Z. 2009. La vision Agrista de los actores de la deforestación en Bolivia. Revista Tinkazos 2(7). Programa de Investigación Estratégica en Bolivia (PIEB).

Viña, A., F. Echavarria and D.C. Rudquist. 2004. Satellite change detection analysis of deforestation rates and patterns along the Columbia-Ecuador border. Ambio 33(3), 118-125.

Walsh, S.J., J.P Messina, K.A. Crews-Meyer, R.E. Bilsborrow and W.K. Pan. 2002. Characterizing and modeling patterns of deforestation and agricultural extensification in the Ecuadorian Amazon. See Ref. 186, pp. 187–214.

WWF. 2012. Freshwater conservation in the Peruvian Amazon. Available online: http://wwf.panda.org/what_we_do/where_we_work/amazon/vision_amazon/wwf_projects_amazon_basin_rainforests/?uProjectID=PE0861

Annex I:
Terra-i Model: Methodology for the land-use change assessment of Amazonia

Introduction

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 (Nelson, 2005). Remote sensing of the earth from satellites has over the years made great progress in monitoring land-cover, although much of the advances have been in the realm of increased spatial resolution and in terms of quality of the land-cover mapping (greater precision, detail in number of classes, among others) (Mayaux et al., 2005).

Within this context, Terra-i is the only near-real time monitoring system for natural habitats across Latin America and the Caribbean that provides data with good spatial (250m) and temporal resolution (16-days). The Terra-i system is based on machine learning algorithms. This tool has the distinct advantage of being able to provide a single objective measure of land-use change across multiple countries and time periods. It is important to point out that the model isn't able to detect forest degradation.

The methodology used for the land-use change assessment based on Terra-i data is explained in the following sections.

Methodology

Terra-i background

Baseline

The Terra-i models need a certain period of time for calibration. The data from the year 2000 to 2003 are therefore used for this purpose which means that the system is operational from January 2004. Therefore, the land use change is assessed during a consolidated period of time, 8-years (2004 to 2011).

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 as possible anthropogenic impacts on natural ecosystems. The model uses a multilayer Perceptron (MLP) neural network combined with Bayesian theory (MacKay, 1992; Bishop, 2007) to identify abnormal behavior in a time-series of vegetation change. The operationalisation of the system pan-tropically is a considerable challenge from a computer science perspective as the resolution of the MODIS sensor (250m) means that even only the Amazonian basin represents more than one billion individual values for each time-frame (every 16 days). This means more than 26 billion values to process per year. Such a large dataset necessitates the use of data mining technologies and distributed programming.

Human activities create disturbances that alter the usual cycle of vegetation greenness for an area. Disturbances can be detected when the Normalized Difference Vegetation Index (NDVI) of the landscape changes from its baseline values. 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 concurrent 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 thus flagged in near real-time as events that land managers, conservationists and policy makers should be aware of.

In order 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, in order to indicate the recent NDVI trend, and the accumulated rainfall (derived from the TRMM daily rainfall product 3b42 (NASA, 1997)) for the preceding 16 days in order to fit the MOD13Q1 temporal resolution.

Because the MODIS data are 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 by Hird and McDermid [2009] to perform better than the others methods, The Harmonic Analysis of NDVI Time Series (HANTS) algorithm (Verhoef et al., 1996; Roerink et al., 2000; Jun et al., 2004) has been chosen as 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 operationalise 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 which correspond to different land use types (Xiao et al., 2002; Huete et al., 2002; Wang and Tenhunen, 2004; Shao and Lunetta, 2010). The clustering procedure is applied on MODIS-NDVI time series from the same period of time as the training dataset. This will group together the pixels which had similar trends over these years and which can be modeled by the same forecasting model. A given period of time series of each cluster are then randomly selected and used as the training dataset for the modeling. As the system should be easily operational on large areas, it should be possible to perform the clustering step without having prior knowledge about the study area. Thus, the unsupervised K-Means algorithm has been selected to perform this task.

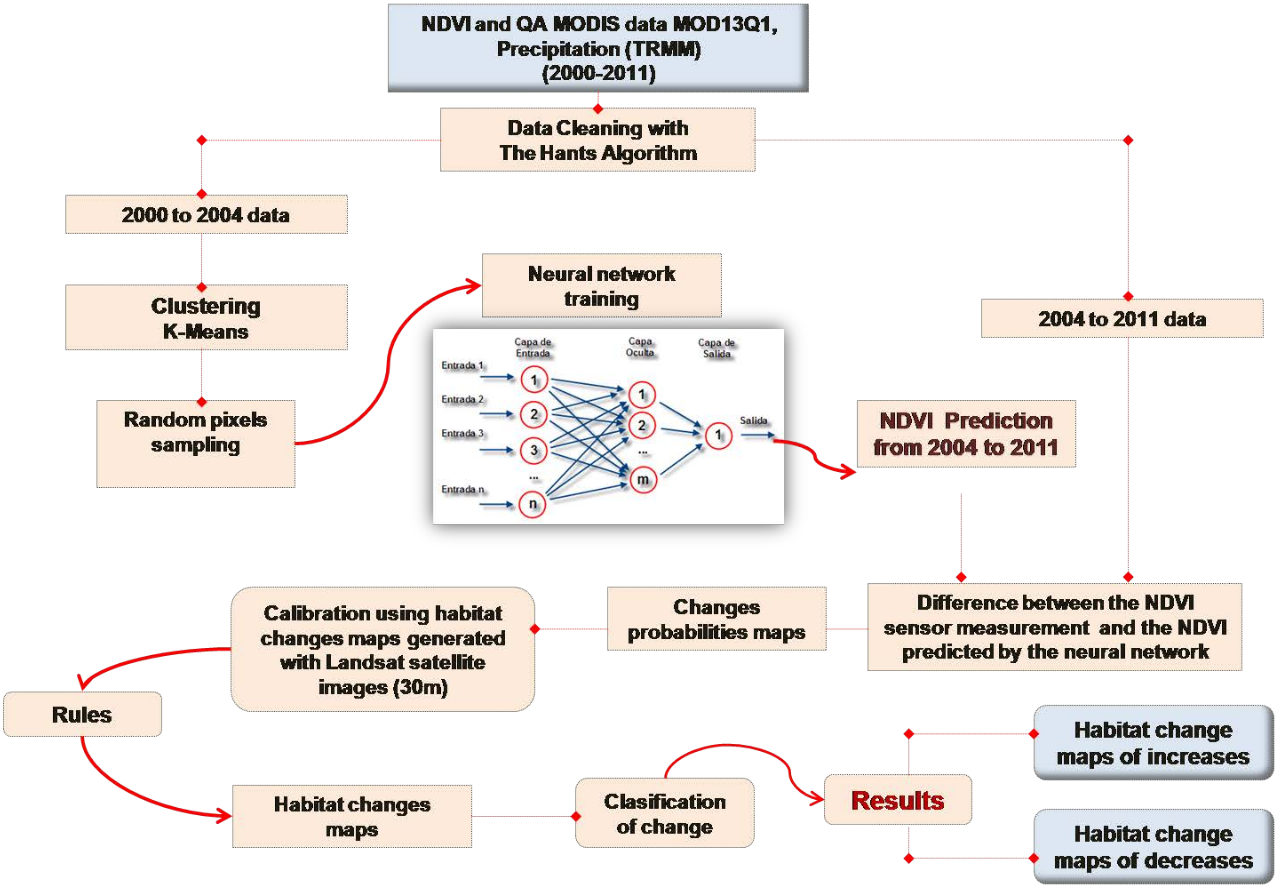

Figure 1: Visual overview of the methodology used.

Once the area has been clustered, Bayesian forecasting models are trained using the training dataset 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, a probability that the observed value is an anomaly is extracted based on the predicted value and some properties of the dataset found during model training. Whenever the probability of being an anomaly exceeds a defined threshold this event 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. In order to reduce the noise due to isolated small clouds or other sources of disturbance, a set of spatial and landscape based rules will also be defined (such as the distance to the closest road and river or to a known deforestation border).

Not only anthropogenic events are the cause of unusual long term anomalies in NDVI time series. Actually, events such as floods should 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.

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

Input data

Terra-i uses data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor which provide global superficies imagery every 1 to 2 days. It 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 covered area is divided into 10 x 10 degree "tiles" or boxes with a global coverage and a spatial resolution of 250m every 16 days since February 18, 2000 to the current date. For the detection of changes in the habitats, Terra-i uses the MODIS vegetation indices from the product MOD13Q1, and precipitation data from the Tropical Rainfall Measuring Mission (TRMM) sensor.

MODIS vegetation indices data

The vegetation indices are designed to provide a permanent and consistent comparison of the temporal and spatial changes of vegetation by responding to the amount of photosynthetically active radiation in a given pixel, to the chlorophyll content, to the leaf area and the structural characteristics of plants (Shao and Lunetta, 2010). The Normalized Difference Vegetation Index (NDVI) (Kozu et al. 2001) is an indicator of whether a given area contains live green vegetation or not. The reliability of this index has been shown multiples times. NDVI measures the spectral response of the vegetation; if vegetation is degraded, it will reflect the blue and even more the red (R) visible spectrum,oOn the other hand, if the vegetation is healthy, it will reflect the near-infrared spectrum (NIR). Following this principle many studies (Kaduk and Heimann, 1996; Moulin et al., 1997; Achard et al., 2002; Zhang et al., 2003) 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 days frequency and a 250m spatial resolution by the MOD13Q1 product.

TRMM precipitation data

The Precipitation Radar (PR) aboard the satellite Tropical Rainfall Measuring Mission (TRMM) is the first weather radar designed to measure the vertical structure of tropospheric precipitation in the tropics and subtropics (Kozu et al., 2001). Terra-i uses data from the TRMM precipitation sensor with a measurement frequency of 3 hours and a resolution of 28km.

Water bodies presence data from MODIS
Terra-i uses the product MOD35 (Cloud Mask) in its final stage of processing to mask the presence of water pixels and thus filter detections due to flooding and/or increscent of water bodies.

Output data
Terra-i generates maps of habitat changes every 16 days for each MODIS tile in Latin America from 2004 to current date.

More information is available from http://www.terra-i.org/ or contact: l.reymondin@cgiar.org

Amazonia land-use change assessment

Input GIS Data
For the land-use change analysis of Amazonia, the next set of thematic data was used to extract Terra-i data:

Global Administrative Unit Layers (GAUL) by FAO
Produced by FAO, this update corresponds to 2008. It contains the borders between countries and administrative units within the countries in first and second administrative levels.

Amazonia limits by the Amazon Cooperation Treaty Organization (ACTO)
A group of experts has provided a scientific basis for delineating the Amazon region based on consensus among disciplines ranging from local scale species distributions to global climate scale roles. Geographically, the proposal of Amazonia limits had two key elements; the entire hydrological Amazon and Tocantins river basin and two additional areas located outside of it, i.e. the Guiana and Gurupí regions.

Global biomes by Olson et al.
Olson et al. (2001) delineated the world's terrestrial biomes and subdivided them into finer-scale ecoregions to define a hierarchy of biogeographic organization from global to regional scales. Nested within biomes, ecoregions reflect finer regional-scale patterns of ecological organization that are shaped by local geography and climate. They are distinguished from one another by the unique assemblages of species and ecosystems found within them.

Global Terrestrial Ecoregions by WWF
This map depicts the 825 terrestrial ecoregions of the globe, and this update corresponds to 2001. The ecoregions are relatively large units of land containing distinct assemblages of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change. This comprehensive, global map provides a useful framework for conducting biogeographical or macroecological research, for identifying areas of outstanding biodiversity and conservation priority, for assessing the representation and

gaps in conservation efforts worldwide, and for communicating the global distribution of natural communities on earth.

World Database of Protected Areas Annual Release

The Annual Release includes all nationally designated (e.g. National Parks, Nature Reserves) and internationally recognized protected areas (e.g. UNESCO World Heritage Sites, Wetlands of International Importance) currently held in the WDPA, up to the end of February 2009. This static version contains all data improvements made by the WDPA since the previous annual release in December 2007. This dataset contains protected area boundaries (delineated) in shapefile (polygon) format.

Data extraction

Annual habitat loss data were generated based on Terra-i for the period 2004–2011 for the focus countries. Thus, a set of maps and charts of annual and accumulated habitat loss was created by country for the analyzed period. Additionally, GIS geodata of biomes, ecoregions and protected areas were extracted and then overlayed with Terra-i data for each country using the software ArcGIS v.10.

In the case of the PAs, only some of them were considered for land-use and land change analysis base on the IUCN categories criteria. Thus, PAs, which haven't been classified yet according to IUCN categories, were excluded.

Lambert azimuthal equal-area projection was used to calculate the habitat loss within Terra-i and GIS data overlayed using a cell size of 250 m.

References

Achard F., D.E. Hugh D., H.-J. Eva, U. Stibig, P. Mayaux, J. Gallego, T. Richards and J.P. Malingreau. 2002. Determination of deforestation rates of the world's humid tropical forests. Science 297(5583), 999-1002.

Bishop, C. 2007. Pattern Recognition and Machine Learning. Springer, 2 edition.

Huete A., C. Justice and W. Leeuwen. 1999. Modis vegetation index (Mod13) algorithm theoretical basis document. Technical report, MODIS.

Jun W., S. Zhongbo and M. Yaoming. 2004. Reconstruction of a cloud-free vegetation index time series for the tibetan plateau. Mountain Research and Development 24, 348-353.

Kaduk J. and M. Heimann. 1996. A prognostic phenology model for global terrestrial carbon cycle models. Climate Research 6(1), 1-19

Kozu T., T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa and H. Kumagai. 2001. Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite in IEEE Transactions on Geoscience and Remote Sensing 39(1), 102-116.

Lloyd, D. 1990. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. International Journal of Remote Sensing 11, 2269–2279.

MacKay, D. 1992. A practical bayesian framework for backpropagation networks. Neural Computation 4(3), 448-472.

Mayaux P., P. Holmgren, F. Achard, E. Hugh, H-.J. Stibig and A. Branthomme. 2005. Tropical forest cover change in the 1990s and options for future monitoring. Philosophical Transactions: Biological Sciences 360(1454), 373-384.

Moulin S., L. Kergoat, N.N. Viovy and G.G. Dedieu. 1997. Global-scale assessment of vegetation phenology using noaa/avhrr satellite measurements. Journal of Climate 10, 1154-1170.

NASA. 1997. Algorithm 3b42 - trmm merged hq/infrared precipitation. Technical report. URL http://trmm.gsfc.nasa.gov/3b42.html.

Nelson, G.C. 2005. Drivers of ecosystem change: Summary chapter. Millenium Ecosystem Assessment, Current State and Trends Assessment.

Olson, D. M., E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. N. Powell, E. C. Underwood, J. A. D'amico, I. Itoua, H. E. Strand, J. C. Morrison, C. J. Loucks, T. F. Allnutt, T.

H. Ricketts, Y. Kura, J. F. Lamoreux, W. W. Wettengel, P. Hedao, and K. R. Kassem. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. BioScience 51(11), 933-938.

Roerink G.J., M. Menenti and W. Verhoef. 2000. Reconstructing cloudfree ndvi composites using fourier analysis of time series. Internonational Journal of Remote Sensing 21, 1911-1917.

Shao Y. and R. Lunetta R. 2010. The use of modis ndvi data for characterizing cropland across the great lakes basin. International Journal of Applied Earth Observation and Geoinformation 12, 81-88.

Verhoef W., M. Menenti and S. Azzali. 1996. A colour composite of noaa-avhrr ndvi based on time series analysis (1981-1992). International Journal of Remote Sensing 17, 231-235.

Wang Q. and J. Tenhunen. 2004. Vegetation mapping with multitemporal ndvi in north eastern china transect (nect). International Journal of Applied Earth Observation and Geoinformation 6, 17-31.

Xiao X., B. Moore, X. Qin, Z. Shen and S. Boles. 2002. Large-scale observation of alpine snow and ice cover in asia: using multi-temporal vegetation sensor data. International Journal of Remote Sensing 23(11), 2213-2228.

Zhang X., M. Friedl, M. Schaaf, A. Strahler, J. Hodges, F. Gao, B. Reed and A. Huete. 2003. Monitoring vegetation phenology using modis. Remote Sensing of Environment 84, 471-475.

Data Source

Vegetation Indices 16-day 250m (MOD13Q1), USGS NASA
https://lpdaac.usgs.gov/content/view/full/6652

MODIS Cloud Mask product 250m (MOD35), NASA
http://modis-atmos.gsfc.nasa.gov/MOD35_L2/index.html

Tropical Rainfall Measuring Mission 28Km (TRMM), NASA
http://trmm.gsfc.nasa.gov/

Global Administrative Unit Layers (GAUL), FAO
http://www.fao.org/geonetwork/srv/es/metadata.show?id=12691

Global Terrestrial Ecoregions, WWF
http://www.worldwildlife.org/science/ecoregions/global200.html

World Database of Protected Areas (WDPA)
http://www.wdpa.org/AnnualRelease.aspx

Annex II
Comparison between Terra-i and PRODES system

The aim of this study was to compare and analyze the output of the PRODES (INPE) and Terra-i (CIAT) systems over the Brazilian Legal Amazon. All data were adjusted to the criteria of data range by year from the PRODES system. The study was realized in three phases: (1) both systems were compared using metrics such as overall precision, recall and kappa index; (2) a dataset of fire spot detections from MODIS imagery, delivered by INPE, was used to explain gaps between the systems; and (3) after the spatial detection of noise (potential natural fires) in the Terra-i data the metrics listed above were calculated once again, showing the potential of cleaning protocols for approximating Terra-i data to systems with higher resolution and field validation such as PRODES.

Methodology

First phase: Terra-i and PRODES comparison

The first step to perform the comparison between PRODES and Terra-i was to create the dataset based on raw data from PRODES. Datasets of annual deforestation detection and annual cloud cover (where PRODES did not perform an analysis) were extracted by classifying the raw data (Table 1).

Table 1: Annual periods from PRODES data used to classify the Terra-i data values for comparison of the two systems. The median of Julian Dates of the Landsat dataset was calculated to define the start and end date of each year, for the period 2005-2011.

Year	PRODES Landsat Imagery			Terra-i data classification	
	# Scenes	Median		Raster values (JD/YYYY)	
		JD	Data	Min	Max
2004	297	219	2004-08-06	-	-
2005	296	264	2005-09-21	>14 (225/2005)	<= 40 (273/2005)
2006	296	230	2006-08-18	>40 (273/2005)	<= 61(241/2006)
2007	296	231	2007-08-18	>61 (241/2006)	<= 84 (241/2007)
2008	292	228	2008-08-15	>84 (241/2007)	<= 107 (241/2008)
2009	293	230	2009-08-18	>107 (241/2008)	<= 130 (241/2009)
2010	292	225	2010-08-13	>130 (241/2009)	<= 152 (225/2010)
2011	292	221	2011-08-08	>152 (225/2010)	<= 175 (225/2011)

In order to ease the comparison, the second step consisted in rescaling both PRODES datasets at MODIS resolution by calculating what proportion (in %) of each MODIS pixel area was either deforested or covered by clouds (Figure 1).

The third step of the comparison process was to shift the Terra-i year window to match the PRODES year window (a PRODES year starts in August).

The detections from the comparison dataset were therefore grouped based on sub-pixel disturbance sizes (10%-20%, 20%-30% […] 90%-100% of a MODIS pixel) and the following metrics were calculated for each of them:

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

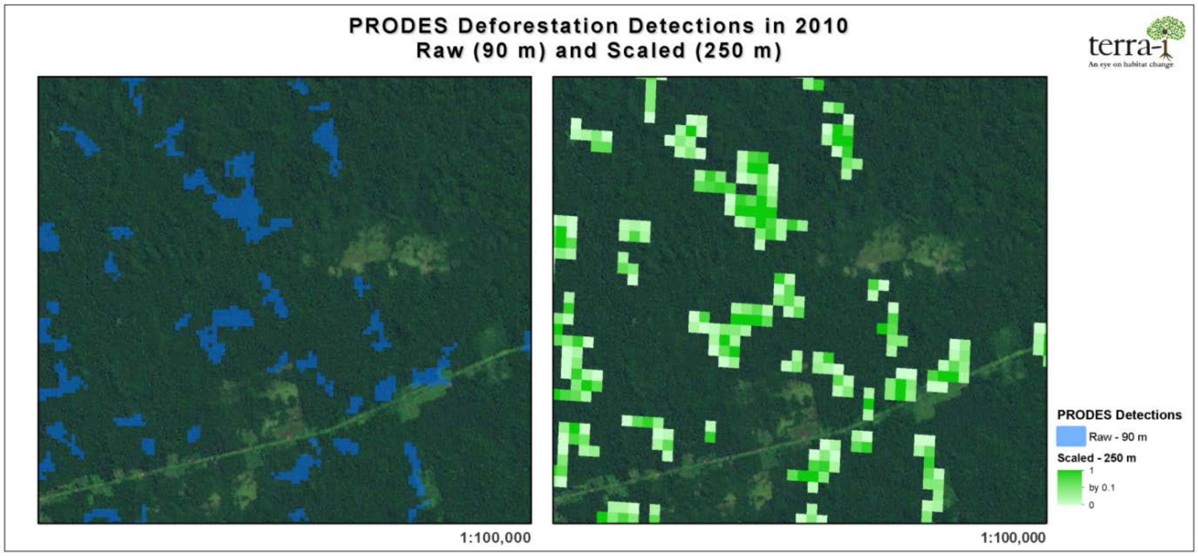

Figure 1: Map showing the PRODES raw data at 90 m (left) and scaled-up to a cell size of 250 m (right). Values of PRODES scaled in terms of proportion (in %) of each MODIS pixel area were covered by PRODES deforestation detection.

With these four inputs, five common similarity measurements often used in information retrieval and pattern recognition can be computed: precision, recall, accuracy and true negative rate. The formulas for these four measures are given below, where tp is the number of true positive pixels, fp the number of false positive pixels, tn is the number of true negative and fn the number of false negative pixels.

$$kappa = \frac{Pr(a) - \Pr(e)}{1 - \Pr(e)}$$

$Pr(a)$ is the percentage of agreement, which is equivalent to the accuracy described below, and $\Pr(e)$ is the probability of random agreement, calculated using the following formula:

Terra-i probability of saying yes: $P_{ty} = \frac{tp+fp}{tp+fp+tn+fn}$

PRODES probability of saying yes: $P_{py}\frac{tp+fn}{tp+fp+tn+fn}$

Probability of random agreement $\Pr(e) = P_{ty}P_{py}$

$$precision = \frac{tp}{tp + fp}$$
$$recall = \frac{tp}{tp + fn}$$
$$accuracy = \frac{tp + tn}{tp + fp + tn + fn}$$
$$true\ negative\ rate = \frac{tn}{tn + fp}$$

Precision measures the probability that a pixel detected by the Terra-i process is really a deforested one and recall measures the probability that a given deforested pixel is detected by the Terra-i algorithms. True negative rate measures the probability that a pixel not detected by the Terra-i process is really not deforested, and accuracy is the overall proportion of correctly classified pixels. We cannot use these measures independently because it is possible to have, for instance, a recall of 1 by setting all the pixels to detected (in this case, fn = 0 and the recall becomes 1). Precision would be extremely low in this case.

Second phase: Natural fires identification

To minimize differences between the two systems (Figure 2), fire data of MODIS AQUA provided by INPE (http://www.inpe.br/queimadas/) were downloaded for each year between 2005 and 2011. To identify non-anthropogenic fires, the first step was to identify Terra-i detection that had all of the three following properties: 1) a large area, 2) a very irregular shape, and 3) the inclusion of a large amount of fire detections from the INPE fire data. In order to ease the classification we first performed a KMeans clustering of all the Terra-i detection polygons and then extracted all the polygons from the clusters that had the relevant properties. This dataset of large fires was then manually checked using Landsat imagery to exclude any misclassified anthropogenic fires.

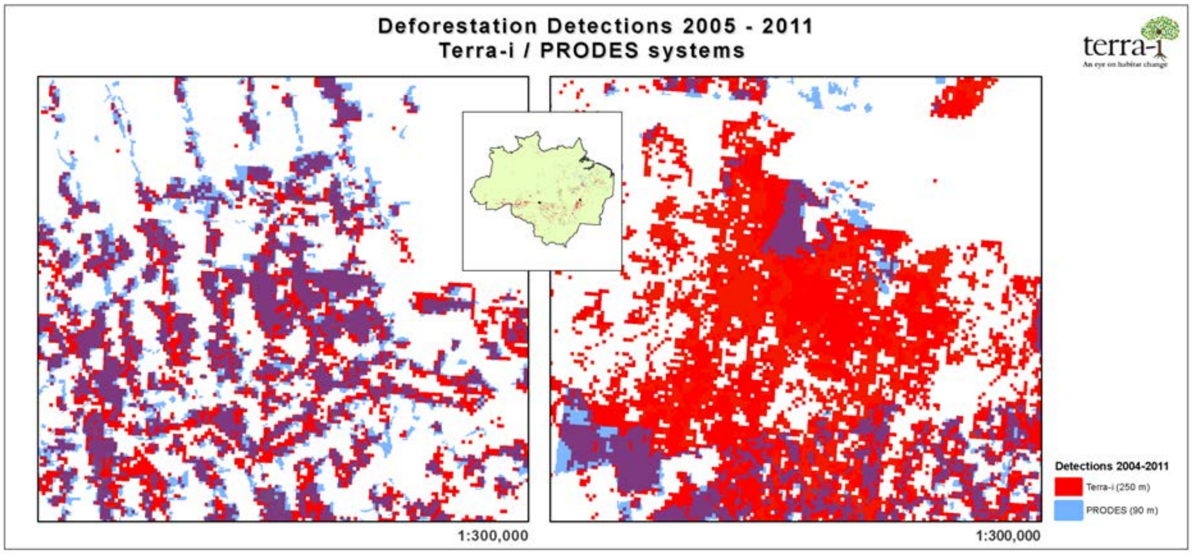

Figure 2: Map showing a good overlapping of Terra-i and PRODES data (left) and noise data such as fires spots (right) over the Brazilian Legal Amazon.

The remaining Terra-i polygons were then automatically classified to identify the ones that included at least one fire registered by the INPE and that were close enough to the large fire areas already identified. Finally, all these polygons were flagged as potential natural fires (Figure 3). This methodology was applied for 2008 and 2011, years for which the largest gaps were evident during the period of comparison between Terra-i and PRODES data.

Third phase: Calculation of similarity measurements between PRODES and Terra-i data (raw and cleaned).

After the spatial detection of noise (potential natural fires) in the Terra-i data, similarity measurements such as overall precision, recall and kappa index were calculated for both raw and cleaned Terra-i data for comparison with PRODES.

Results

Comparison of trends

The first analysis (Figure 4) showed that the general trends of Terra-i detections (red line) and PRODES results (blue line) are reasonably similar. The green line shows the trends that one could expect given the difference in pixel size between Terra-i (250 m) and PRODES (90 m).

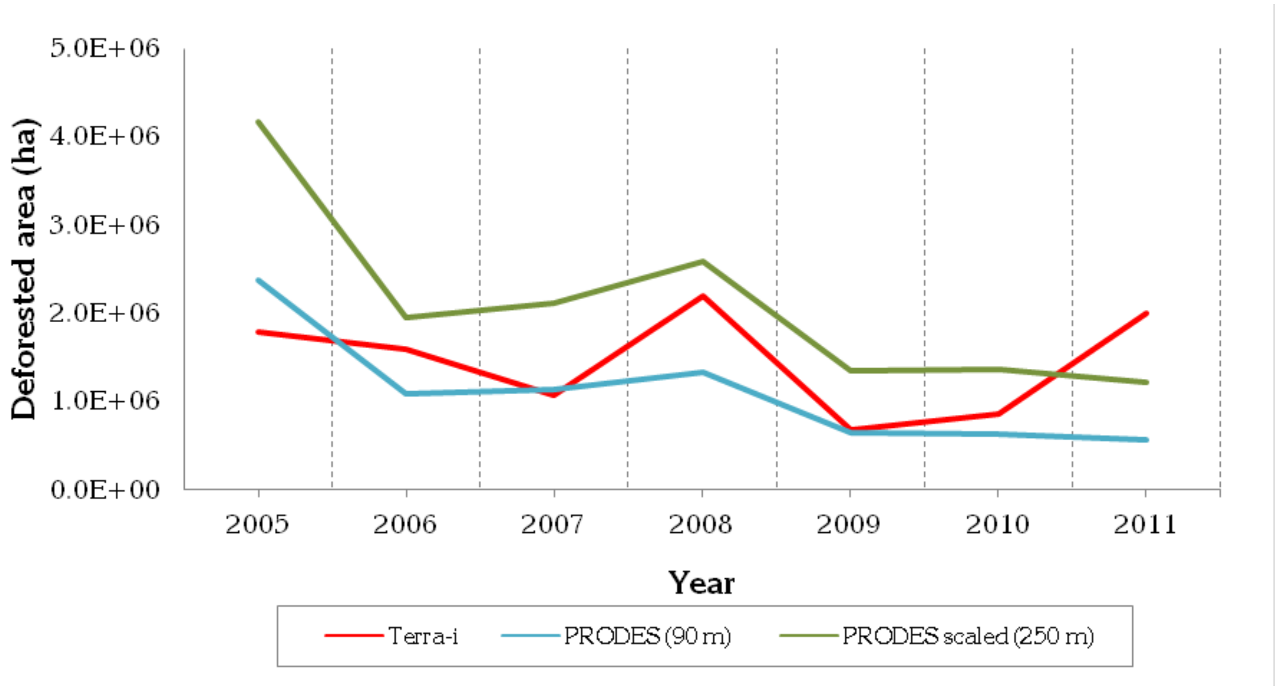

Figure 4: Systems trends comparison per year over the Brazilian Legal Amazon for the period 2005-2011.

Chart A of Figure 5 shows the different cumulative detections and average annual rates for the Brazilian states located in the Amazon Basin. On chart B, one can see the comparison of average annual rates as measured by Terra-i against the PRODES measurements.

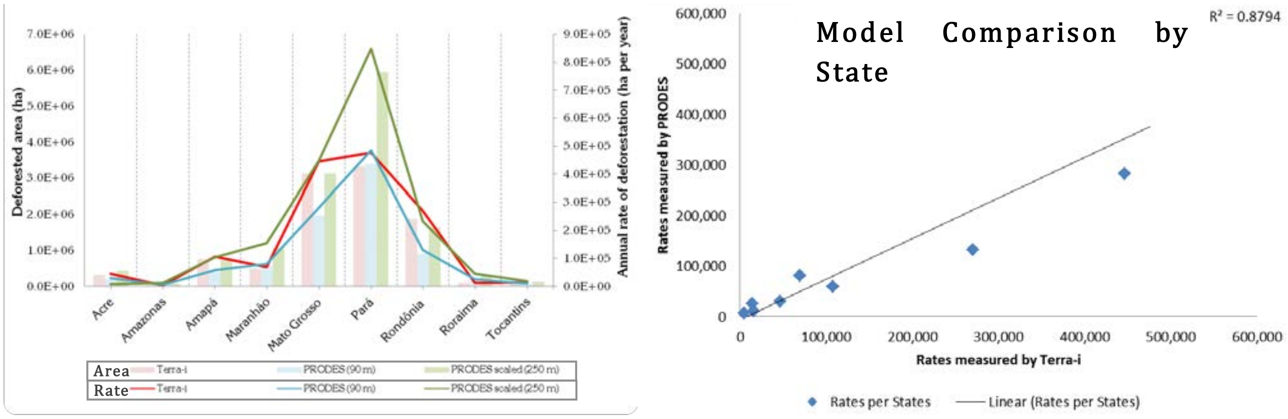

Figure 5. Systems comparison for calculation of total area and annual rate of deforestation per state in the Brazilian Legal Amazon for the period 2005-2011 (left). Correlation between average annual deforestation rates as measured by Terra-i and as measured by PRODES (right).

The average deforestation rates for the states analyzed are consistent with an R2 of 0.88 showing that on average, the Terra-i detections are quite similar to the PRODES detections.

Nevertheless, as shown in Figure 5, the trend given by Terra-i for 2011 is not consistent with PRODES. As explained below, this is mainly due to the fact that Terra-i detects natural fires and classifies them as anthropogenic events.

Natural fires identification

Detection of potential natural fires clarifies the spatial and temporal trends of the larger differences between Terra-i and PRODES data. Spatially, the states of Mato Grosso and Para account for most of the noise in Terra-i data (Table 2). Similarly, the years 2005, 2008 and 2011 all registered differences that were greater than during the comparison period (Figure 6).

Table 2: PRODES annual period data used to classify the Terra-i data values for comparison of the two systems. The median of Julian dates of the Landsat dataset was calculated to define the start and end date of each year for the period 2005-2011.

State	**Critical year**							
	2008				**2011**			
	Terra-i Detections + noise	**Natural fires isolated from Terra-i**	**Terra-i cleaned detections**	**% Fires**	**Terra-i Detections +noise**	**Natural fires isolated from Terra-i**	**Terra-i cleaned detections**	**% Fires**
Acre	62,688	0	62,688	0	88,819	0	88,819	0
Amazonas	3,694	0	3,694	0	9,056	6313	2,744	70
Amapá	99,281	0	99,281	0	170,525	0	170,525	0
Maranhão	146,513	8,238	644,475	1	49,250	0	49,250	0
Mato Grosso	740,044	95,569	721,925	12	579,588	2E+05	376,550	35
Pará	799,188	77,263	305,231	25	650,919	2E+05	442,450	32
Rondônia	305,231	0	17,488	0	436,488	19544	416,944	4
Roraima	18,063	0	18,063	0	6,569	0	6,569	0
Tocantins	25,650	575	25,075	2	15,650	862.5	14,788	6

Total Legal Amazon	**2,200,350**	**181,644**	**1,897,919**	**8**	**2,006,863**	**483,225**	**1,568,638**	**22**

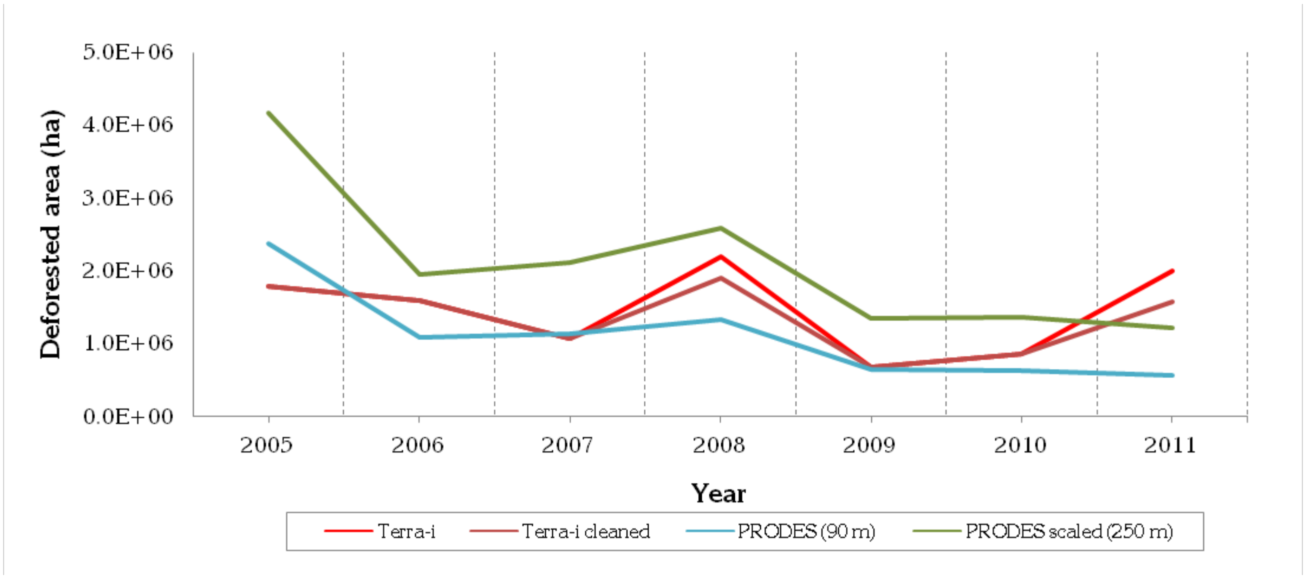

Figure 6: Model comparison after potential natural fires identification.

The preliminary results showed that Terra-i responded favorably to approximation of its gross data (250 m) to the rates and measurements of deforestation reported by systems with higher resolution and field performance such as PRODES, as well as reduction of gaps (Table 3) between the two systems.

Table 3: Summary table showing % difference between Terra-i data (both raw and cleaned) and PRODES data for 2008 and 2011.

	Detections in the Brazilian Legal Amazon by target year (Ha)			
Year	**Terra-i / noise data (TN)**	**Terra-i / cleaned data (TC)**	**% difference from PRODES**	
			TN	**TC**
2008	2,200,350	1,897,919	-39.7	-30.0
2011	2,006,863	1,568,638	-71.6	-63.7

Similarity measurements

Table 4: Comparison of results (in pixels) before and after the natural fires identification process.

	TP	FP	TN	FN
Raw	1591138	929529	90549522	983510
Cleaned	1571599	857683	90611368	1003049

The overall KAPPA coefficient of the model is 0.98, a robust result (Table 5). However, this result is biased on the unbalanced population size of converted pixels and pixels still covered with natural vegetation. This result must therefore be contrasted with the analysis of the other similarity coefficients.

Table 5: Kappa coefficient, based on cleaned data.

	PRODES yes	PRODES no
Terra-i yes	1571599	857683
Terra-i no	1003049	90611368

Terra-i probability of saying yes	0.027377145
PRODES probability of saying no	0.025831417
Percentage of agreement	0.980214177
The probability of random agreement	0.00070719

KAPPA	0.980200175

The KAPPA coefficient value before the identification of natural fires is 0.979645. The implementation of this methodology did not have a great impact on the KAPPA value as it resulted in an improvement of only 0.00055.

Accuracy

The overall accuracy of the model is high (0.98). However, this result is biased on the unbalanced population size of converted pixels and pixels still covered with natural vegetation. The high accuracy is therefore mainly explained by the good performance of the system in the true negative rate section.

Recall

The recall was calculated for different event sizes to show the accuracy of Terra-i at different scales (Figure 7). Recall is quite high (0.87) for large events (80% to 100% of a MODIS pixel deforested). On the other hand, due to the MODIS resolution Terra-i is performing poorly on events of a small scale, with recall falling to 0.43 when the event size is 10% to 20% of the MODIS pixels.

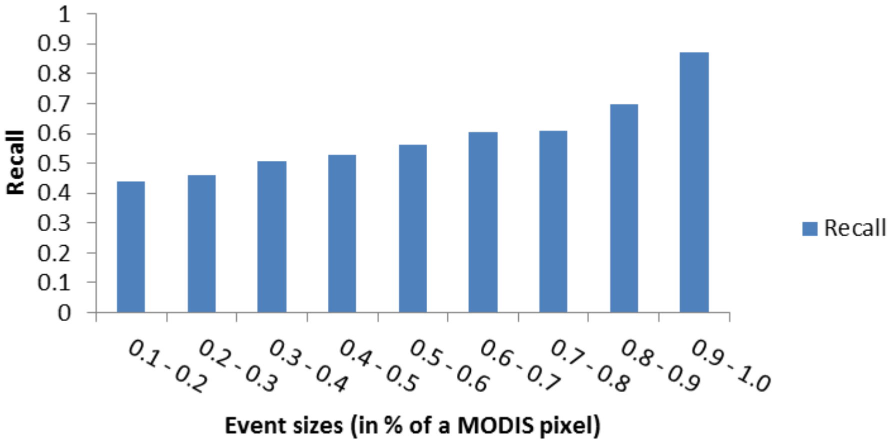

Figure 7: Recall for different event sizes (in % of a MODIS pixel).

The recall calculated with the raw data, before the natural fires extraction, was 0.88 for large events and 0.44 for small events. This shows that very few of the events that were identified as natural fires were indeed actual anthropogenic deforestation events.

Precision

The precision measured for Terra-i with the PRODES data is 0.6 when calculated with the raw data. As shown in Figure 3, Terra-i is detecting natural fires as deforestation. These natural fires are not mapped as anthropogenic changes by the PRODES team. Implementation of a natural fires identification methodology allowed for improved precision, up to 0.65. This change shows that the large majority of events that were deleted during the cleaning process were indeed actual natural fires.

True negative rate

The true negative rate measured for Terra-i in comparison with PRODES data is 0.99. This statistic means that if Terra-i does not detect a pixel as deforested, the probability that this pixel is still covered by natural vegetation is high.

Conclusion

On average, Terra-i gives results similar to those of the PRODES system. The comparison of average rates for the Brazilian States located in the Legal Amazon is consistent and recorded an R2 of 0.88. Moreover, the Kappa coefficient (0.98), the accuracy (0.98), the true negative rate (0.99) and the recall for deforestation events of about 6 hectares (0.87) also show the similarity of results between systems.

Nevertheless, Terra-i is performing poorly when it comes to detecting small scale events, as shown by a recall of only 0.43 for events of around 1 hectare. Additionally, Terra-i is classifying natural fires as anthropogenic events. This strongly increases false positive detections (giving a precision of 0.65) and biases the estimation of deforestation rate (particularly in 2011).

A preliminary methodology has the potential to reduce the effect of natural fires. The methodology is based on the fire dataset provided by INPE and the general features of the converted polygons. This methodology shows promise as it allowed 2011 figures to be reduced by 483,225 hectares.

Although the detection of natural fires is useful for reducing noise in Terra-i data, a detailed analysis should be performed to explain the remaining inconsistencies between models. For instance, the contrasting spatial resolution of MODIS and LANDSAT imagery could be considered to explain the vast majority of differences. Assuming that digital analysis of coarse resolution (1–8 km) data can over-estimate deforestation by up to 50% (Malingreau & Tucker 1988; Cross et al. 1991; Downton 1995; Malingreau et al. 1995), the Terra-i system (250 m resolution), has a potential margin of error of 10 to 20% in comparison to the detections of high resolution images (30-60 m).

References

Cross, A.M., Settle, J.J., Drake, N.A. & Paivinen, R.T.M. (1991) Subpixel measurement of tropical forest cover using AVHRR data. International Journal of Remote Sensing 12: 1119–1129.

Downton, M.W. (1995) Measuring tropical deforestation: development of the methods. Environmental Conservation 22: 229–240.

Malingreau, J.P. & Tucker, C.J. (1988) Large-scale deforestation in the southeastern Amazon basin of Brazil. Ambio 17: 49–55.

Malingreau, J.P., Achard, F., D'Souza, G., Stibig, H.J., D'Souza, J., Estreguil, C. & Eva, H. (1995) AVHRR for global tropical forest monitoring: the lessons of the TREES project. Remote Sensing Reviews 12: 29–40.