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METHODOLOGY FOR FOREST MONITORING USED IN PRODES AND DETER PROJECTS

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Amazon Monitoring Program -
PAMZ +
National Institute for Space Re-
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Methodology of INPE's PRODES and DETER Systems

1 Introduction

The Monitoring Program for the Amazon and Other Biomes (PAMZ +) is a program developed by the Earth Observation and Geoinformatics Division (DIOTG) and by the Spatial Coordination of the Amazon (COEAM), in the National Institute for Space Research (INPE).

PAMZ+ executes three operational projects for land use and land cover monitoring based on remote sensing satellite images in the Amazon region: the Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES), the Real-Time Deforestation Detection System (DETER) and the land use and land cover mapping system (TerraClass). These systems are complementary and have been created to achieve different objectives. This document details the PRODES and DETER methodologies.

2 Deforestation concepts in satellite monitoring

PRODES defines deforestation as *the suppression of areas of primary forested physiognomies by anthropogenic actions*. Deforestation is an only process that begins with an intact forest and ends with the conversion of this original forest to other covers. So, it is important to consider not only the extremes of deforestation, easier to identify in remote sensing images, but also the gradient of forest degradation during the deforestation process, that can occur slowly over time, by continuous logging and/or by successive occurrences of forest fires.

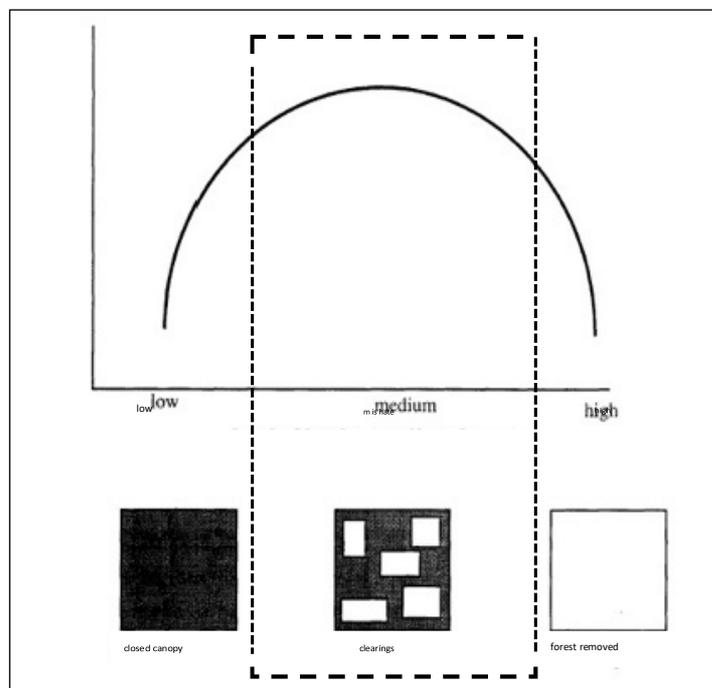


Figure 2.1 - Relationship between the level of disturbance and the heterogeneity of the landscape observed by remote sensing. Source: Lambin (1999).

Figure 2.1 shows a diagram in which the intensities of environmental disturbances produce a gradient of landscapes that ends with the complete removal of

the forest canopy. As the disturbance increases, the landscape becomes more heterogeneous in terms of spectral response; as the forest cuts increase, the landscape becomes homogeneous again for lack of original cover (Lambin, 1999). Some of these changes are hard to identify in remote sensing images, especially in the early stages, when the forest canopy is not much altered and when the signal of exposed soil is still weak.

2.1 Deforestation by Rapid Clear Cuts

Clear-cutting actions result in the complete removal of forest cover in a brief period. The forest is totally removed and replaced by other covers and uses (agricultural, pasture, urban, hydroelectric, etc.). The area can also be abandoned and enter in a regeneration process. Figure 2.2 illustrates the main steps.

The process normally begins before or during the rainy season that precedes the actual cutting of the forest. The smaller trees are cut with scythe or ax to facilitate the cutting of the larger trees that will take place in the next phase.



Figure 2.2 - Deforestation process by shallow cut, called “cut and burn”, in which all vegetation is felled and burned in a short time.

During the rainy season, these plants degrade and thus avoid accidents during the cutting phase. Larger trees are felled with chainsaws at the beginning of the dry season. The biomass remains in the soil, which is generally burned between July and September in the Amazon. At the end of this process, the remaining biomass is grouped in windrows for subsequent burning. Pasture is formed by sowing fodder grasses, well adapted to Amazon climate and fire. This strategy of deforestation was predominant in the region between the 1970s and 1990s. Clear-cut deforestation leaves scars very evident in satellite images of land observation, contrasting to the surrounding forest, making it relatively easy to detect.

2.2 Deforestation due to Forest Degradation

The second process is progressive degradation, which is slower and more difficult to detect using satellite images. The first step is the removal of the woods with highest commercial values, then the woods for civil construction and, finally, the remaining light woods are harvested for the production of plywood and slabs. This process can take a few years, as these forest explorations are usually made by different undertakings, each specialized in a different phase.

Smaller trees are then cut down, and all undergrowth is destroyed. Few leafy trees remain, like the species which are protected by law, such as chestnut trees, or those with no commercial value, such as palm trees. This remaining biomass makes deforestation difficult to be detected. At this time, about 50% of the canopy (tallest trees) has been removed.

The grass is planted at the same time as forest degradation occurs, taking some time to grow. After a year, cattle and livestock enter the forest, which has not yet disappeared. This grass is burned in the second year, causing a second clearing of the forest. After the second burning, only about 10% to 20% of the forest canopy remains, with a large number of dead trees standing. The burnt grass, which does not lose its roots in the fire, sprouts again, allowing cattle grazing in the degraded area. In the third year, another burning is done, which destroys the initial forest's remains. Figures 2.3 and Figure 2.4 illustrate the process of deforestation by progressive degradation.

The final phase of progressive degradation, in which the pasture is gradually introduced, can last two to three years. The challenge of satellite detection for surveillance purposes is significant. The medium resolution (20 to 30 meters) of satellite images makes difficult to detect the point where degradation correspond to the collapse of forest structure and can thus be classified as deforestation.

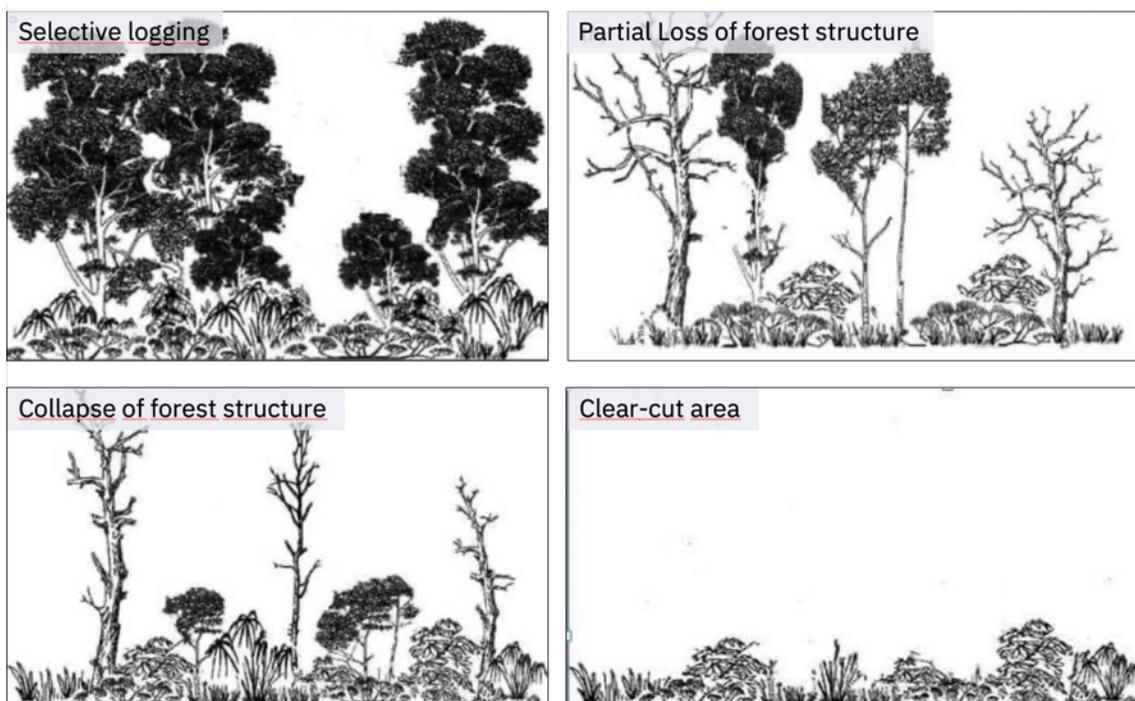


Figure 2.3 - Illustration of progressive degradation. Source: Barlow and Peres (2008).



Figure 2.4 - Photos of progressive degradation process. Source: INPE and MMA (2008).

3 PRODES - Materials and Methods

Since 1988, PRODES carries out the inventory of primary forest loss through the interpretation of satellite Earth observation images in the Brazilian Legal Amazonia (BLA). The objective of PRODES is to estimate the annual rate of deforestation by clear cuts of primary forest in BLA.

3.1 Coverage area

The Brazilian Legal Amazon is a political entity aimed at regional planning and development, created by Law 1,806 of 1/6/1953, subsequently amended by Law 5,173 of 10/27/1966 and Supplementary Law 31 of 10/11/1977. It occupies 59% of the Brazilian territory and encompasses eight states (Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima and Tocantins) and part of the State of Maranhão (west of the 44°W meridian), totaling close to 5.0 million km².

Within the Legal Amazon, PRODES maps the loss of primary forest cover in the areas under a forest vegetation domain. The forest types identified under this domain correspond to the following International Geosphere-Biosphere Program (IGBP) land classes: Evergreen Broadleaf Forest, Deciduous Broadleaf Forest, Mixed Forests, and Woody Savannas. In 1988, when PRODES was created, INPE mapped the areas that do not belong to this domain, defining precisely their location. This so-called non-forest area occupies about 960,000 km² and is not considered in the systematic mapping carried out by PRODES (see Figure 3.1).

3.3 Methodology

The PRODES methodology is based on the following assumptions:

- PRODES only identifies deforestation polygons by clear cut or by forest degradation that results in the complete removal of primary forest cover.
- PRODES maps deforestation using photointerpretation by specialists.
- Deforestation is assumed to occur mainly within the dry season, when the spectral characteristics of vegetation are ideal to detect deforestation and when cloud cover is reduced. Thus, the interpreted images are preferably obtained within the dry station.
- Given the large extent of the BLA, the dry season varies depending on the latitude. For each scene (Figure 3.2), the reference time interval for the dry season was established using climatological parameters.
- The potential images are characterized by a 20-30 meters spatial resolution, 5 to 16 days revisit rate and at least three spectral bands.
- PRODES only identifies deforestation polygons which area is greater than 6.25 ha.
- The type of satellite used (low and almost polar orbit) prevents from purchase all necessary images to cover the BLA in an only reference day / month every year.
- There may be unobservable areas due to cloud cover. INPE takes these areas into account when calculating the estimated increment for each image. In cases of high cloud coverage, images from multiple satellites and different dates can be used.
- Where cloud cover is high in a specific area, more than one image can compose a Landsat scene, by using different sensors and / or dates.
- PRODES uses incremental mapping. For each image, deforestation increments that occurred between the PRODES dates of the previous and current year are mapped.
- From the annual increments of each PRODES year, an annual rate is calculated. For example, the annual rate for PRODES 2020 year estimated the deforestation that occurred between 2019/08/01 and 2020/07/31. This interval is called the PRODES year or PRODES calendar year.
- Deforestation in non-observed areas because of cloud cover is estimated through the methodology detailed in 3.3.3 item and in the Annex I.
- To provide an annualized rate of deforestation in a scene, the increments are projected to a common reference date. Considering that the dry season for most images runs from June to September, the PRODES reference date for each year is August 1st (211st Julian day).

The operationalization of this methodology is described in the following steps.

3.3.1 Images selection step

The image selection starts on August of each PRODES year. For interpretation, the images should have a reduced cloud cover and their dates be preferably included in the dry season interval. The use of “Landsat class” images ensures that the results obtained will be compatible with the historical series produced by INPE since 1988. Currently, images from the Landsat-8, CBERS-4/4A and more recently SENTINEL-2 are used. The images are directly available from the Remote Sensing Data Center (CDSR) of the INPE in the following link <http://www.dgi.inpe.br/catalogo/>, or in the ESA open access hub.

The selected images are then enhanced in order to highlight the deforested areas. Figure 3.3 shows a location in a Landsat-8 image before and after applying a contrast operation.

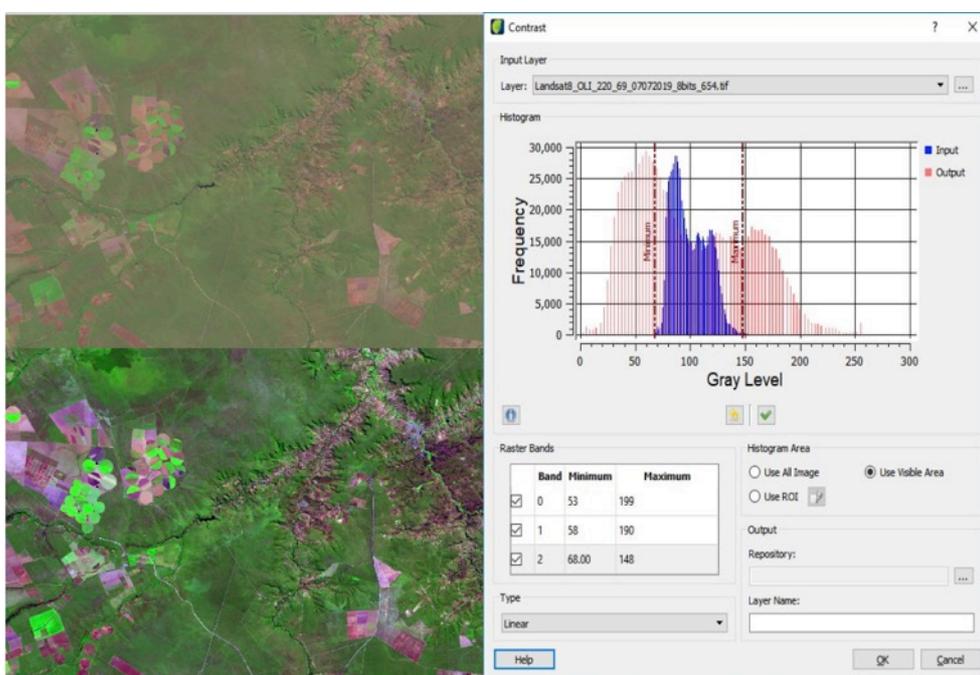


Figure 3.3 – Example of Landsat-8 image enhancement.

3.3.2 Mapping deforestation increments step

Deforestation mapping is done by visual interpretation. Trained specialists identify deforestation polygons on the computer screen. Experts look for a change in forest cover due to clear cut based on the main elements: tone, color, form, texture, and context, following the standardization bands shown in Figure 3.4.



Magenta / reddish or very light green (faded).
 Regular shape, smooth texture, well-defined boundaries between the polygon with exposed soil and the forest.

Figure 3.4 – PRODES image interpretation standards for clear-cut deforestation identification.

These elements are analyzed comparatively between images from different years for each Landsat scene of the BLA. Figure 3.5 shows the deforestation polygons mapped in the Boca do Acre (AM) region. The polygons are highlighted in yellow and superimposed on the images of 2017 and 2018. It is possible to identify changes between the two years and to map them in PRODES 2018 year. An auditing covering 100% of the number and area of Landsat scenes is conducted by specialists in order to avoid false positive deforestation polygons and to reduce omissions. In some critical scenes, where the deforestation is considered harder to detect or located in the deforestation hotspots, a reinforced auditing can be carried out to ensure a better map quality.



Image of 20-07-2017

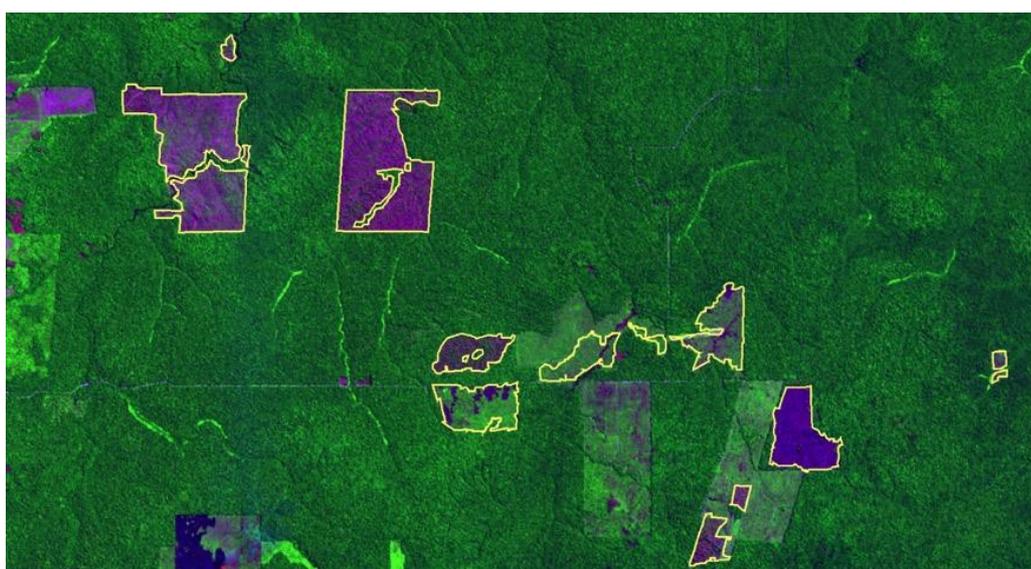


Image of 24-08-2018

Figure 3.5 - Landsat-8 sub-images, identified by path 001 and row 066, in region near the municipality of Boca do Acre / AM, in 2017 and 2018.

PRODES uses incremental mapping, so that for each PRODES year the system identifies the **new** deforestation increments. An exclusion mask covers areas deforested in previous years (Figure 3.6) to prevent the re-mapping of old deforestation by interpreters.

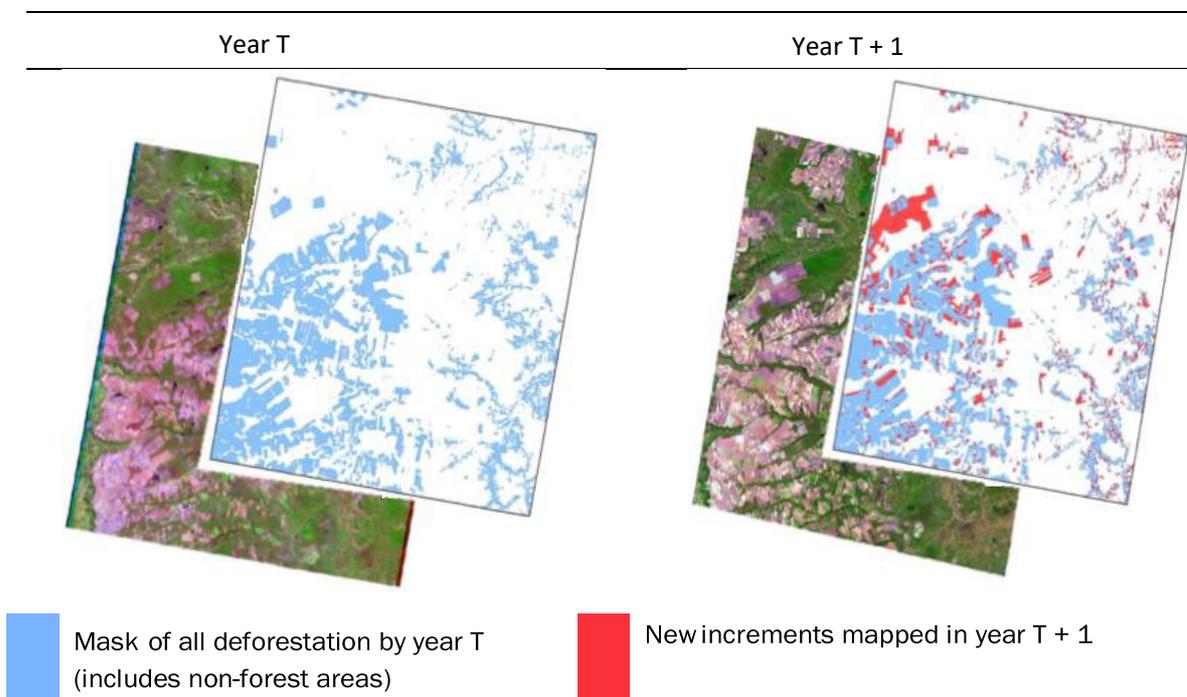


Figure 3.6 - Incremental approach of the PRODES methodology.

The mask also covers areas with no natural occurrence of forests, water, and wetland areas.

3.4 Calculating the annual deforestation rate

The annual rate estimates the deforestation that occurred within the PRODES year (1 August/31 July), considering that all the forest area in the BLA has been investigated. In some areas of the Amazon, it is impossible to get cloud-free images. Even using multiple satellites, there may be unobserved areas because of persistent cloud cover. These unobserved areas integrate the rate estimation assuming that the proportion of deforestation in these areas is the same as the forest area observed in that image (see Annex 1 for details).

A special case is when increments are observed in areas with cloud cover in previous years. Such increments are not entirely added to the deforestation of the year of detection but are negatively weighted by the number of unobserved years. This procedure prevents deforestation detected in a given year but may have happened in previous years from being fully credited to the current year (see Annex 1 for details). However, we should point out that the deforestation under clouds only reaches 5% of the PRODES annual rate, in average.

PRODES estimates the deforestation in a 365-day period, assuming that the forest removal process is linearly distributed along the dry season. Since the mapped images have different dates (Figure 3.5), it is necessary to convert increments to rates. This is done by applying a pro rata correction to calculate the estimated deforestation

between the reference dates of two successive years. The detailed procedure for calculating rates depends on the dates of acquisition of the image in the year under review and in the two previous years. Details of the cloud estimates and the harmonization for the reference data are described in Annex 1.

The annual rates are performed in two stages. The first is to carry out the estimated rate in priority scenes of BLA, still during the civil year of PRODES images. Priority scenes must respect three criteria: 1) to cover the region where at least 90% of previous year deforestation in PRODES have been identified; 2) to cover the region where at least 90% of DETER deforestation alerts area has been detected for the current PRODES year; and 3) to cover the priority municipalities for inspection and control established in the Decree 6,321/2007 and periodically actualized by the Environment Ministry (MMA). Based on the resulting maps of increments for priority scenes and using the PRODES methodology, the annual rates is estimated for the whole BLA and published between November and December. The second step aims to estimate the consolidated, and so final, annual rate of deforestation, based on the map of all Landsat scenes that cover BLA, during the next civil year.

The PRODES historical series since 1988 is presented in Figure 3.7. These data and the corresponding annual maps can be accessed in the TerraBrasilis platform, available at <http://terrabrasilis.dpi.inpe.br>.

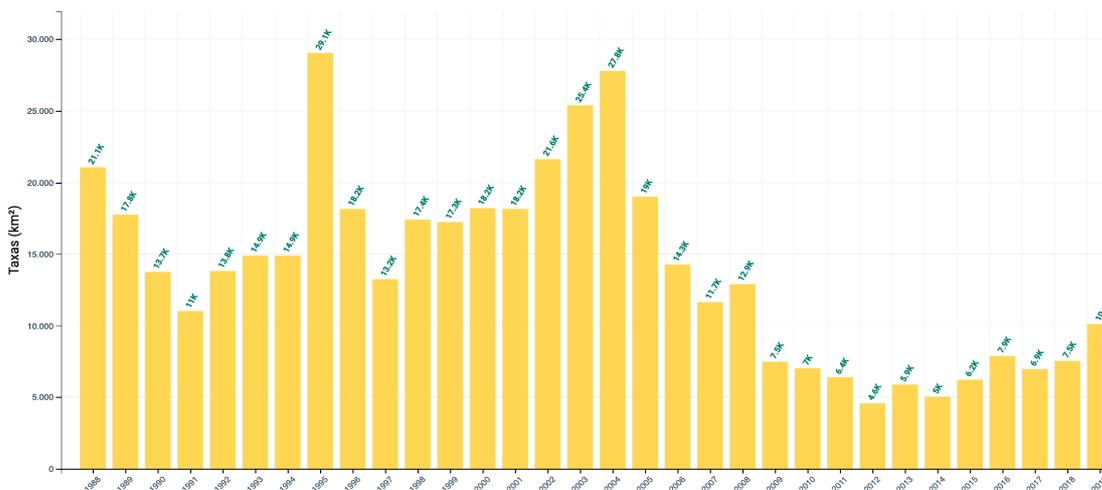


Figure 3.7 - PRODES historical series.

4 DETER - Materials and Methods

DETER, launched in 2004, is a system for inspecting and controlling deforestation and degradation support, that maps original forest anthropogenic changes in Brazilian Legal Amazonia (BLA). DETER produces daily alerts on changes in forest cover for areas larger than or equal to 3 hectares. The alerts indicate areas that have been fully deforested (clear cut, mining and deforestation with vegetation) and those undergoing forest degradation (logging, burning, and others). These alerts are available through a geo-services architecture on the web for all environment agencies, for example the National Institute of Environment and Natural Resources (IBAMA) and the State Secretaries of Environment, in order to support their inspection and control operations. All the data are

also available and public in the TerraBrasilis portal.

4.1 Images used

Until 2015, DETER used images from two sensors: (a) MODIS sensor onboard the Terra satellites; (b) WFI, onboard the Sino Brazilian satellite CBERS-2B. Both images have a spatial resolution of 250 meters, generating alerts with a minimum mapping unit of 25 hectares, without any discrimination between forest degradation and removal. In 2015, DETER improved its methodology (Diniz, et al., 2018) by using images from the WFI sensor onboard the CBERS-4/4A satellite. These images have a spatial resolution of 64 meters, which allowed to differentiate deforestation and degradation classes and to reduce the minimum mapping unit to 3 hectares.

WFI images have a field of view of 866 km, allowing that the same region to be imaged every three days, considering the combination of CBERS-4 and CBERS-4A images. Every day at least one strip of the Amazon is covered, allowing the continuous monitoring of its vegetation. With the launch of INPE's Amazonia-1 planned for February 2021, which also carries the WFI sensor, the revisit rate will drop to 2 days.

When using DETER, one has to distinguish between *time of occurrence* and *time of detection*. A forest can be deforested step by step, but its detection as clear cut or degraded area occurs only when the conditions for satellite observation are favorable. In DETER, all deforestation identified in an image, and not detected previously, is considered to be a new deforestation regardless of the actual date of occurrence of the event, that is not known.

CBERS-4/4A images are respectively available at <http://www.dgi.inpe.br/catalogo/> and <http://www2.dgi.inpe.br/catalogo/explore>. The DETER team consults the CDSR catalog every day in order to identify the new images that have been acquired over the Amazon and that reach the spectral conditions to be used, attempting to maximize the observed area.

Figure 4.1 shows an example of a quick look of a CBERS-4 / WFI scene, identified by the path/row 162/105, obtained on July 12, 2019. Despite some cloud cover, there is a large part of the cloud-free image that can be used in mapping.



Figure 4.1 - Example of AWFI / CBERS-4 image selected to be analyzed in DETER.

The CBERS-4 / AWFI sensor captures images in four spectral bands, three in the visible region of the electromagnetic spectrum (blue, green, and red) and one band in the near-infrared region suitable for mapping changes in vegetation coverage. DETER uses a color composition that associates the bands red (630-690 nm), near-infrared (770-890 nm), and green (520-590 nm) to the red, green and blue colors, respectively.

DETER uses a Linear Spectral Mixing Model (LSM) to generate soil and shadow fractions used for photointerpretation. These fractions highlight, respectively, features related to selective logging and burning. LSM is a technique for estimating soil, vegetation, and shadow fractions in an image. LSM estimates the soil, vegetation, and water/shadow components within each pixel using pure pixels' spectral signatures for these components (Shimabukuro & Smith 1991). These fractions support the interpreters to identify deforestation and degradation,

4.2 Methodology

At the beginning of each DETER monitoring cycle, the PRODES deforestation maps of the previous year, non-forest areas, and hydrography are used as an exclusion mask, where new alerts cannot be mapped. This mask prevents areas already deforested from being unduly mapped.

Photo interpreters map deforestation and degradation using the soil fraction image. Interpreters also use CBERS AWFI images with the color composition 5 (R), 4 (G) and 3 (B), shadow and vegetation fractions, as well as multitemporal series of Landsat, Sentinel, and CBERS complementary images. The forest cover pattern identification is based on the main elements: tonality, color, form, texture and context.

The alerts indicated by DETER are divided into two groups. The first refers to deforestation classified as either: (a) deforestation with exposed soil; (b) deforestation with vegetation; and (c) mining (Figure 4.2). In the second group are degradation alerts, classified as either: (a) degradation; (b) selective geometric cut; (c) selective cut; and (d) forest fire scar (Figure 4.3).

The polygons are digitized on the computer screen, over the color composites of the WFI images, overlaid by the mask of previously deforested areas, on a scale of 1:100,000. This allows detecting the alerts with areas bigger than 3 hectares. Figure 4.4 shows, as an example, an alert mapped by DETER in 2019.

With this methodology, the system can differentiate between natural and anthropogenic disorders since the former mainly presents irregular and non-linear forms, while the latter presents geometric and linear forms.

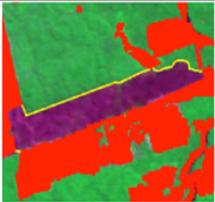
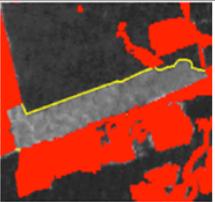
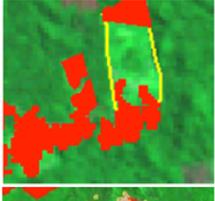
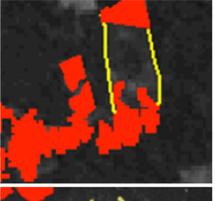
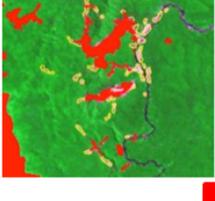
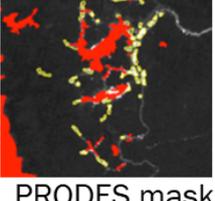
WFI / CBERS-4	Soil Fraction	Alert Type
		Clear-cut deforestation
		Deforestation with vegetation
		Mining
 PRODES mask		

Figure 4.2 - Examples of Deforestation alerts.

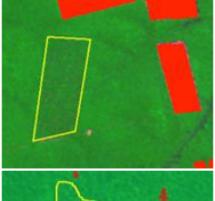
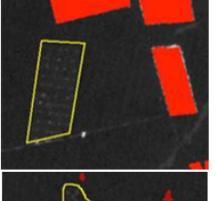
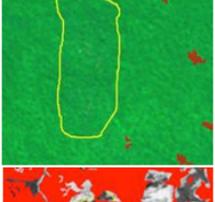
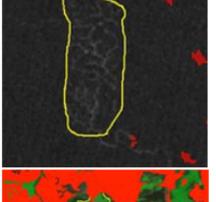
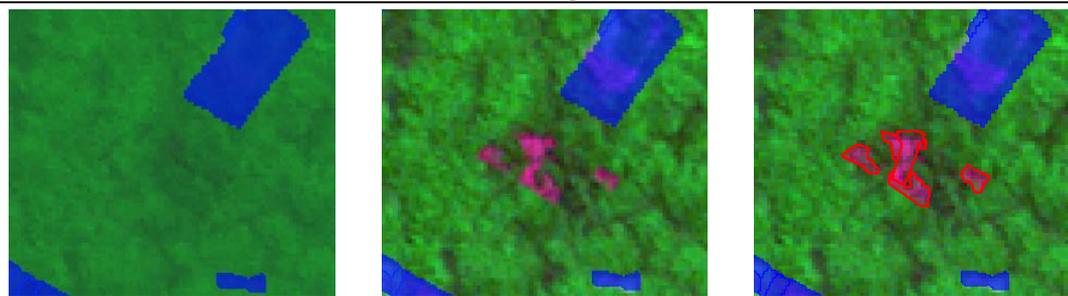
WFI / CBERS-4	Soil Fraction	Alert Type
		Degradation
		Selective Geometric Cut
		Disorderly Selective Cutting
		Fire scar
 PRODES mask		

Figure 4.3 - Examples of Degradation alerts.

Location: -5.59428 South, -51.70507 - Image WFI / CBERS-4, Scene 166/105



Picture on 06/30/019

Picture on 07/26/2019

Alert Mapped on 07/26/2019

Figure 4.4 – Example of a DETER alert (PRODES mask in blue)

Once detected, the polygon is incorporated into the alert exclusion mask, which is updated daily. Polygons identified as deforestation will remain unchanged in their shape and class until the end of the DETER period's observation cycle. Polygons mapped as degradation can be partially or entirely reclassified to one of the deforestation classes. An area initially identified as degradation can be reclassified in the future as deforestation. This possibility makes monitoring more effective for inspection actions. Changes that are subject to inspection are identified and classified since the beginning of the original forest cover intervention.

The alert polygons are inserted into a database. These alerts can be consulted individually by date (or intervals between two dates) or by area of interest (e.g., municipalities). The database also allows queries by type of deforestation or forest degradation.

The number of alerts mapped daily varies according to the availability of viable images to be analyzed. The time between the image availability, the alerts mapping, their audit, and ingestion in the database sums between 48 and 72 hours, except specific variations in the working schedule of the team.

DETER captures only part of the changes due to the lower resolution of the sensors used and cloud cover restrictions. For this reason, it is important to distinguish between the occurrence and detection dates, which interval depends on the cloud regime.

Since availability of reduced cloud cover images varies from one month to the next, comparison between DETER data from different months and years is strongly discouraged. Comparisons, when necessary, must be realized with due care, considering at least a three month period and comparing the same interval between different years.

5 The TerraAmazon software

INPE's interpreters perform the entire process of analyzing satellite images using TerraAmazon, software (Figure 5.1) in PRODES and DETER project. This application, developed by INPE, offers image processing and vector data algorithms, vector editing tools with topological consistency and management of geographic data. It can manage from different sensors or for different purposes.

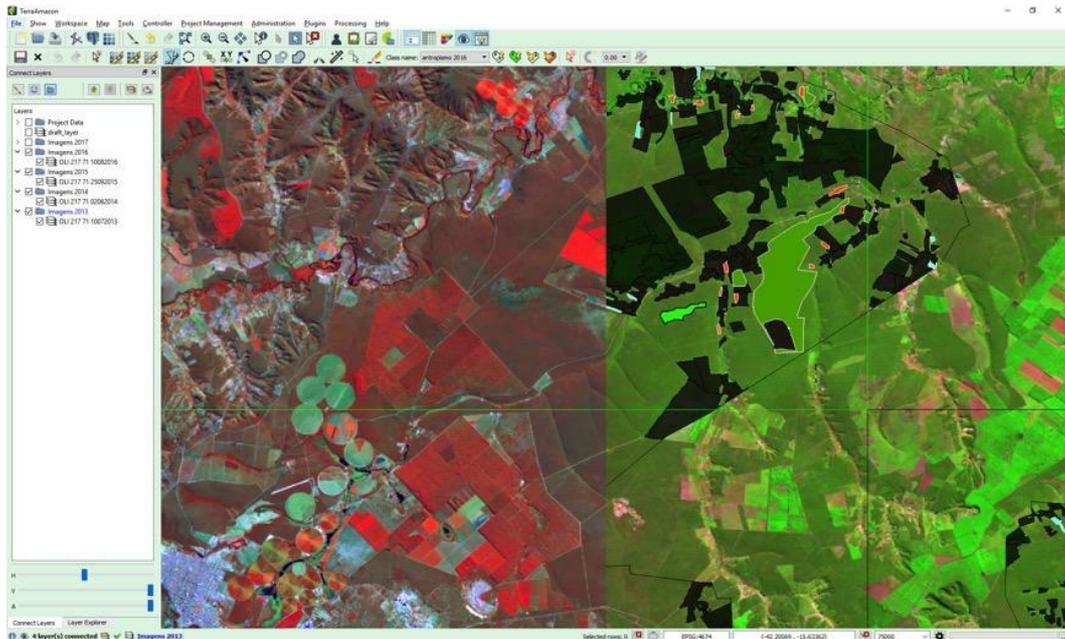


Figure 5.1 TerraAmazon screen.

The algorithms implemented in TerraAmazon are robust and capable of processing a large volume of raster and vector data. There is no need for other applications, which streamlines the process, equalizes procedures and optimizes work.

Using TerraAmazon, INPE maintains a corporate geographic database containing the processed images and the resulting vector data (polygons) of the mappings carried out on the two systems. During the execution of the monitoring, two instances of the database are maintained, one of internal production to the INPE network and another optimized for the dissemination of the resulting data on the internet, ensuring information security, redundancy, and fault tolerance. Automated routines perform database maintenance and synchronization processes.

6 Data availability

On the date of public disclosure, the reference year's deforestation rate is included in the PRODES historical series. The mapped increments are also available in the form of maps that show your location on the ground, in digital format, on the portal <http://terrabrasilis.dpi.inpe.br>, both for the estimated and consolidated rates

DETER alerts are made available on the internet as they are produced for the environmental agencies for inspection and controls, and with a user / login control; that is, daily, the database is fed with mapped and audited alerts. Access to this database also takes place through the TerraBrasiliis portal, with a weekly actualization delay for the produced alerts, every Friday morning.

Monthly consolidations of alerts are made at the end of the month and published on the TerraBrasiliis portal in the aggregated alerts tab. **Due to the variable cloud cover from one month to the next and the spatial resolution (minimum size of the area imaged by the sensor) of the images used, INPE strongly discourages the comparison between the alert area measured in different months.**

INPE emphasizes that DETER is an expeditious alert system developed methodologically to support inspection. Information on areas is so that the entities responsible for inspection can identify priority areas for inspection and should not be understood as a monthly deforestation rate. The official INPE number to measure the annual rate of clear-cut deforestation in the Brazilian Legal Amazon has been provided, since 1988, by the PRODES project that works with images with better spatial resolution.

7 TerraBrasilis

To improve data dissemination of the Monitoring Program for the Amazon and Other Biomes, INPE has developed an internet portal that aggregates PRODES and DETER data at the website <http://terra-brasilis.dpi.inpe.br>. TerraBrasilis provides services and data.

Users can visualize data in two ways. The map view shows the spatial location of the alerts (Figure 7.1). The analysis view presents graphics with numbers, area, and type of alerts. Users can aggregate data by geographical areas such as municipalities, states, or conservation areas (Figure 7.2). When accessing data, users can download spatial data from PRODES and DETER in shapefile format, which is the standard format for exchanging vector files of geographic data.

TerraBrasilis also offers an access interface via web services, allowing other applications to access PRODES and DETER data through programming interfaces, from computer to computer. This allows data from INPE's monitoring projects to be integrated into the National Spatial Data Infrastructure (INDE), under Decree No. 6,666, of November 27, 2008.

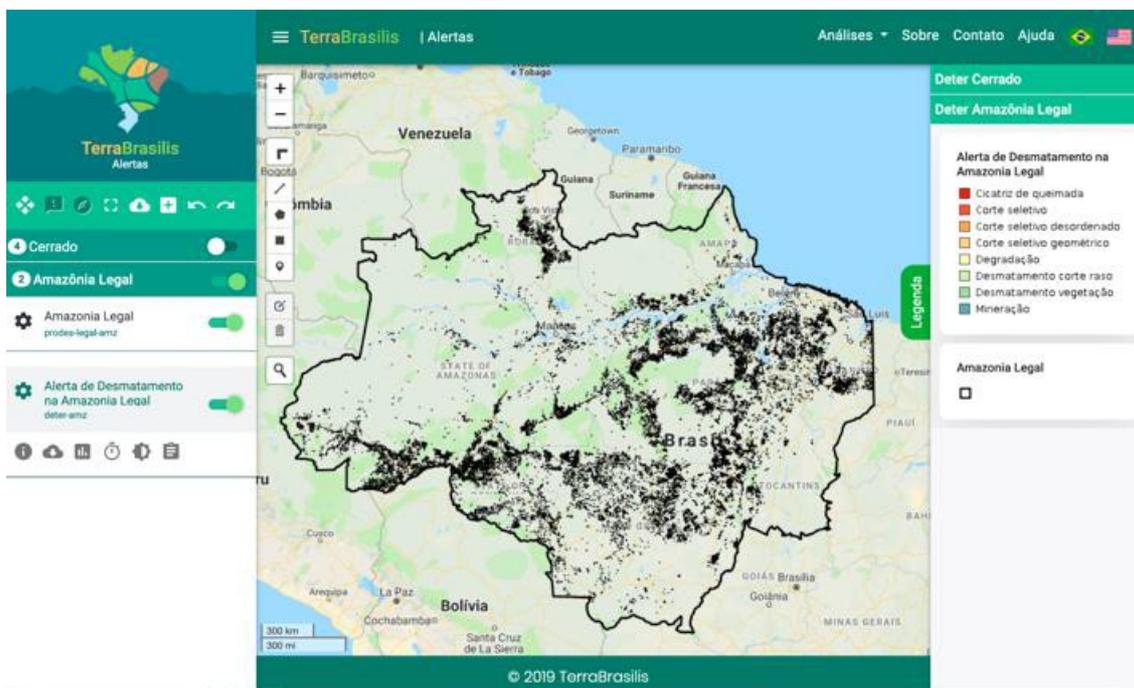


Figure 7.1 - Access panel to alerts produced by DETER since 2016.

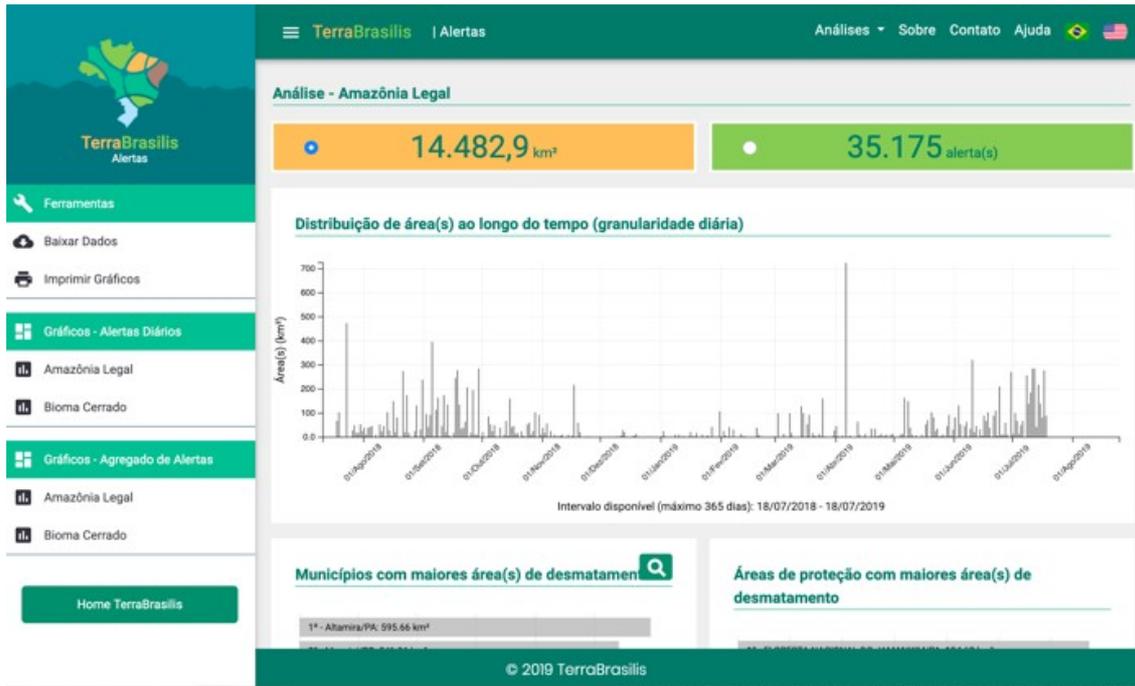


Figure 7.2 - Access panel to graphs and queries about DETER data.



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ANNEX I

Method for calculating the PRODES annual rate of deforestation

Input data

After mapping the increments of deforestation for the reference year, in addition to the polygons that delimit the increments, a table is also generated with aggregated information about each processed image. Table 1 shows an extract from this table, considering that the mappings were made for the year 2004. This example will be used to explain how the deforestation rate calculations are made.

Table 1 - Result of the mapping of the deforestation increments in some images.

pathrow	state	codigo	julnday	fstarea	dfsarea	increm	fstclds	dfcld_01	dfcld_02	---	dfcld_07	dfcld_out
22466	PA	1	223	12215	11969	830	559	19	0	...	0	29
22765	PA	1	197	5778	378	82	9	0	0	...	0	5
22765	PA	2	197	17990	2226	546	80	0	0	...	0	25
22768	MT	1	213	13397	8472	897	201	0	0	...	0	83
22769	MT	1	228	11465	7660	893	0	0	0	...	0	85
22867	MT	1	204	14115	5482	673	0	0	0	...	0	5
22867	MT	2	204	4045	1070	177	0	0	0	...	0	0
22967	MT	1	211	19977	5753	669	0	0	0	...	0	27
22969	MT	1	211	7205	1572	103	0	0	0	...	0	60
22969	RO	1	211	1876	1615	51	0	0	0	...	0	23
23267	RO	1	215	15130	8537	866	295	1	0	...	0	443

The meaning of each column in Table 1 is:

- *pathrow*: point-orbit of each image;
- *state*: federation state covered;
- *cod*: identifies the cloudless cutout (or as little as possible) of one of the images used to process the entire scene. The union of the clippings makes up the whole image;
- *julnday*: Julian day of the observed image;
- *fstarea*: forest area remaining in the image;
- *dfsarea*: area deforested in the image seen previously; *Increm*: increase in deforestation seen in the image;
- *fstclds*: forest area covered by clouds in the Ft image;
- *dfcld_01*: deforested area, covered by clouds in the previous year;
- *dfcld_02*, *dfcld_03*, *dfcld_04*, *dfcld_05*, *dfcld_06*, *dfcld_07*: deforested area, covered by clouds in the (two, three, four, five, six and seven) years prior to the observation date.

- *dfcld_out*: deforestation area registered in 2004, but already existing in 2003 or in previous years. This data is not considered in the annual estimate because it is not considered data for the current year. Despite not being included in the calculation of the annual estimate, the deforested area is incorporated into the shape files representing the deforestation accumulated so far (called the PRODES mask).

8 Estimating deforested area under clouds

After processing each image, the estimated area deforested under clouds is estimated. This estimate assumes that the proportion of deforestation in the unobserved area is the same as that of the forest area observed in the image. The procedure is illustrated in Figure 1.

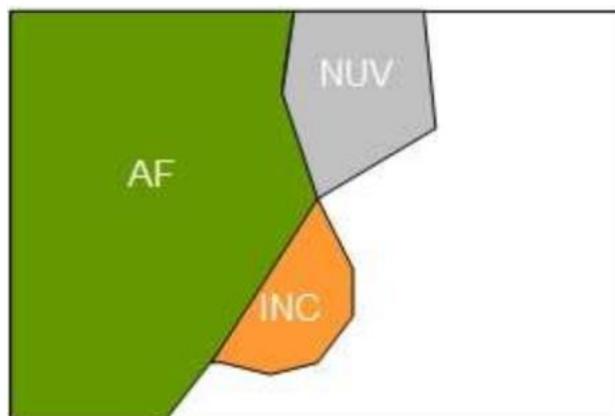


Figure A.1 - Illustration of the procedure for estimating deforestation in an unobserved area.

In Figure 1, AF is the remaining forest area, INC the increment seen in the image, and NUV the unobserved area, the estimated increment under clouds (*inc_nuv*) is calculated as the proportion of observed deforestation multiplied by the cloud area. The total increment (*inc_tot*), used in the calculation of the deforestation rate, it is considered as the sum of the observed increment with the estimated increment under the cloud, plus the deforestation observed on the occurrence of clouds for one or more previous years.

$$inc_nuv = NUV * (INC / (AF + INC))$$

$$inc_tot = INC + inc_nuv + previous_dsf$$

$$previous_dsf = (dfcld_01 / 2 + dfcld_02 / 3 + dfcld_03 / 4 + \dots + dfcld_07 / 8)$$

The contribution of the previous years (*previous_dsf*) is calculated according to the number of years that the area was covered by clouds, plus the current year. Thus, if an area was covered by clouds for 2 years and in the current year it was possible to observe deforestation (*dfcld_02*), the observed value is divided over 3 years, with no burden on the current year. For *dfcld_01* it is considered 2 years, *dfcld_02* is considered 3 years and so on up to a maximum of 7 years of cloud cover. As an example, in 2004 the data in the orbit point 224/66 had 12,215 km² of remaining

forest area, an increment of 830 km², an area under clouds of 559 km² and an area of deforestation over clouds for the past year (*dfcld_01*) of 19km². The estimated total increment was 875 km².

When the best selected image has many clouds, the part without coverage is processed and images from other satellites from nearby dates are used to interpret the part covered by clouds. Calculations of *inc_nuv* are made for each part used to compose the final processed image. When this happens, previous years they are also cut with the same cut used to process that image so as not to affect the calculation of the estimates.

Determination of the dry season

To calculate the deforestation rate, the first step is to establish the dry season associated with the image. Figure 2 shows the different climatologically defined dry seasons for the Amazon, with the respective start and end days. Note that the vast majority of images are associated with a dry season that begins on Julian Day 151 (May 31) until Julian Day 242 (August 29). These images correspond to the region of Mato Grosso, Rondônia and South of Pará.

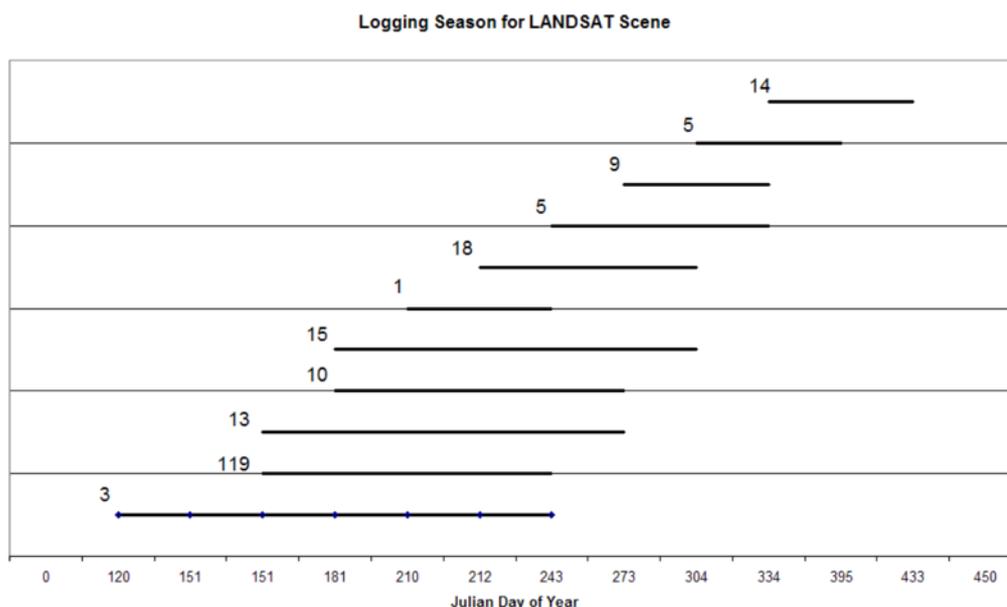


Figure 2 - Dry season in the Amazon and number of associated LANDSAT images.

9 Proportional estimate for reference date

The next step is to make the time compensation for all increments, for the same reference date. Considering the large number of images whose dry season is between the months of June and September (see Figure 2), the date of August 1 (Julian Day 211) was taken as the reference date for calculating annualized rates. The detailed procedure for calculating the fee will depend on the dates of acquisition of the image in the year under review and in the two previous years. To illustrate the procedure, we took the example in which the two acquisition dates of the images are within the dry season (see Figure 3). The remaining cases are calculated in a similar way.

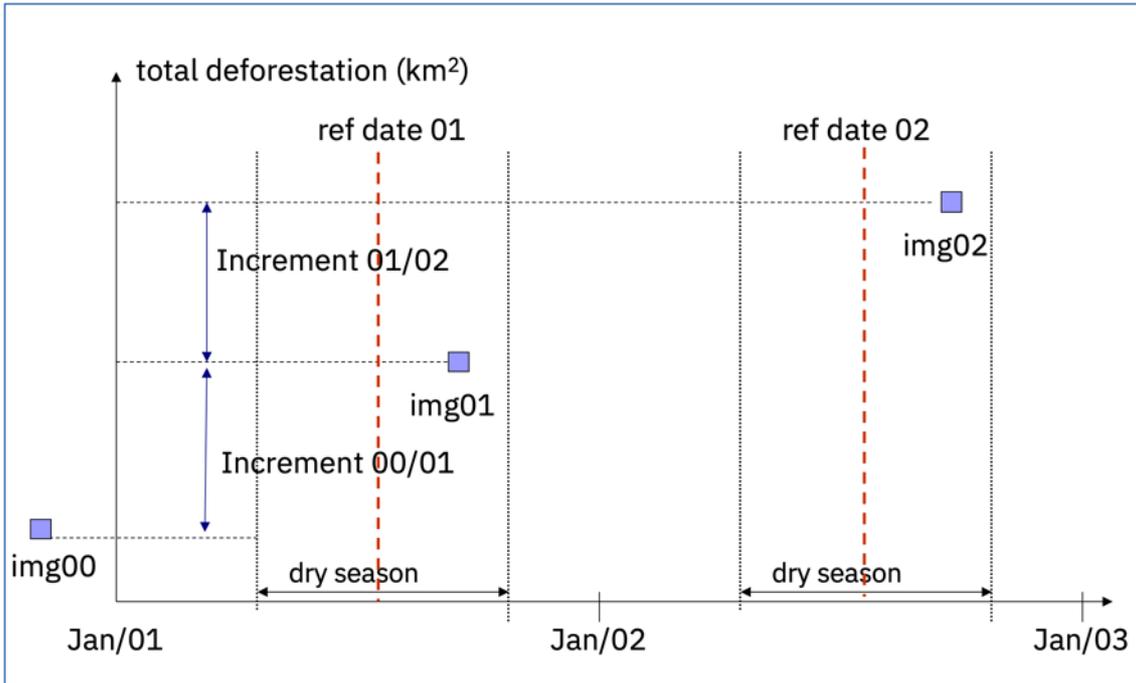


Figure 3 - Calculation of the annual deforestation rate - step 1: location of the images in relation the dry season (*ref* is the reference date).

Figure 3 shows the need for distinguishing between increments and annual rates. An increment is the difference in deforestation measured between two images. Figure 3 shows the increments between two consecutive years. In the example, we have the increments between 2000 and 2001 and between 2001 and 2002. However, the images used for mapping the increments in 2000, 2001 and 2002 may have arbitrary time differences, that can be bigger or smaller than 365 days. They do not coincide with the reference date for both years (taken to be 1 August). Furthermore, we assume that deforestation only takes place during the dry season. The problem of estimating rates can be described as follows:

“Given three images from consecutive years with different acquisition dates, and the deforestation increments measured between them, what is the the annual deforestation rate between the reference dates, considering that deforestation only takes place during the dry season?”

The key to answer this question is to calculate the estimated daily deforestation rate during the dry season. As shown in Figure 4, two rates need to be estimated:

- (a) dr_0 – daily deforestation rate during the dry season in year 2001 between the start of the dry season and the date of acquisition of the image in 2001 and the reference date.
- (b) dr_1 – daily deforestation rate during the dry season in year 2002 between the start of the dry season and the date of acquisition of the image in 2002 and the reference date.

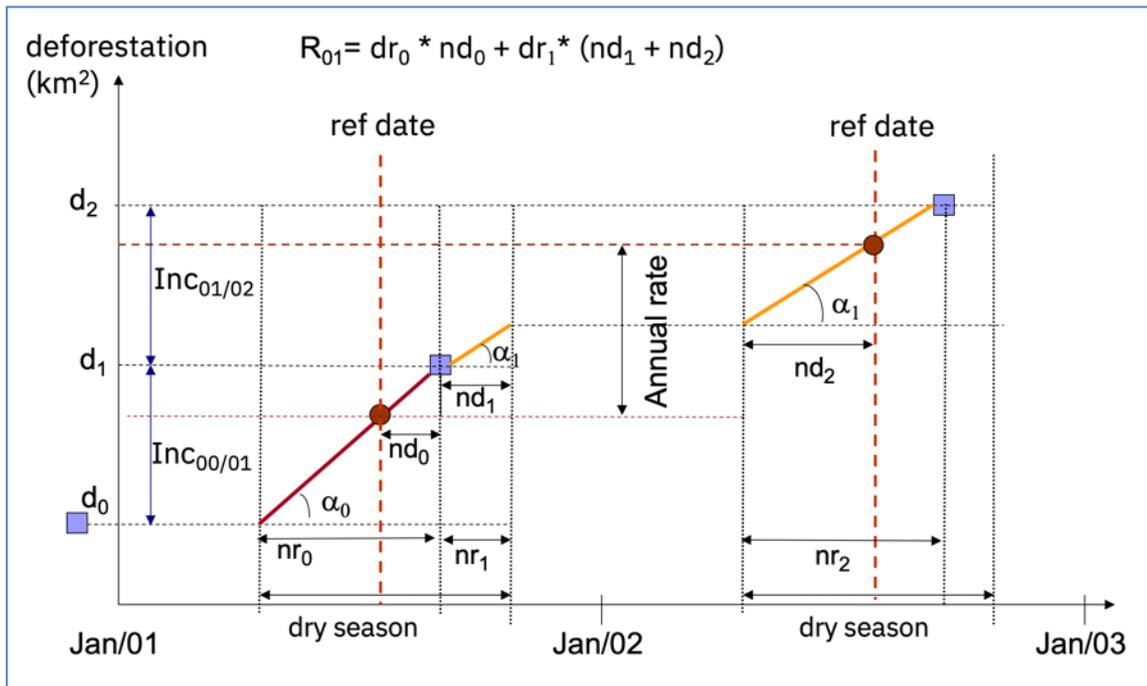


Figure 4 - Calculation of the daily rates of deforestation (dr_0 and dr_1) and Annual Rate

The daily deforestation rates are calculated considering how many days of dry season have elapsed between each image and the previous one. Therefore,

$$dr_0 = Inc_{00/01}/nr_0$$

$$dr_1 = Inc_{01/02}/(nr_1 + nr_2)$$

where:

- $Inc_{00/01}$ – total increment in deforestation measured in the 2001 image, relative to year 2000.
- $Inc_{01/02}$ – total increment in deforestation measured in the 2002 image, relative to year 2001.
- nr_1 - number of days in dry season in 2001, elapsed between the 2001 image and the end of the dry season in 2001.
- nr_2 - number of days in dry season in 2002, elapsed between the 2002 image and the start of the dry season in 2001.

After calculating the estimated daily deforestation rate during the dry seasons of 2002 and 2001, we can now estimate the annual deforestation rate between 2001 and 2002 as:

$$r_{01/02} = dr_0 * nd_0 + dr_1 * (nd_1 + nd_2)$$

where:

- nd_0 - number of days in dry season elapsed between the 2001 image and the 2001 reference date.

- nd₁ - number of days in dry season elapsed between the 2001 image and the end of the 2001 dry season.
- nd₂ - number of days in dry season elapsed between the 2002 image and the start of the 2002 dry season.

Table 2 - Input data - scene 22466

	pathrow	state	cod	julnday	fstarea	dfsarea	increm	fstclds	dfcld_01	dfcld_02	...	dfcld_07	dfcld_out
2004	22466	PA	1	223	12215.29	11969.00	829.87	558.74	18.53	0	...	0	28.53
2003	22466	PA	1	236	13661.41	11153.48	776.79	84.65	36.78	0	...	0	0
2002	22466	PA	1	209	13923.80	10402.36	751.13	635.83	0.00	0	...	0	0

Table 3 - Estimation of Deforestation Rates - scene 22466

	PathRow	Sta	ScId	Jul2	Jul1	Jul0	StClim	EndClim	Rate	Increm	CorrInc	...
2004	22466	PA	1	223	236	209	151	242	916.75	829.87	874.68	...
2003	22466	PA	1	236	209	214	151	242	619.79	776.79	799.73	...
2002	22466	PA	1	209	214	164	151	242	831.66	751.13	783.67	...
...	InclstYear	CorrLstYear	PercRate	PercClds	DRate2	nd2r	nd1r	DRate1	nd1			
...	776.79	799.73	5	5	10.93	61	7	6.66	26			
...	751.13	783.67	-23	3	6.66	61	32	8.91	0			
...	1078.83	1078.83	6	4	8.91	61	29	7.54	4			

Tables 2 and 3 show an example of rate estimation. Note that the first step is to correct the increase in the 2004 image to take into account the area covered by clouds. The total estimated increase in agreement was 874.87 km². With these data, the parameters of the previous equation can be calculated, shown in Table 3. As it turns out, the estimated rate for 2004 is 916.75 km². This rate is higher than the observed increase (829 km²) because the annual estimate takes into account the increment corrected according to the clouds in the image. The data presented in Table 3 are described as:

- *Pathrow* - point-orbit of each image;
- *Sta* - federation state covered;
- *Cod* - identifies the cutout with as few clouds as possible from one of the images used to process the entire scene. The union of the clippings makes up the whole image;
- *Jul2* - Julian day of the observed image (current year - 2004)
- *Jul1* - Julian day of the previous year's image (ex. 2003)
- *Jul0* - Julian day of the previous year's image (eg 2002)
- *StClim*- Beginning of the dry season for the scene
- *EndClim* - End of dry season for the scene
- *Rate* - annual rate estimated by the formula presented above (annual)
- *Increm* - increase in deforestation seen in the image



- *CorrIncr* - increment corrected for clouds
- *InclStYear* - increase seen in the previous year
- *CorrLstYear* - increment corrected in the previous year
- *PerRate* - indicates the percentage difference between *Rate* and *CorrIncr*
- *PerClds* - indicates the percentage difference between *Increm* and *CorrIncr*
- *DRate2* - daily rate for the current year
- *nd2r* - number of dry season days between the beginning of the dry season and the reference date of the current year
- *nd1r* - number of dry season days between the reference date and the previous year's image
- *nd1* - number of dry season days between the previous year's image and the end of the dry season
- *Drate1* - previous year's daily rate
- *ndnxtY*: number of days between the reference date and the date of passing the image. This interval will be computed only when calculating the rate for the following year. Note that the increment may be greater than the estimated rate, because the rate is projected for the reference date.

The above rules need also to consider the possible effects of areas with a lot of cloud cover. To minimize the possible effect of clouds on the total annual estimate, we use two additional rules, described below. In the case of images that meet the criteria set in rules 1 and 2, we use the measured increment instead of the estimated rate.

Rule 1: selects images with big difference between *increm* and *CorrIncr* corrected by the effect of clouds in the current year or in the previous year.

$(perClds1 > 100\% \text{ and } incr1 > 50km^2)$ for the current year

or

$(perClds0 > 100\% \text{ and } incr0 > 50 km^2)$ for the last year

Rule 2: Rule 2 is applied after rule 1 and selects images with a large difference between the rate calculated in the year (without the previous year's portion *Drate1* * *ndr1*) and the corrected increment.

$100 * [(RATE - Drate1 * ndr1) - CorrIncr] / CorrIncr > 50\%$

The cutoff parameters used are 100% for clouds and 50% for rate.

Projected annual rate

The projected annual rate is an intermediate result that estimates the value of deforestation based on a significant set of images. This value is calculated based on the rates of pairs of images in two consecutive years, and the data actually processed in the previous year.



Table 4 - Projection of Annual rates

	#IMGS Pairs	RATE-Pairs Km2	#IMGS good	RATE -good (Km2)	#IMGS regra 1 e 2	INCR-regra 1 e 2 (Km2)	Sum (Km2) RATE+INCR	#IMGS Total	ProjRATE Total-Km2
2005	94	17174							18831
2004	94	24279	164	24849	52	1773	26622	216	26622

Analyzing the table for the pair 2004-2005, we have that for the same 94 images, the estimated rate for 2004 is 24,279 km² and for 2005 it is 17,174 km². Of the total (216) of images processed in 2004, the estimates for 52 images were discarded by rules 1 and 2 described above. For these 52 images, the observed increment was used instead of the estimated rates (1,773 km²). Thus, the projected rate in 2005 for the 216 images is 18,831 km² ($17,174 * 26,622 / 24,279$). The same rule is used to calculate the projected rates per state.