

Article

Monitoring Forest Dynamics in the Andean Amazon: The Applicability of Breakpoint Detection Methods Using Landsat Time-Series and Genetic Algorithms

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Abstract: The Andean Amazon is an endangered biodiversity hot spot but its forest dynamics are less studied than those of the Amazon lowland and forests from middle or high latitudes. This is because its landscape variability, complex topography and cloudy conditions constitute a challenging environment for any remote-sensing assessment. Breakpoint detection with Landsat time-series data is an established robust approach for monitoring forest dynamics around the globe but has not been properly evaluated for implementation in the Andean Amazon. We analyzed breakpoint detection-generated forest dynamics in order to determine its limitations when applied to three different study areas located along an altitude gradient in the Andean Amazon in Ecuador. Using all available Landsat imagery for the period 1997–2016, we evaluated different pre-processing approaches, noise reduction techniques, and breakpoint detection algorithms. These procedures were integrated into a complex function called the processing chain generator. Calibration was not straightforward since it required us to define values for 24 parameters. To solve this problem, we implemented a novel approach using genetic algorithms. We calibrated the processing chain generator by applying a stratified training sampling and a reference dataset based on high resolution imagery. After the best calibration solution was found and the processing chain generator executed, we assessed accuracy and found that data gaps, inaccurate co-registration, radiometric variability in sensor calibration, unmasked cloud, and shadows can drastically affect the results, compromising the application of breakpoint detection in mountainous areas of the Andean Amazon. Moreover, since breakpoint detection analysis of landscape variability in the Andean Amazon requires a unique calibration of algorithms, the time required to optimize analysis could complicate its proper implementation and undermine its application for large-scale projects. In exceptional cases when data quality and quantity were adequate, we recommend the pre-processing approaches, noise reduction algorithms and breakpoint detection algorithms procedures that can enhance results. Finally, we include recommendations for achieving a faster and more accurate calibration of complex functions applied to remote sensing using genetic algorithms.

Keywords: forest dynamics; Landsat time-series; genetic algorithms; breakpoint detection

1. Introduction

Since an open data policy was adopted by the Landsat program, an increasing number of data-driven algorithms for monitoring forest dynamics using Landsat time-series (LTS) have been developed [1]. They highlight abrupt events (e.g., clear-cutting, crown fires) or slower processes (e.g., degradation, succession dynamics) that, within a longer time span, cause deviations or illustrate longer-duration changes from a presumably stable condition [2]. Typically, these algorithms are called breakpoint detection algorithms (BDA), and according to Banskota et al. [3], they can be classified according to their methodological basis and scope. This research establishes breakpoint detection as a useful implementation of LTS analysis; however, conditions in the Andean Amazon—high topographic relief, cloud cover that prevents the production of more than a few clear observations throughout the year, and landscape variability—complicate this type of analysis.

Furthermore, pre-processing approaches and noise-reduction algorithms for Landsat have evolved in recent decades [4], making for significant variation in preparing the data it generates to enhance breakpoint detection [5–7]. For this reason, the interpreter's experience plays an important role in selecting, calibrating, and applying an algorithm. Inappropriate selection or calibration can introduce systematic errors that can be difficult to detect. This problem is particularly overwhelming, with a large number of complex algorithms interlinked. Breakpoint detection requires a dense time-series of Landsat images that are radiometrically homogeneous, free of cloud and shadow, and geometrically corrected. Achieving these levels of processing is challenging since parametrization of these algorithms is not an easy task, and computer-processing LTS data is highly demanding.

For these reasons, it has become necessary to optimize the complex processing chains that combine pre-processing, noise reduction, and BDA procedures. There is little research in this field. Nonetheless, optimization has been shown to be successful in remote sensing. Examples vary according to the field and the search algorithm applied [8–10]. Genetic algorithms (GAs) have a long history of refinement since it became popular through the work of Holland [11]; extensive research has reported it as a robust and efficient optimization algorithm with a wide range of application in areas such as engineering, numerical optimization, robotics, classification, pattern recognition, and product design, among others [12,13]. Therefore, we chose a GA as our methodological approach to designing a processing chain based in BDA and to evaluate if this procedure might be a feasible approach for monitoring forest dynamics in the Andean Amazon. Since this is our first step before exploring other complex optimization procedures that, according to Eberhart et al. [14], should be emphasized in the new hybrid implementations, we avoid extending our discussion in search of new algorithms. Such discussion is beyond the scope of this paper. We therefore recommend that interested readers review the references mentioned throughout this paper.

Our particular research objective focuses on conducting a GA optimization of different processing chains using different BDA in order to determine if it is possible to monitor the forest dynamics in the Andean Amazon. If the methodology is applicable, patterns of forest gain and forest loss should be evidenced during a period of time along a typical part of the Andean Amazon. Furthermore, since there are multiple methods of enhancing time-series quality, we also analyze different pre-processing approaches and noise reduction algorithms for improving breakpoint detection. In order to do this, we develop a function called a processing chain generator (PCG) to link these approaches as processing chains and evaluate if their results highlight patterns of forest dynamics. Since calibrating the PCG is not straightforward, due to the number of parameters involved in algorithms calibration (24 parameters with a total of 5.7491×10^{20} possible combinations), GA was used as the basis for exploring and designing an optimal calibration for the PCG. For this reason, our research also constitutes a novel approach for solving the calibration of complex models in remote sensing by reducing uncertainties through parametrization. This method is different from other optimization approaches in remote sensing, where the principal application is classification and pattern recognition [8–10]; however, it is closer to the approach of Reference [15] for calibrating a model of cellular automata.

As this research considers landscape variability an important factor in monitoring the Andean Amazon, different study areas located in Ecuador were selected. They are characterized by frequent cloud cover, high topographic relief, and different forest management practices along a gradient of altitude. We found that these conditions mean the application of any remote sensing-based methodology is not straightforward.

2. Materials and Methods

In this section, we describe general aspects of the study area, the Landsat data acquired for conduct our experiments, and the validation datasets used. Moreover, since a highly accurate co-registration is required for breakpoint detection, we include an assessment of the Landsat standard terrain correction (Level 1T) to ensure that images used were properly co-registered.

2.1. Study Area

The study area covers in total 241 km² distributed across three areas of 100, 52, and 89 km² termed A, B, and C, respectively. Their selection criteria were based on the different landscape configurations along a gradient of altitude and on forest management practices observed in the region. The areas studied are located in the central foothills of the Napo province in Ecuador (Figure 1), where mountainous terrain, foothills, and lowland evergreen forests constitute the main ecosystems [16]. The principal river is the Napo, which joins the Amazon River after 1800 km. The geomorphology is characterized by hilly (slopes between 0° and 26°) and mountainous (slopes greater than 26°) landscapes with high biodiversity [17]. The altitude covers a range of 300–3875 m a.s.l. Therefore, the region is characterized by a distinct climatic gradient with annual precipitation of 2000 mm–4000 mm and a mean temperature of 6 °C–24 °C. The main land use systems are grasslands used for cattle grazing and croplands used for cacao, passion fruit, and corn production [18]. The land cover change area, which included forest loss and gain classes for the period 2000–2014, covered 3862 ha [19]. The respective study areas measured 324 ha (Area A), 1575 ha (Area B), and 1963 ha (Area C) as a result of their different forest management practices.

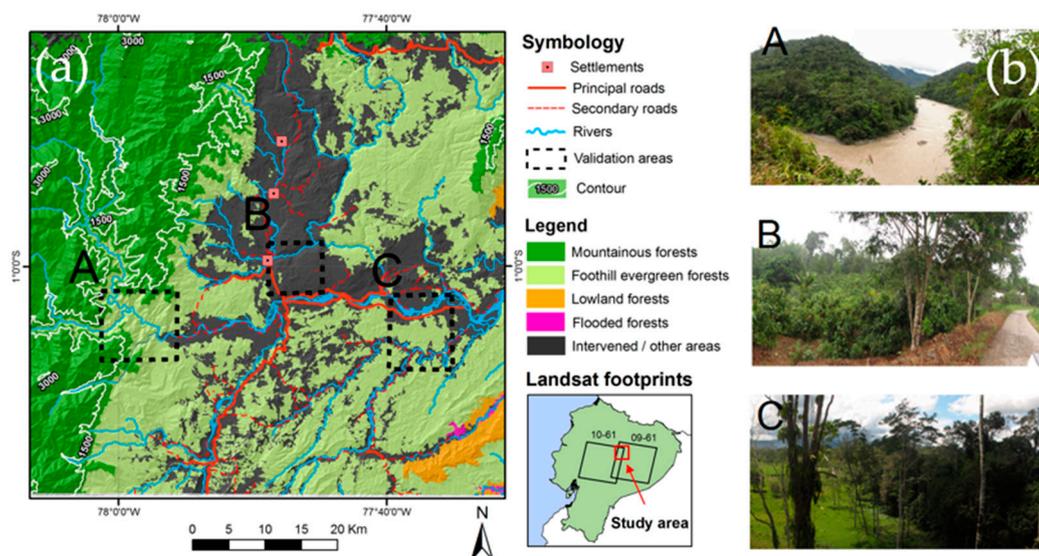


Figure 1. (a) Location of study areas. (b) Photographs observed at A, B, and C study areas. A is located in the vicinity of a protected area, B is located close to a settlement, and C is located in a private forest reserve, surrounded by agricultural land.

Area A (mountainous, 2300–750 m a.s.l.) is located in the vicinity of a protected area where forest loss is rare and it is mainly caused by natural events (landslides or river floods); Area B (mainly hilly,

750–500 m a.s.l.) is located in the vicinity of a settlement where forest loss is common and caused principally by expansion of the agricultural land; and Area C (mainly flat, 500–350 m a.s.l.) is located in a private forest reserve, whose borders suffer forest loss as a result of road construction but the interior is experiencing forest gain as a result of ecological success after some areas were acquired for conservation.

2.2. Landsat Data Acquisition and Geometry Correction Assessment

For this study, we obtained 826 surface reflectance images for a subset of two Landsat footprints (path and row: 09–61 and 10–61; total area: ~4400 km²), which were processed through National Landsat Archive Processing System (LEDAPS) [20]. They were downloaded from the US Geological Survey through their Internet website [21]. After applying the cloud mask “cfmask” product [22] 677 of these images were not used due to low image quality, including excessive no data cover (>90%) (Figure 2a). The remaining 149 images employed in this analysis were originally acquired for three Landsat sensors: 28 images by Thematic Mapper (TM), 94 images by Enhanced Thematic Mapper Plus (ETM+), and 27 images by Operational Land Imager (OLI). All imagery was processed to the standard terrain correction (Level 1T), and metadata reported a root mean square error (RMSE) of less than 7 ± 3 m. A summary of acquisition parameters for these images is shown in Table 1. The images selected for analysis covered an 18-year period (1996–2015) with a mean time interval between images of 47 days.

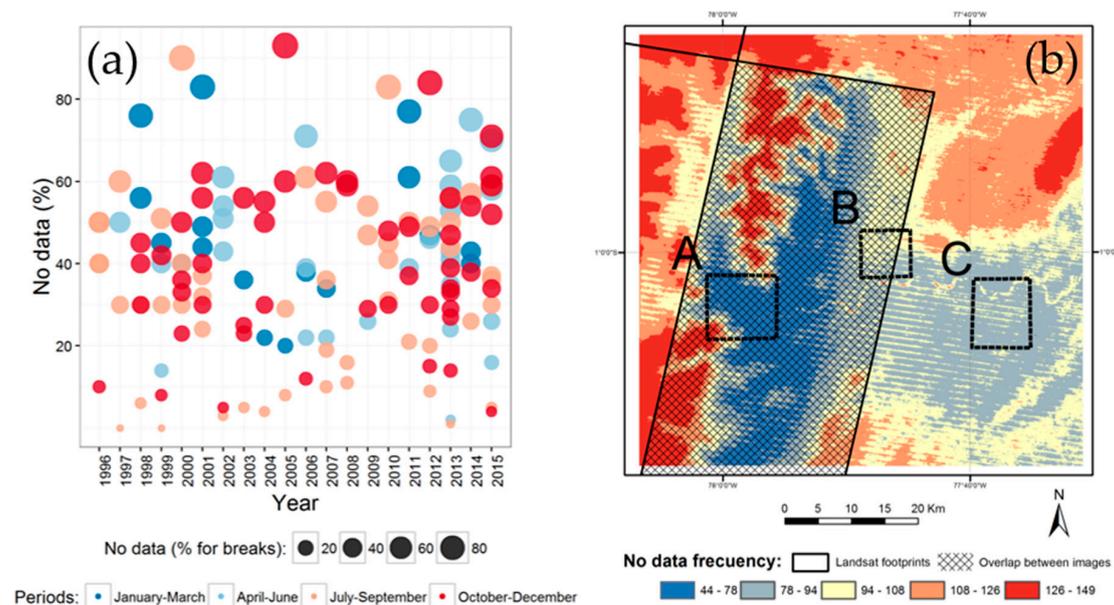


Figure 2. (a) No data percentage observed for period 1996–2015 for the subset of two Landsat footprints used (149 images selected). (b) Spatial distribution of no data frequency.

Table 1. Acquisition parameters of the used images.

| Parameters | Range | Average | Standard Deviation |
|--------------------------------------|-------------------|----------|--------------------|
| Sun Azimuth | 45°–132° | 92° | 38° |
| Sun Elevation | 53°–62° | 58° | 3° |
| Crossing time | 14:40:08–15:28:42 | 15:12:50 | 9 min |
| Cloud cover (%) | 19–89 | 68 | 16 |
| Time interval between images (days) | 1–304 | 47 | 53 |
| Number of ground control points | 9–240 | 75 | 49 |
| RMSE of geometric residuals (meters) | 3–11 | 7 | 3 |

As geometric accuracy of Landsat data is based on its footprint, we considered it necessary to evaluate it again for our study, as our research sites were less than a footprint. Therefore, we first

applied a new co-registration to all images to evaluate if geometric accuracy would improve. For this, a Sobel filter was applied to near-infrared channel (band 4) for each image in the LTS. We selected this band because it was less affected by cloud contamination compared to other bands. Then, edge masks were created thresholding these outputs and applying a linear registration to obtain match points and their transformation matrix. We used an affine model that uses 12 degrees of freedom to find match points and the nearest neighbor to resample images. This was done following the procedure and software package of Reference [23]. To establish a geometric reference, a Landsat 5 image acquired in November 2000 was selected. For this image, the reported RMSE was 3.4 m with 240 points. To verify if co-registration improves results, displacements were calculated from control points to their new positions. Control points were identified in the reference image as stable areas during the 19 years of the LTS and they are described in Table 2.

Table 2. Acquisition parameters of the used images.

| Study Area | Control Point Details | X and Y Mean Displacements in New Co-Registration (in Meters) | Number of Point Matches with Overlap >80% |
|------------|-----------------------|---|---|
| A | River confluence | 81.2 | 62 |
| B | Road | 576.4 | 182 |
| C | Property boundary | 97.3 | 667 |

The results of the described co-registration, however, did not improve the geometric accuracy of the images. On the contrary, the new co-registration increased displacements in the images; thus, this step was omitted from the analysis. In Figure 3, the results of the co-registration procedure displacements can be seen as red crosses, while control points as white dots. Results in Table 2 indicated that Area C was the easiest to co-register, but it was not enough to replace its existing geometric correction. Because of this, we applied other procedure for evaluate co-registration. It consisted in add the edge masks created in the steps before for observe if they overlap along the LTS. Since the maximum overlap corresponds to areas where all images match, it was normalized from 1 (no overlap) to 100 (all images in the LTS overlaps). Then, pixels whose overlap exceeds 80% were filtered (Figure 3). All three areas showed match points, except in areas where cloud cover was frequent or do not have relevant borders. As 20% of the images in the LTS remained uncertain, they were identified and visually inspected to manually improve their co-registration or eliminate them.

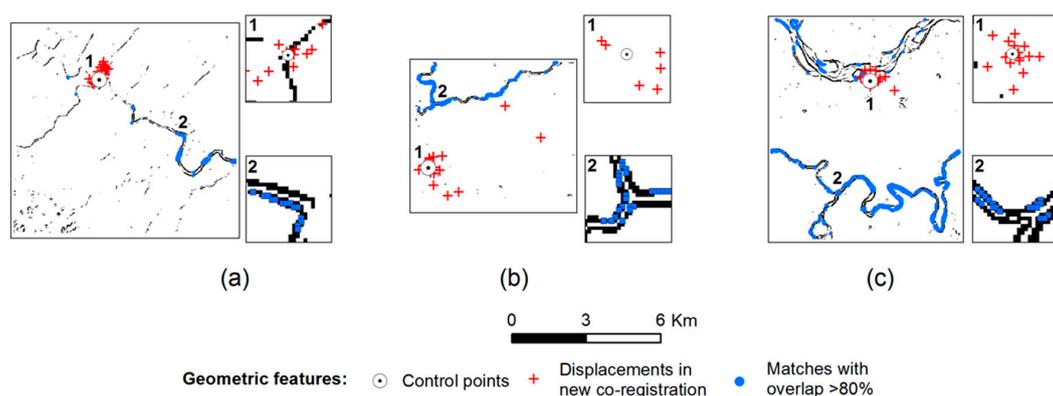


Figure 3. Edge mask from reference image (November 2000) and control, displacements, and matching points with overlap greater than 80% in the: (a) Study area A, (b) Study area B, and (c) Study area C.

2.3. Ancillary Data for Sampling, Validation, and Pre-Processing

To establish a land cover change map (LCCM), two maps were created, forest and non-forest. The time periods used for establishing them were 1997 and 2015. Both maps were obtained using a trial-and-error threshold approach to classify the Natural Burn Ratio (NBR) index derived from the

first and last images in the LTS. After a visual inspection and correction, these maps were finalized and changes between 1997 and 2015 were established corresponding to five classes: stable non-forest, stable forest, forest lost, forest gain, and no data. This map was used later to extract the stratum needed for sampling (training and reference) and to perform visual assessments (Sections 5.3 and 6.4).

To validate training and reference samples, a dataset comprised of high-resolution imagery acquired from different sources was used. These images included aerial photos, RapidEye images, Google Earth, and ASTER imagery. These images were acquired for the years 1978, 1982, 2000, 2005, 2010, and 2015. Additionally, a field visit was done during the first semester of 2016 to corroborate the study area's land cover.

Finally, as topographic correction was indicated for Landsat pre-processing, we acquired a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) [24] with a resolution of 90 m, as its interpolation quality was better than the 30-m version, especially in areas with data gaps of hilly landscapes.

3. Additional Landsat Pre-Processing Calculations

Because we need to evaluate different Landsat pre-processing approaches to determine the best calibration of the PCG, we describe in this section all the procedures implemented. These were applied to the subset of two Landsat footprints; therefore, its extension was larger than the study areas. As we calculated different vegetation indices and mosaics ensembles from each Landsat pre-processing approach, we also provide an overview of their procedures.

3.1. Topographic Correction and Radiometric Normalization

Topographic correction is considered a fundamental preliminary procedure before multi-temporal analyses because solar zeniths and elevation angles, as well as direct topographic effects, differ from image to image [5]. Both Richter et al. [25] and Riaño et al. [26] concluded that the C-correction method was preferred over other related topographic correction algorithms because it better preserves the spectral characteristics of the imagery. C-correction calculation incorporates the wavelength of each individual spectral band along with its diffuse irradiance. C-correction was originally proposed by Teillet et al. [27], and we applied it to our LTS using the DEM in combination with the solar and azimuth elevation angles described in the imagery metadata.

Then, for radiometric normalization, we followed a procedure described by Hajj et al. [28]. This approach applies a relative radiometric normalization based on calculations of linear regressions between target and reference images and uses invariant targets to obtain regression coefficients. An important advantage of this technique is based on its absolute calculations. Vermote et al. [29] described this methodology within the context of the 6S model. The 6S model relies on atmospheric data to reduce the effects of atmospheric and solar conditions relative to a reference image. Another advantage of this procedure is its ease of implementation and computation.

To implement radiometric normalization, a nearly cloud- and haze-free OLI surface reflectance image acquired by Landsat 8 on 2 September 2013 was used as reference. Its date corresponds to the low regional precipitation regime (with monthly rainfall below 250 mm) in the region [30]. As with all other images used, this reference image was cloud-masked and dimensionally homogeneous with the rest of the images. Afterwards, invariant target masks were generated from a Normalized Difference Vegetation Index (NDVI) ratio, where the NDVI of the target image was divided by the NDVI of the reference image [31]. In most change detection algorithms, the separation of no-change pixels is based on a histogram of outputs, where the mean or median value is used as the benchmark to define its range [32]. This principle was observed in the NDVI ratio outputs and was implemented by computing different possible ranges in a loop calculation. This operation started from the mean value of the NDVI ratio, and the minimum and maximum values increased by a factor of 0.1% in each loop iteration. The process terminated when the number of pixels within the range exceeded 2% of the total number of pixels in the NDVI ratio. This percentage was considered sufficient to represent

a wide diversity of features: primary forests, bare soils, water bodies, and urban infrastructures, among others. Hajj et al. [28] and Mahiny and Turner [33] both applied percentages below 1% with the recommendation that this figure should be increased as much as possible. Finally, the range was used according to each image to reclassify and create the invariant target masks. After the calculation of invariant target masks for each target image (148 in total), the regression coefficients were calculated using a linear regression. For this step, we applied the invariant target mask to the reference and target images and then calculated the regression coefficients for each image's spectral band. In this procedure, each of the surface reflectance images normalizes its values according to the reference image.

To evaluate the performance of topographic correction, radiometric normalization and other combinations of these pre-processing approaches, different time-series boxplots were made for each case (Figure 4a). These plots used a sample set of 1678 pixels taken with a precision of 99%. They were randomly taken from the predominantly sun-exposed (839 samples, azimuth range areas: 45° – 132°) and shadowed areas (839 samples, azimuth range areas: 225° – 313°) (Figure 4b). Since variance should be similar in both sun-exposed and shadow-exposed areas if LTS achieves its temporal homogeneity, the standard deviation was calculated for each case. We obtained measurements of 0.11 for surface reflectance (REF), 0.11 for topographic correction (TOPO), and 0.07 for radiometric normalization of surface reflectance (NREF); and 0.15 for radiometric normalization of topographic correction (NTOPO). Based on these values, it was established that the NREF pre-processing approach reduced LTS temporal variability, while other approaches, such as REF, TOPO and NTOPO, increased it.

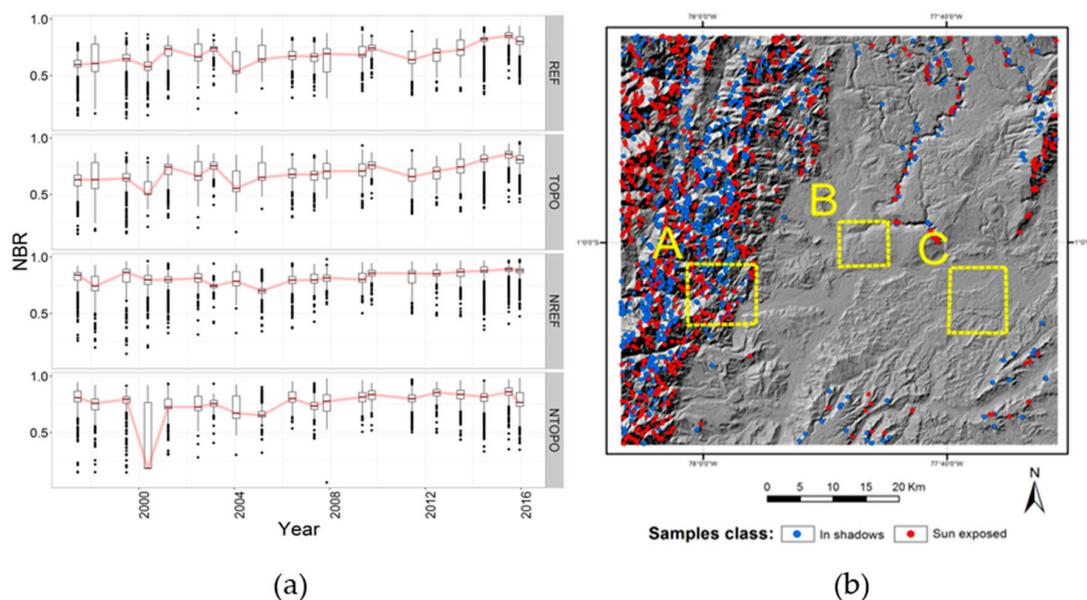


Figure 4. (a) Examples of different pre-processing approaches using yearly mosaics and the NBR vegetation index. Boxplots were based in samples located at sun-exposed and shadow areas. Red lines highlight mean values in the time-series. The acronyms on the right stand for: REF or surface reflectance; TOPO or topographic correction; NREF or radiometric normalization of surface reflectance; and NTOPO or radiometric normalization of topographic correction. (b) Map of the samples used in boxplots. Blue dots identify shade-exposed samples while red dots identify sun-exposed samples.

3.2. Vegetation Indices Derivatives

With the pre-preprocessing outputs, a set of vegetation indices based on visible and infrared bands was calculated. Selection criteria were based on a literature review, considering the atmospheric effects described by References [34,35]. Moreover, because the time-series was based on the surface reflectance Landsat products, Tasseled Cap Transformations (TCTB, TCTG, and TCTW) were applied using the coefficients described by Baigab et al. [36]. The indices calculated can be classified in three groups:

- Using red and infrared bands: the NDVI [31], Global Environmental Monitoring Index (GEMI) [37], and Modified Soil Adjusted Vegetation Index (MSAVI) [38];
- Using only infrared bands: The NBR [39], the Aerosol Free Vegetation Index 1.6 μm band (AFRI16), and the Aerosol Free Vegetation Index 2.1 μm band (AFRI21) [40];
- Using the complete sensor bandwidth: Tasseled Cap Transformation Brightness (TCTB), Greenness (TCTG), and Wetness (TCTW) [41].

The topographic correction procedure can negatively impact the detection of low-magnitude changes in the landscape [42]. Therefore, all vegetation indices were calculated for each pre-processing approach (REF, TOPO, NREF, and NTOPO) to expand the PCG calibration alternatives.

3.3. Mosaic Calculation

Following the calculation of the vegetation indices from the different preprocessing approaches, output images were mosaicked. The image acquisition dates and yearly, semesterly, and trimesterly time periods were the principal considerations in structuring the image mosaic. The one-year timeframe is appropriate for use with Landsat archive data considering data acquisition limitations and the 16-day satellite repeat cycle [2]. However, consideration of the shorter temporalities for mosaics was necessary to validate this affirmation.

For this procedure, we followed the methodology described by Griffiths et al. [43]. Images were selected according to their acquisition date and the number of data gaps included in each. Images with fewer and less extensive data gaps are preferred within a particular time period. As each image is selected, any data gaps are filled with data from alternate images from the same time period. Twenty yearly mosaics, 37 semesterly mosaics, and 64 trimesterly mosaics were obtained to establish different periodicities and time-series arrangements. Figure 5 shows that no data percentages that remained after the mosaics were calculated.

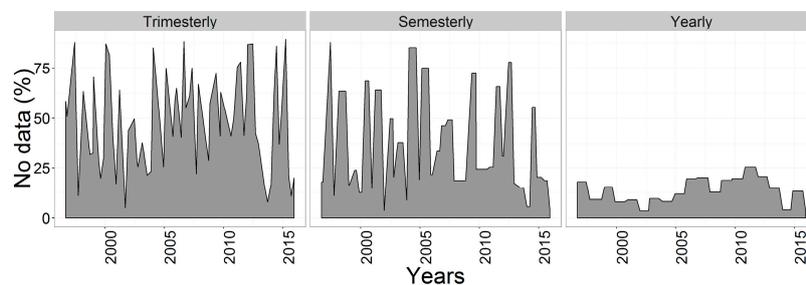


Figure 5. Remaining no data percentages in mosaics temporalities.

4. Description of the PCG Function and Its Algorithms Integrated

In this section, we describe each algorithm integrated in the PCG before its optimization with GA. Algorithms were executed in three steps, of which the workflow is shown in Figure 6. Starting with the time-series compilation, all steps are further described below.

4.1. Step 1: Time Series Compilation

To construct a time-series, the PCG needs to define which one of the pre-processing approaches, vegetation indices and mosaic temporalities is used in this operation. All these procedures were previously described in Section 3; therefore, we do not extend their discussion. For the first step in the PCG, combining 4 pre-processing approaches, 9 vegetation indices, and 3 mosaics temporalities; a total of 108 time-series compilation alternatives were available. With no clear reason to select a particular one of these alternatives, our decision was based on defining a combination of the three elements mentioned before. These combinations among others parameters required by the PCG are summarized in Table 3.

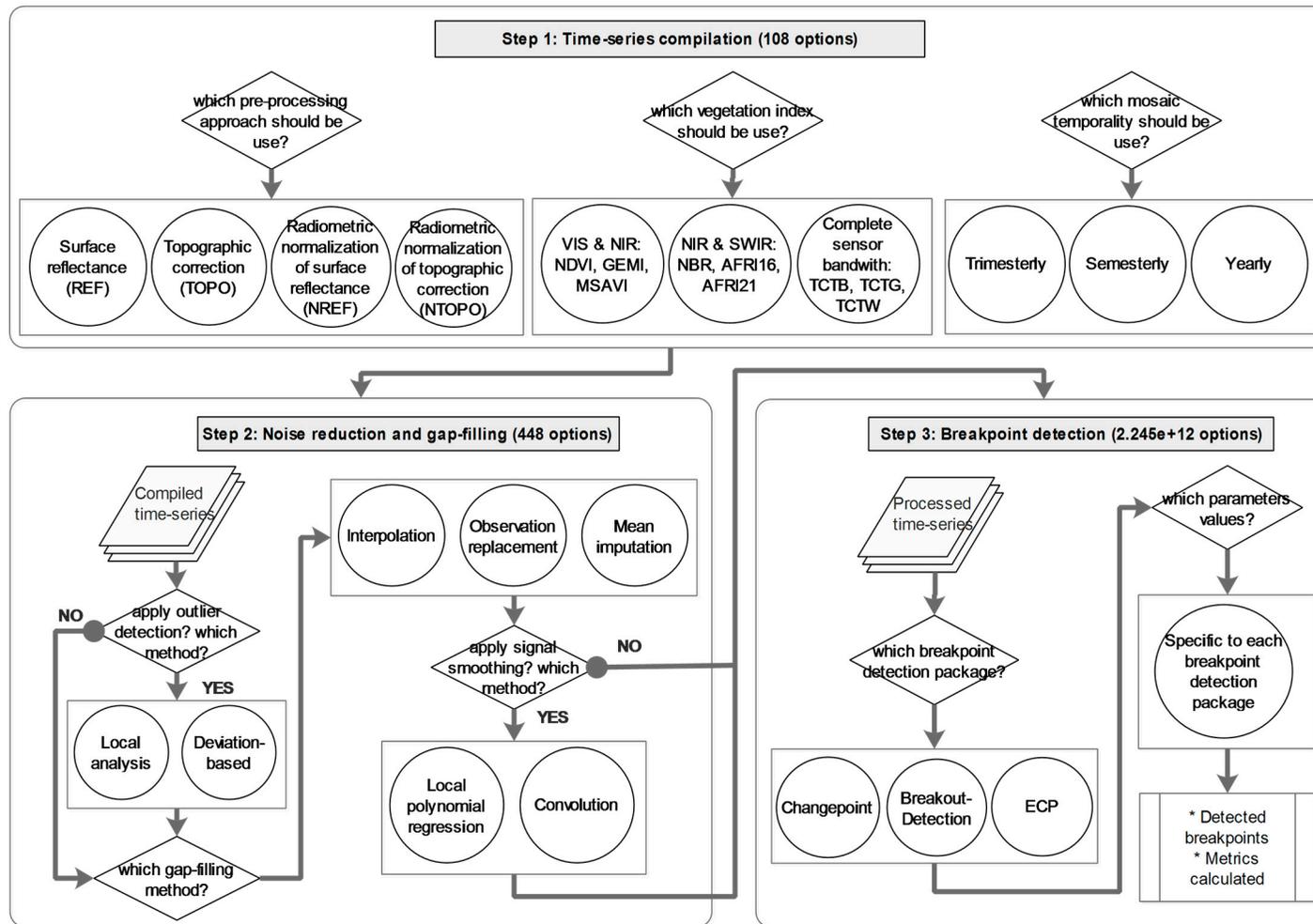


Figure 6. PCG workflow.

Table 3. Summary of PCG steps, methods, algorithms, packages, parameters, values, steps, and their search space size.

| Steps | Methods | Parameters ¹ | Values | Steps | Total ² |
|---|--|---|--|-------|--------------------------|
| 1: Time series compilation | Random selection | P1: Pre-processing and mosaic temporality | REF, TOPO, NREF, NTOPO | - | 108 |
| | | | Yearly, semesterly, trimesterly | - | |
| | | P2: Vegetation indices | AFRI16, AFRI21, GEMI, MSAVI, NBR, NDVI, TCTB, TCTG, TCTW | - | |
| 2: Outlier detection and removal ³ | Decision | P3: Apply it? | No, LOF, deviation | - | 448 |
| | Required for all | P4: Window size | 2–5 | 1 | |
| | Local outlier factor (LOF) | P5: LOF factor | 2–15 | 2 | |
| | Deviation-based test (deviation) | P6: Threshold | 0–14 | 1 | |
| 3: Gap-filling | Decision | P7: Which method? | Interpolation, locf, mean imputation | - | 54 |
| | Interpolation | P8: Type | Lineal, spline, stine | - | |
| | Observation replacement (locf) | P9: Direction | Forward, backward | - | |
| | Mean imputation | P10: Type | Mean, median, mode | - | |
| 4: Signal smoothing ³ | Decision | P11: Apply it? | No, polynomial, convolution | - | 98 |
| | Local polynomial regression fitting (polynomial) | P12: Degree smoothing | 0.5–3 | 0.19 | |
| | Savitzky–Golay filter (convolution) | P13: Filter order | 1–10 | 1.3 | |
| 5: Breakpoint detection | Decision | P14: Which BDA package? | Changepoint, BreakoutDetection, ECP | - | 2.245 × 10 ¹² |
| | Required for all | P15: Segment size | 3–10 | 1 | |
| | Changepoint | P16: Statistical property | Mean, variance, mean and variance | - | |
| | | P17: Algorithm | PELT, binary segmentation | - | |
| | | P18: Max breakpoints | 0–10 | 1 | |
| | | P19: Penalty mode | SIC, BIC, MBIC, AIC, Hannan-Quinn, Manual | - | |
| | BreakoutDetection | P20: Penalty for manual mode ⁴ | 0–1 | 0.01 | |
| | | P21: Penalty percentage ⁴ | 0–1 | 0.01 | |
| | | P22: Penalization polynomial | 0–2 | 1 | |
| | | P23: Significance level ⁴ | 0–1 | 0.01 | |
| P24: Moment index ⁴ | | 0.1–2 | 0.01 | | |
| ECP | | | | | |

¹ The letter “P” and number indicates the code used in this manuscript for identify parameters. ² Refers to the total search space as number of alternatives. ³ Modules are optional in the processing chain. ⁴ Threshold parameter.

Following the stacked time-series, different noise reduction and gap-filling algorithms could be applied in the PCG. The following sub-sections summarize the available options, their characteristics, parameter space sizes, and developer references.

4.2. Step 2: Noise Reduction and Gap-Filling

As the PCG required us to define how and whether to enhance the quality of the compiled time-series, multiple algorithms were integrated in the PCG to enhance breakpoint detection. Here, we describe each of them:

1. Outlier detection, which constitutes the detection and removal of anomalous values in the time-series. Typically, they constitute cloud and shadow pixels that were not properly masked. This step was considered optional and its principal parameters were window size, which defines the moving window to analyze the time series, and the threshold for sensibility control. In total, 448 alternatives were available in the parameter search space. Two algorithms were available for this step:
 - Local analysis, using the local outlier factor algorithm (LOF) [44], which calculates for an object a metric to measure how isolated it is with respect to the surrounding neighborhood.
 - A deviation-based test using the Hampel filter, which calculates the median absolute deviation to find outliers [45].
2. Gap-filling, which constitutes the procedure for filling data gaps in the time-series caused by cloud and shadow masking or the Landsat 7 ETM+ sensor scan line error. Gap filling was a compulsory step to enable breakpoint detection. The parameters in this step refer to the different methods and options for its execution. Thresholds were not required, so parameter search space was limited to 54 alternatives. Three algorithms were available:
 - By interpolation, which estimates new data points with methods such as linear, spline, and stine interpolation [46].
 - Observation replacement, through which missing values are replaced with a temporally adjacent value—the last observation being carried forward or the subsequent observation carried backward.
 - Mean imputation, which replaces missing values with either median, mean, or mode data values.
3. Signal smoothing, which enables the increase of signal-to-noise ratio in a time-series and enhances the detection of breakpoints. This step was optional since it is not required in breakpoint detection. For all the algorithms included, only one parameter was required to define a threshold for sensibility control. In total, 98 alternatives constituted the parameter search space. Two algorithms were available:
 - Local Polynomial Regression Fitting [47], which involves the local fitting of a polynomial surface determined by one or more data points.
 - Convolution, using the Savitzky–Golay filter [48], which fits a linear least-squares low-degree polynomial to successive subsets of adjacent data points.

4.3. Step 3: Breakpoint Detection

The ultimate step in the PCG is the detection of breakpoints. After it is executed, the PCG gives as outputs the position of the breakpoints found within the time-series analyzed. For this purpose, three different BDA packages were considered since they were programmed in the open source R language [49] and this made it possible to observe their codes and integrate them easily to the GA used [50]. Other alternatives, such as BFAST [51], was discarded as our LTS was not extensive enough to fit a history model. Based on different approaches, two types of BDA were considered:

1. BDA based in parametric statistics:

- Methods for Changepoint Detection package (Changepoint) [52], which implements the detection of changes in mean and/or variance values of a univariate time series based on a normality test or cumulative sums. Additionally, Changepoint requires a penalty approach provided by any of five included automatic methods: Hannan-Quinn or Schwarz (SIC), Bayesian (BIC), Modified Bayesian (MBIC), and the Akaike information criterion (AIC). Finally, it includes three algorithms, but we focus on only two. The first one, called binary segmentation, applies a statistical test to the entire dataset and splits it if a single breakpoint is identified. Afterwards, it repeats this operation until no breakpoints are found. The second, called PELT (pruned exact linear time), is based on the algorithm of Jackson et al. [53] but it reduces computational cost and improves accuracy by using a dynamic programming approach.

2. BDA based in non-parametric statistics:

- Breakout detection via Robust E-statistics package (BreakoutDetection) [54] is an algorithm based on energy statistics. It implements a novel statistical technique called E-divise with medians for estimate the statistical significance of breakpoints through a permutation test. Its design aims to be robust against anomalies.
- Non-Parametric Multiple Change-Point Analysis of Multivariate Data package (ECP) [55]. This package constitutes an upgrade of the E-divise algorithm developed by the authors of BreakoutDetection. Its novelty is the use of E-divise together with the E-agglomerative technique to reduce processing time by segmenting data before analyzing it.

To avoid any bias caused by unequal search space sizes between BDA packages, threshold parameter ranges were set to similar sizes. Considering all parameters combinations, a total of 2.2×10^{12} alternatives were available in this step.

5. Genetic Algorithm Implementation

Since GA is the search algorithm for analyzing the PCG parameter search space, in this chapter we describe the concept behind it, the sampling needed for its implementation, the associated reference data, the fitness evaluation, and the calibration applied to GA.

5.1. Genetic Algorithms

GAs are a class of evolutionary algorithms that include scientific models of evolutionary process and search algorithms [15]. They became popular thanks to the work of John Holland and his colleges during the 1970s [11] and are inspired by principles of natural selection and survival of the fittest. GAs have four principal advantages: the capability to solve complex problems, an emphasis on global searches, the provision of multiple solutions, and parallelism.

The workflow of GAs aims at evolving a population of feasible solutions for a target problem, or objective function. A fitness evaluation is then made in which each solution is executed and evaluated for its performance with respect to a validation dataset. This process involves an evolution-directed search in the parameter search space of the objective function to create new solutions. In each new generation, the best solutions are selected, reproduced, and mutated with respect to a set of operators used by the GA:

- Selection: Controls the survival of the best chromosomes according to their fitness value and selects them as parents of a new generation.
- Elitism: An optional selection rule that selects the best chromosomes directly for the next generations to guarantee their existence.
- Crossover: An operator that creates offspring of the pairs of parents from the selection step. Its probability determines if the offspring will represent a blend of the chromosomes of the parents.

- Mutation: Adds random changes to the chromosomes.

To facilitate computation and gene representation, integer encoding is used by GA. This allows the transformation of discrete and continuous parameter values to integer codes and permits GA operators to experiment with them as they were genes. Since discrete parameters are represented by an exact number of alternatives, their representation as integer-codes is relatively easy. However, for continuous parameters, it is necessary to subset their ranges by steps in order to facilitate their operation. Therefore, this process should be carefully defined according to the sensibility behavior of the parameter and the instructions provided by the developer of the algorithm analyzed.

Since GA terms require a homology, the reader should keep in mind that the following terms refer to: (1) PCG as objective function; (2) all possible methods and parameter values in the PCG as search space; (3) accuracy assessment of detected breakpoints by the PCG as fitness evaluation; (4) any PCG calibration as chromosome and; (5) a parameter value for any algorithm in the PCG as a gene.

For a better understanding of these concepts, Figure 7 shows how the PCG is integrated with GA.

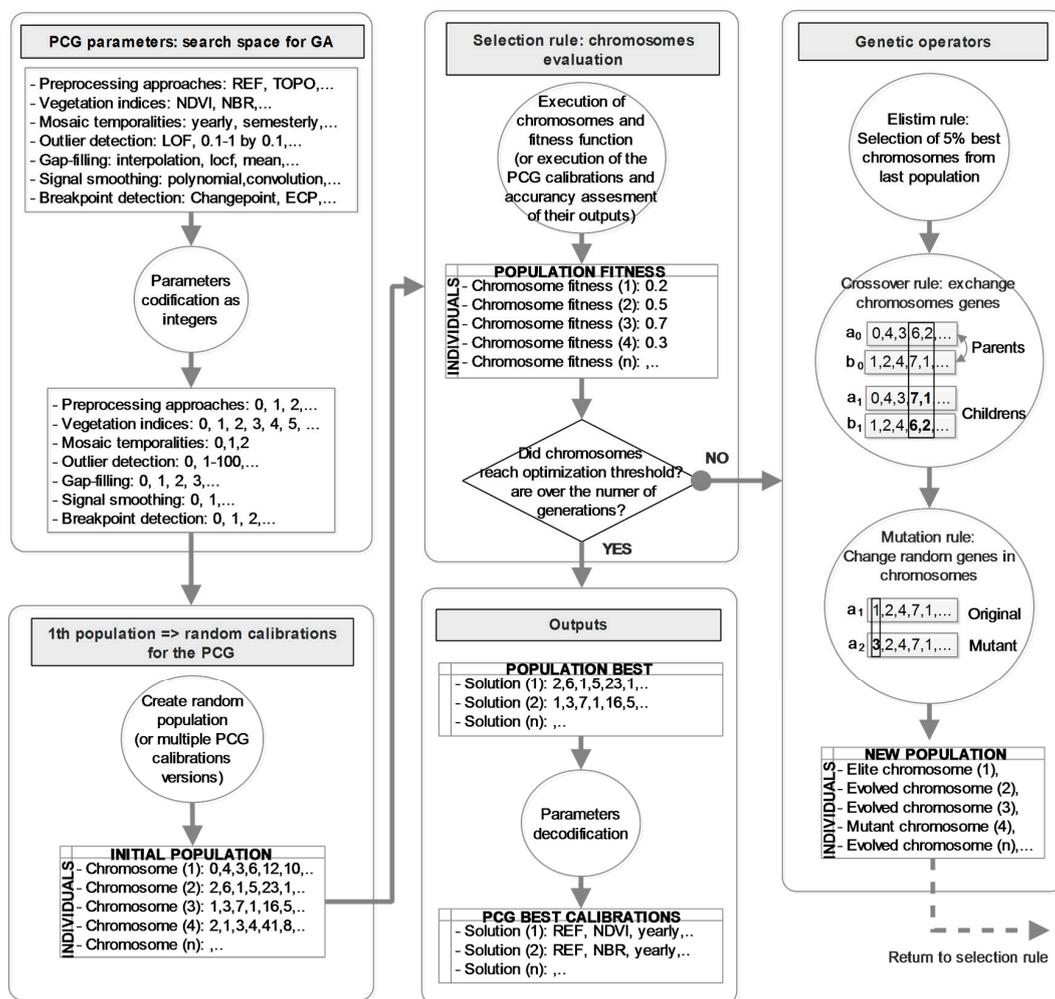


Figure 7. GA applied to PCG workflow.

Depending on the complexity of the objective function, GA can be computing-intensive. In this instance, the GA package [50], which allows for flexible manipulation and analysis of the GA, was used. This package was developed for a parallel computing environment and has been proven to solve different cases of optimization problems, such as the Rastrigin function, Andrews Sine function, curve fitting, and subset selection, among others.

There are other GA drawbacks. Convergence toward local rather than global optimization can be an infrequent problem. Larger populations and more generations are needed to obtain better results, but this demands large simulations. Moreover, due to GAs reliance on a stochastic search method, each run constitutes a different approximation to the solution as its initial population is randomly created [56]. This can affect solution finding as GA can become stuck in a subset of parameter search space, depending on its execution of a random mutation for exploring new parameter combinations.

5.2. Training Sampling Design

To get training samples for the GA task, an optimal allocation technique to perform a stratified sampling using a random scheme was applied. This method minimizes the variance of the estimated overall thematic accuracy of the dataset and is recommended for use when the number of map classes is relatively limited [57].

To calculate sample sizes, the LCCM (Section 2.3) classes were used to extract two strata, which we named change (merging forest gain and forest lost classes) and no-change (using stable forest class). The size of each strata was allocated according to its expected variances. For this step, we followed the sampling design procedure outlined by Olofsson et al. [57], under which informed conjecture of the user's accuracy can indicate these values. Applying a sampling precision of 70% and standard deviations of 1 and 4, the samples were calculated for all validation areas (100 in total, 54 for no-change and 46 for change areas). Since sample size constitutes an important factor in GA, because it controls the amount of data that chromosomes should ingest to produce breakpoints in a manageable processing time (Figure 8), we considered these samples sufficient, given our limited computing resources (4 cores, Intel i5 processor), for following the GA calibration recommendations (Section 5.4) to get results in approximately 5 to 15 min.

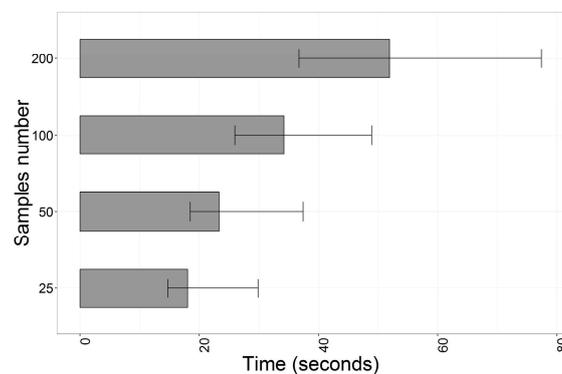


Figure 8. Processing time measured for different sample size sets. The PCG was equal configured in all cases, executing GA for 10 times to average its processing time. For testing purposes, GA population size was set at 30 individuals and 10 generations.

5.3. Samples Interpretation and Fitness Evaluation

The fitness evaluation includes the design and execution of a specific function for evaluating proposed solutions during the GA execution. The fitness evaluation in our case was formed by an accuracy assessment of the PCG outputs. Our implementation for this task again followed the recommendations of Olofsson et al. [57] for two components: response design and accuracy analysis.

Starting with the response design, we chose an array of 5 neighbor pixels arranged in an “x” shape as the sampling unit and applied the visual interpretative approach. For this purpose, we plotted yearly mosaics of 5, 4, and 3 Landsat bands, composed as color compositions, along with high-resolution images. This task was facilitated by a developed tool similar to the TimeSync system [58] but with specific functionalities (Figure 9). The protocol for interpreting each sample unit can be summarized as follows.

1. Any of four conditions was a basis for rejecting and replacing a sample, or in some cases, a neighbor pixel in the sample unit, if:
 - There was a lack of high-resolution images, obscuring most of the land cover history of the sample unit;
 - Visual interpretation of the sample unit was compromised because of unmasked clouds, shadows, haze, or water bodies (Figure 9a);
 - A neighbor pixel exhibited a land cover history different from the majority of pixels included in the sample unit;
 - The number of eliminated neighbor pixels in a sample unit exceeded 4 cases.
2. To consider a sample unit as a forest gain, clear evidence of continuous regeneration was needed. According to Guariguata and Ostertag [59], early forest development within the tropical forest environment is achieved approximately five years after the disturbance event. We followed this condition to accept samples as forest gain (Figure 9b) or reject samples and cast replacements.
3. In the case of forest loss samples, an absence of the regeneration period was a necessary condition for validation (Figure 9c).
4. For stable forest samples, the unique condition required was an absence of disturbances (such as clear cuts or fires) during the period analyzed (Figure 9d).

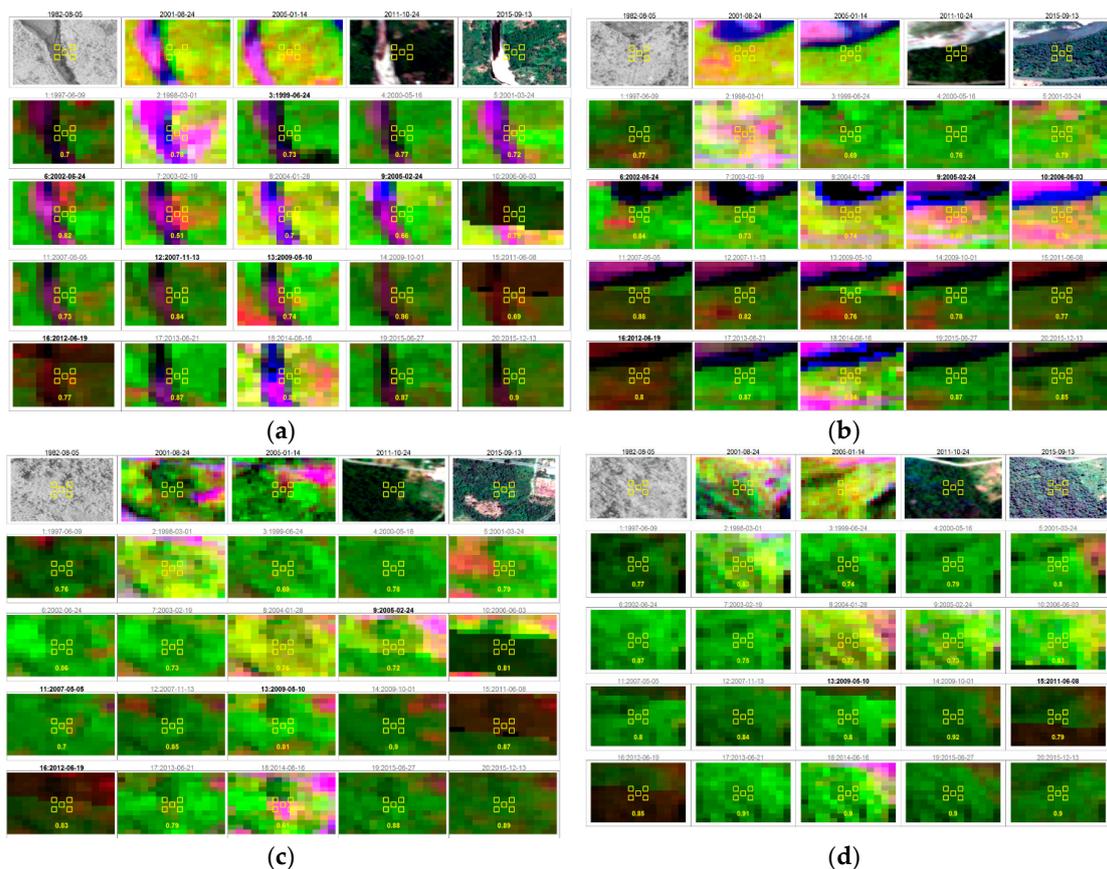


Figure 9. Interphase for samples interpretation. First row (from left to right) refers to high resolution imagery composed by aerial photos (1982) and images from ASTER (2001 and 2006), Rapid Eye (2011) and Google Earth (2015). The rest of the image chips correspond to the LTS as yearly RGB composites. Following protocols, we interpret these cases as follows: (a) Sample rejected by unmasked river, (b) Forest gain after disturbance observed in the 3rd row, (c) Forest lost with a short regrown period, and (d) Stable forest sample.

As visual interpretation of breakpoints dates is not an easy task, we preferred to ensure that a sample unit belonged to the classes described in the protocol instead of introducing more uncertainties by subjective interpretation of disturbance dates. Subsequently, the samples were grouped into change and no-change classes to apply this information to training samples.

For the accuracy analysis, using a straightforward matching procedure, the fitness value of our samples was based on the calculation of their overall accuracy. This measure helped us to overcome local optimal convergence experienced when R^2 and adjusted R^2 were tested. Other measures such as kappa, omission and commission errors, etc., were avoided since only two classes were examined.

5.4. GA Calibration Settings

Following the interpretation of training samples, the GA was executed. The procedure for analyzing the search space of the PCG and calibrating GA according to its characteristics followed the recommendations of Kumar and Jyotishree [60], and Eshelman and Schaffer [61]. These recommendations guided the design of two types of searches. The first mode, called “explorative” was created to reduce the size of the search space of the processing chain and provide insights for its calibration as a whole. For this, BDA threshold parameters with a search space size of 100 alternatives were contracted, increasing step values and shortening its range to 12 alternatives (left side of Figure 10). The second mode, called “exploitation,” was created to analyze in detail BDA threshold parameters. Therefore, its step values were maintained as shown in Table 3, conserving its 100 alternatives in all cases (right side of Figure 10).

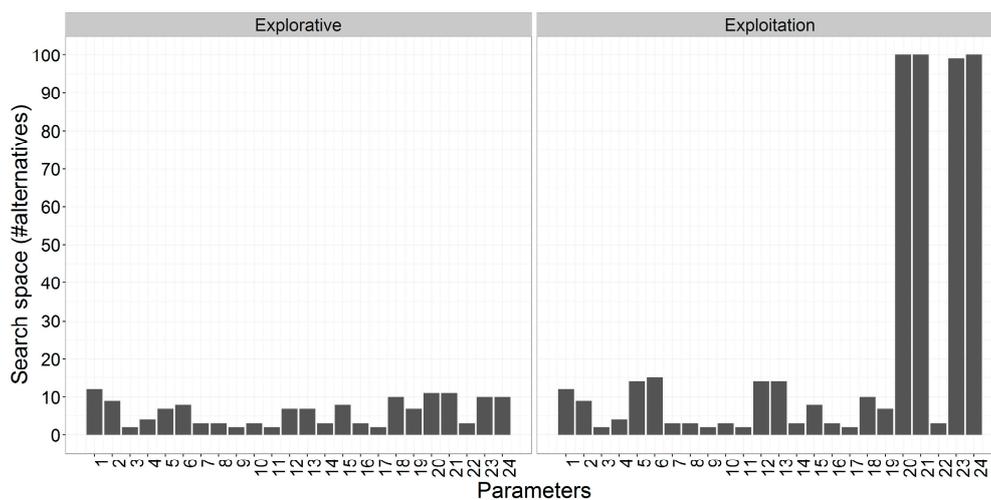


Figure 10. Search space size allowed for the explorative and exploitation modes.

Other specific GA calibration parameters were applied following the recommendations of Scrucca [50]. This application indicated an elitism rate of 0.05 and a uniform crossover probability of 0.8. A random mutation rate was tested with 0.5 and 0.1 for experimental purposes. The tournament selection was the mechanism set to favor the selection of better individuals, as suggested by Miller and Goldberg [62].

To codify each parameter value as genes, integer codes were applied to discrete and continuous parameters. Details of the steps and ranges applied to continuous parameters are shown in Table 3. With this codification of parameters, the “real-value” GA type was chosen. This allowed us to obtain floating-point representations of numbers, which can be converted into integer values and define a parameter value from the search space.

6. Results

After the calibration of GA, in this section we describe the procedures for exploring PCG parameter search space, the optimized PCG calibrations found, their execution for visual and accuracy assessment, and their processing time.

6.1. GA Search Approaches and Calibrations Found

To find the best solutions, different GA executions and experiments were implemented. For all BDA packages, these procedures were similar; however, two approaches were applied to consider different management of the PCG parameters search space. For this step, our approach was divided, according to the parameters, by analysis and the type of GA search applied. Two different approaches were considered, where the main difference was the application or non-application of noise-reduction algorithms and a predefined pre-processing input.

1. Search with only BDA packages (reduced processing):

- In this sequence, the BDA parameter search space (parameters P14-P24 as is noted in Table 3) is analyzed in detail, but the rest of parameters are defined by a default mode.
- The default mode defined the NBR mosaics yearly, since short-wave infrared (SWIR) region metrics are more sensitive to forest changes [2] and this mosaic temporality helped to reduce data gaps. They were calculated from the Landsat surface reflectance products for reducing uncertainties with respect to radiometric normalization and topographic correction performance. Noise reduction algorithms, including outlier detection and signal smoothing, were deactivated, which focused the GA on BDA parameter search space exclusively.
- For this approach, the GA was set to the “exploitation” mode, executing it twice with each BDA package. The first run had a mutation rate of 0.1 and the second run, a rate of 0.5 (enhanced diversity). Each GA execution had 120 generations and 30 individuals.

2. Search with pre-processing and noise reduction + BDA packages search (extended processing):

- This search consisted of split search space, executing shorter GA runs, and splitting pre-processing and noise reduction parameter search space from each BDA.
- To find a calibration solution for the pre-processing and noise reduction algorithms (parameters P1-P13 as noted in Table 3), GA was set to the “explorative” mode during a first run of 60 generations and 30 individuals.
- After determining a pre-processing and noise reduction calibration, it was applied before the BDA parameters search space was analyzed in detail. For this step, a second GA run was applied, changing the search mode to “exploitation” but only for 60 generations of 30 individuals.
- Hence, GA was executed four times: two for pre-processing and noise reduction, and two for the BDA parameters search space, considering again the two mutation rates applied in the first approach (0.1 and 0.5).

Results from these sequences and the best solutions achieved are shown in Figure 11, where the fitness value and its peaks are highlighted as colored dots. These peaks suggest that the ECP and BreakoutDetection packages performed best when a reduced processing approach (left side of Figure 11) was applied. Furthermore, all packages improved their results drastically after applying the extended processing approach, which assigns a pre-processing and noise reduction calibration before the BDA is optimized by GA. The right side of Figure 11 shows the enhancement that ChangePoint, BreakoutDetection, and ECP provided, increasing their overall accuracy: 0.03, 0.11 and 0.13, respectively. This demonstrates that the extended processing approach was better for optimization, providing us better calibration solutions, so we chose these enhancements for further analysis.

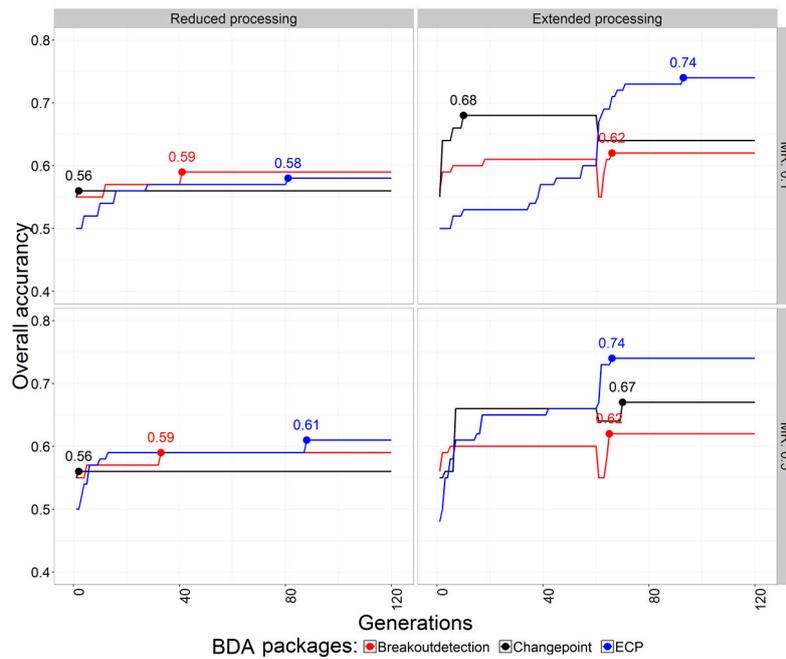


Figure 11. BDA fitness value evolution.

Details for the extended processing calibration solutions are shown in Table 4. The time-series compilation step shows that yearly mosaics and vegetation indices based on infrared bands (NBR and AFR16) were mostly preferred; however, is not clear which radiometric correction was most beneficial since topographic correction (TOPO), surface reflectance (REF) and radiometric normalization of topographic correction (NTOPO) were all present in the different calibrations. Noise reduction algorithms, such as outlier detection and signal smoothing, showed that calibrations using LOF and Polynomial regression methods gave improved results. This was not the case for the gap-filling step, where different methods were selected. Regarding BDA calibrations, the segments size parameter showed different behaviors between BDA packages. Because of this, the number of breaks obtained by each BDA package differed, but we maintained them because of our experimental design. The rest of the BDA parameters were unique and incomparable, as each of them were specific to each BDA package parameters.

Table 4. Parameter selection by GA as best calibration solutions.

| PCG Steps | BDA Packages | | |
|----------------------------|--|--|--|
| | Breakout Detection | Changepoint | ECP |
| 1: Time series compilation | TOPO, yearly, NBR | NTOPO, yearly, MSAVI | REF, Yearly, AFR16 |
| 2.1: Outlier detection | LOF, window size 2, LOF factor 8 | LOF, window size 4, LOF factor 2 | LOF, window size 2, LOF factor 4 |
| 2.2: Gap-filling | Observation replacement, forward direction | By interpolation, spline method | By interpolation, linear method |
| 2.3: Signal smoothing | Polynomial, degree smoothing 0.5 | Polynomial, degree smoothing 1.7 | Polynomial, degree smoothing 1.7 |
| 3: Breakpoint detection | Segment size 5, penalty percentage 0.09, penalization polynomial 1 | Size segments 3, variance as statistical property, binary segmentation algorithm, 7 breakpoints, manual penalty mode, penalty in manual mode 0.5 | Size segments 9, significance level 0.2, moment index 0.94 |
| Overall accuracy | 0.62 | 0.68 | 0.74 |

6.2. Execution of Calibration Solutions and Visual Assessment

After the best calibration profiles were determined, we proceeded to apply them to each study area (Figure 12), considering that each LTS pixel must include a minimum of 10 observations (a full time-series pixel includes 20 observations). Therefore, it was possible to observe BDA performances under different conditions. Artifacts such as horizontal stripes indicated Landsat 7 scan-off error, while irregular patches showed areas of unmasked clouds and shadows. Despite these hindrances, some patterns of land cover change were present in all outputs. In this regard, ECP (Figure 12, column d) looked less affected in comparison to the reference change 1997–2015 mask (Figure 12, column a). The rest of the BDA packages, such as Breakoutdetection and Changepoint, did not perform well in all areas as compared to the change 2000–2015 mask. Following these initial insights, the ECP package was selected for further analysis and manual calibration, described in the next section.

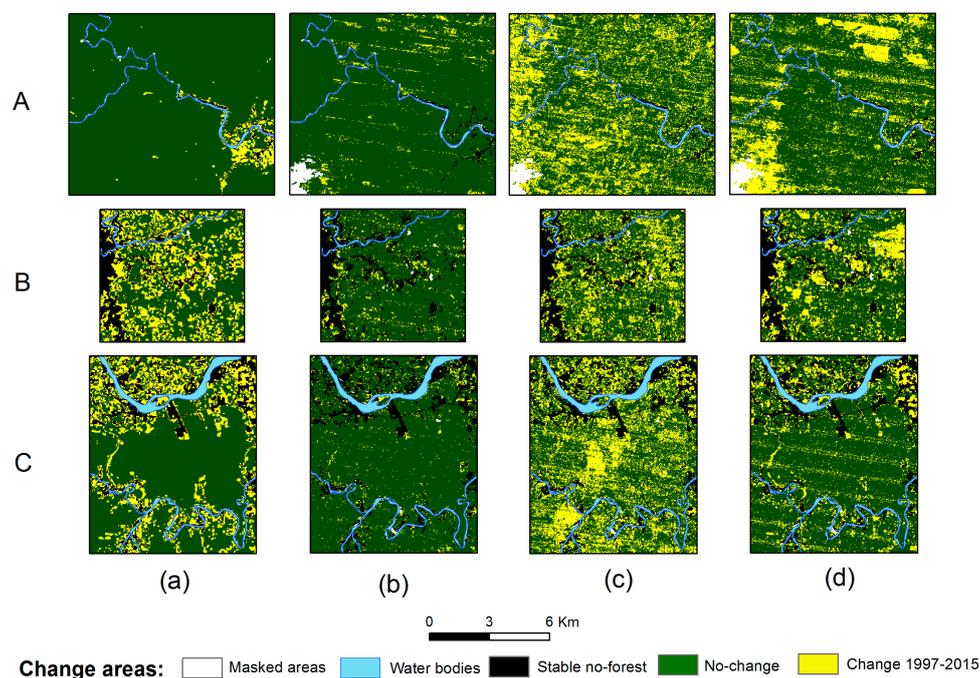


Figure 12. Spatial representations of the best BDA solutions. Study areas are shown in rows (A, B, C) and column refer to (a) The Change 1997–2015 mask, (b) BreakoutDetection, (c) Changepoint, and (d) ECP results. In all cases, no-forest areas before 1997 are shown in black, while areas not analyzed are shown in white.

6.3. Manual Optimization of ECP Calibration Solution and Execution of the PCG for a Larger Area

As GA provided us with a preliminary calibration of the ECP processing chain, we started to play with different parameters in order to see if we could improve results. After experimenting with different configurations, we observed that the only parameter that enhanced results was segment size, since it affects the number of breakpoints detected in the time-series. Therefore, we redefined this parameter into 5 (with the condition that the first breakpoint detected should be observed from the 2001 data) but we keep the other parameters as shown in Table 4. We then executed the PCG, but now applied to a larger area that contained the three study areas (Figure 13, column c). To differentiate forest dynamics classes (forest gain and forest loss), the breakpoints identified by the PCG were used to isolate two segments: (1) the “before-change” segment, which takes the segment in the time-series that happens before the first breakpoint was detected; and (2) the “after-change” segment, which takes the segment in the time-series that happens after the last breakpoint was detected. With each of them, the mean value was calculated and subtracted to obtain a residual. This was classified into 5 natural

breaks classes for enhancing different levels of greening and browning patterns, which are associated with forest gain and forest loss dynamics [6] (Figure 13, column b). As this layer highlights these dynamics, it was used for accuracy assessment using the reference samples extracted from the LCCM (Figure 13, column a). This procedure is explained in the next section.

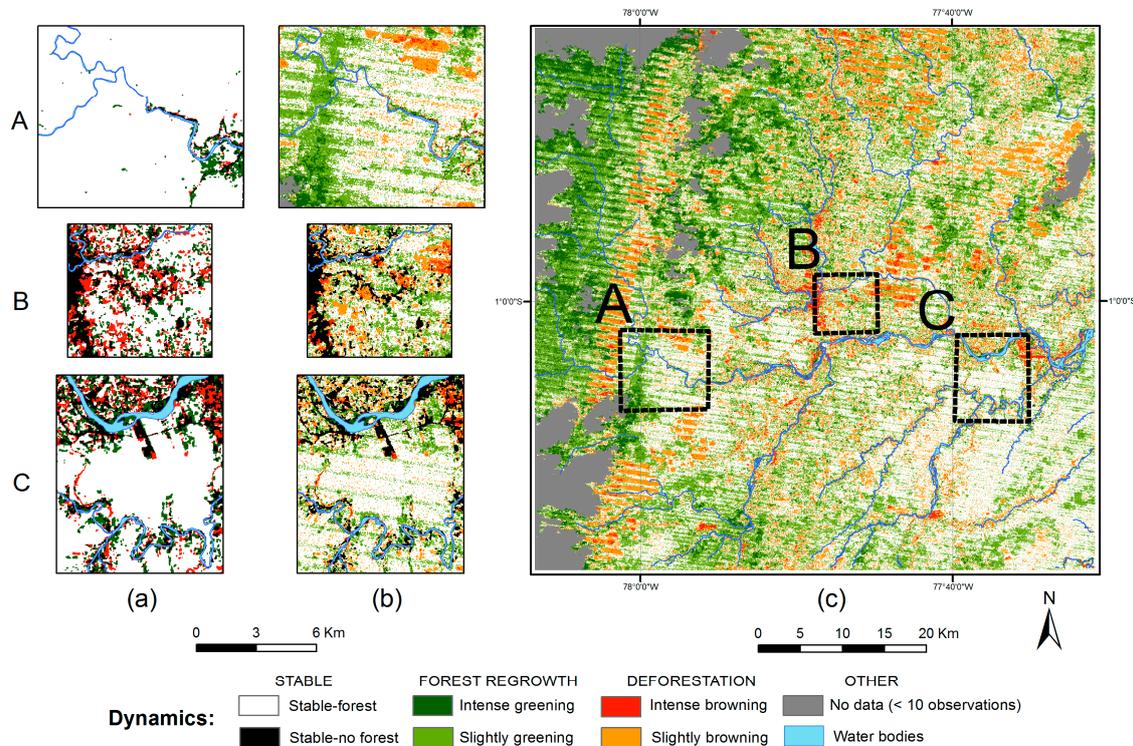


Figure 13. Application of the ECP-optimized processing chain. Study areas are shown in rows (A, B, C) and columns refer to (a) LCCM, (b) The forest dynamics map obtained, and (c) Its application to a larger area.

6.4. Accuracy Assessment

The accuracy assessment followed a similar procedure to that explained in Sections 5.2 and 5.3 but emphasized the results obtained for the forest dynamics map. To determine a sample size, we used a sampling precision of 75% and standard deviations of 1, 4, and 4 for the classes stable forest, forest gain and forest loss. The stratum were again extracted from the LCCM and this gave us a total of 551 samples, divided into 226 stable-forest, 159 forest-gain and 166 forest-loss samples. Reference information for interpreting the samples follows the same criteria explained in Section 5.3. Since the forest dynamics map contains five classes, it was reclassified for match the categories of the LCCM. This led to merging intense and slightly greening as forest gain; intense and slightly browning as forest loss; and stable class as stable forest. Results from the confusion matrix, using the evaluated pixels (1970 in total) for each sample are shown in Table 5:

Table 5. Confusion matrix for the forest dynamics map.

| Assigned Classes | Referenced Classes | | | User Accuracy |
|-------------------|--------------------|-------------|-------------|------------------------|
| | Stable-Forest | Forest Gain | Forest Loss | |
| Stable-Forest | 691 | 165 | 121 | 0.70 |
| Forest Gain | 230 | 278 | 23 | 0.52 |
| Forest Loss | 81 | 35 | 346 | 0.74 |
| Producer Accuracy | 0.68 | 0.58 | 0.70 | Overall Accuracy: 0.66 |

Overall accuracy for three study areas indicates that this map achieved an overall accuracy of 0.66, where stable-forest and forest loss were less inaccurate than forest gain (Table 5). This was less than we predicted (≥ 0.74 of overall accuracy) based on GA accuracy results. Continuing with the accuracy assessment, other measures were calculated for each study area to evaluate its specific precision. This is shown in Table 6.

Table 6. Accuracy measures for the three study areas.

| Study Areas | Classes | Measures | | | Overall Accuracy |
|-------------|---------------|-------------|-------------|-------------------|------------------|
| | | Sensitivity | Specificity | Balanced Accuracy | |
| A | Stable forest | 0.58 | 0.58 | 0.58 | 0.56 |
| | Forest gain | 0.34 | 0.71 | 0.52 | |
| | Forest loss | 0.50 | 0.88 | 0.69 | |
| B | Stable forest | 0.59 | 0.70 | 0.64 | 0.62 |
| | Forest gain | 0.56 | 0.83 | 0.69 | |
| | Forest loss | 0.70 | 0.89 | 0.80 | |
| C | Stable forest | 0.85 | 0.72 | 0.78 | 0.76 |
| | Forest gain | 0.63 | 0.89 | 0.76 | |
| | Forest loss | 0.72 | 0.97 | 0.84 | |

These results show that overall accuracies were particularly bad for study areas A and B, but better for Area C, so we further describe that section's accuracy results by class. By class, stable-forest and forest-loss classes are shown to be easier to detect, as sensibility and specificity were greater than 0.7; but forest gain is harder, since sensibility was below 0.7. As balanced and overall accuracy was greater than 0.75, breakpoint detection seems to have worked better for this unique case.

6.5. Speed Performance

As we considered processing time a key issue in breakpoint detection, average times were measured for each BDA calibration solution, running each 10 times with a sample set of 100 pixels on an Intel i7-processor-based personal computer with 8 cores. The results are shown in Figure 14a: the ECP optimized processing chain took the longest (6.5 s), followed by the Changepoint and BreakoutDetection packages (5.11 and 5.03 s, respectively). Applied to our larger area ($\sim 4400 \text{ km}^2$, ~ 5 million pixels), processing time is estimated at ~ 4.9 h for BreakoutDetection, ~ 5.06 h for Changepoint and ~ 6.4 h for ECP. However, this depends on the algorithms associated to their processing chains and not on the breakpoint detection packages themselves.

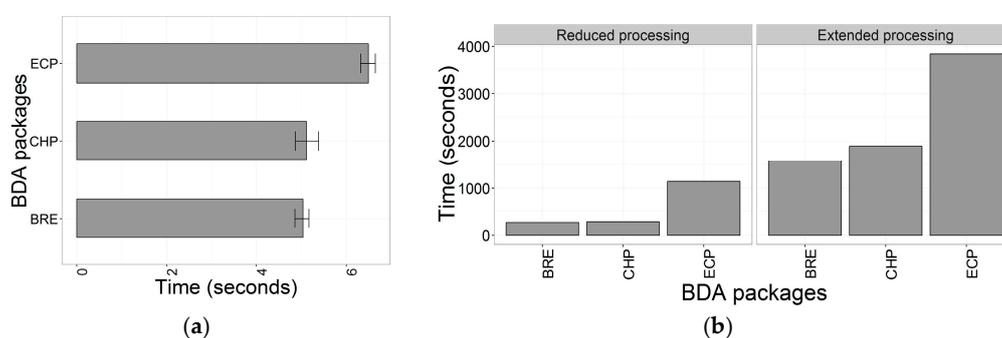


Figure 14. Execution time measured for: (a) Each BDAs optimized processing chain, running 10 times with a sample set of 100 pixels. (b) Total GA execution time obtained for each BDA package and approaches applied. Acronyms used for BDAs are: BRE for BreakoutDetection; CHP for Changepoint; and ECP for the package of the same name.

Total time for optimization using the two GA approaches are shown in Figure 14b. It was observed that extended processing (0.5–1 h) more than doubles the time required by the reduced processing

approach (0.13–0.27 h). This was partly because in the extended processing approach, GA must run the BDA packages twice, as well as running the rest of the algorithms included for noise reduction.

7. Discussion

In this paper, we present the application of a GA for optimizing a processing chain and evaluate if breakpoint detection is applicable for monitoring forest dynamics in the Andean Amazon in Ecuador. We tested this procedure on three different study areas characterized by limited data availability, high topographic relief, and landscape variability. To organize this discussion, we divide this chapter into three subsections.

7.1. Objections Regarding Breakpoint Detection and Its Applicability in the Andean Amazon

Our results show that breakpoint detection using LTS failed for the study areas A and B since breakpoints were not properly detected, while in Area C, results were better despite the fact that forest-gain class was imprecise, as sensibility was below 0.7. Furthermore, breakpoint dates detected by the ECP-optimized processing chain do not clearly reveal change events. Forest dynamics patterns we observed through the calculated metric constitute an approximation based on assumed dates of detected changes that could not be real. This contrasts the position of DeVries et al. [63] using BFAST, where forest dynamics monitoring was applied to a tropical montane forest in Ethiopia. In that research, breakpoint dates and magnitudes allowed researchers to track down and classify forest changes, indicating, however, that excessive unmasked clouds and shadows, and limited data for fit a history model, would restrict the use of the algorithm. Both sources of errors impacted our case, since data availability in some areas was less than 41 images (reddish areas, Figure 2b) with some of those affected by unmasked clouds and shadows, in some cases resulting in one or no usable observations for a year or more. This prevented our using that algorithm, supporting our objection regarding breakpoint detection and its applicability in some areas of the Andean Amazon.

On the other hand, our exercise of calibrating the PCG and implementing breakpoint detection with scarce and noisy data conditions introduced additional problems since parametrization was complex and had to be solved by a GA. On this point, if we consider the implementation of breakpoint detection for a larger area in the Andean Amazon, calibration could be a problem since parametrization will be unique to each landscape configuration and its specific data conditions. For this reason, the processing time required to optimize such processing chains also constitutes a drawback. As we seen, GA is a computing-intensive simulation the implementation of which was only possible when a small training sample size was applied to optimize the PCG. This certainly affected the effectiveness of the optimization, since overall accuracy between training and reference samples differed significantly (0.74 against 0.66, respectively, for the ECP-optimized processing chain). Finally, even if the calibration problem is solved, a complete Landsat footprint could require ~49 h of processing time using a personal computer with 8 cores (Intel i7 processor) and the ECP-optimized processing chain. Considering these results, processing time is certainly excessive for a single Landsat footprint, whose noisy outputs, applied on a relatively larger scale in our research, did not satisfy our expectations regarding its use in the Andean Amazon.

7.2. Considerations When Data Quantity Allows the Implementation of Breakpoint Detection

Despite these objections, some results deserve to be mentioned as they seem to diminish the effect of some problems and improve breakpoint detection in some specific cases observed in our study areas. First of all, as Area C obtained an improved result, data quantity and geometric accuracy are the first factors to consider for a successful implementation. As was seen in Figure 2b, the spatial distribution of no data frequency in Area C was almost homogeneous. This suggests that the threshold required for using the ECP-optimized processing chain was around 55 to 71 observations. However, these observations should be distributed along the time-series in order to have yearly mosaics almost free of gaps and properly co-registered in order to allow breakpoint detection [64]. As data quantity

requirements are not always made explicit by developers of BDAs, and geometric accuracy of image subsets could be different than the value reported on its metadata, it is worth knowing these aspects before a BDA is considered for its use.

To diminish the effects of atmospheric contamination, the aerosol-free vegetation index (AFRI), and other indices derived from shortwave infrared bands using only the Landsat surface reflectance products, seem to ameliorate this effect and enhance analysis of forest dynamics as Matricardi et al. [35] also found. However, it was seen in Figure 13c that the application of the ECP-optimized processing chain for a larger area was affected by radiometric differences between Landsat footprints. This was concluded after observing the asymmetries between left and right sides of the metric calculated. Therefore, users of Landsat surface reflectance products should notice that sensor calibration is not homogeneous and radiometric normalization should be applied. In our case, the relative radiometric normalization procedure applied does not seem to reduce this effect; therefore, authors do not recommend its application, and a better method independent from the footprint area should be considered. Furthermore, as cloud and shadow masks fail from time to time, its correction is our first recommendation. However, as outlier detection with a local outlier factor algorithm helped to reduce the incidence of these pixels as false-positive breakpoints, its appliance should be considered but carefully calibrated, as forest changes could be erroneously interpreted as outliers in some cases.

With regard to enhancing the calibration sensibility of BDAs, signal smoothing with a local polynomial regression-fitting algorithm helped us to improve it, especially when threshold parameters did not react and a subtle sensibility to breakpoint detection is required. Other researchers found this procedure useful when LTS is used and the adjustment of models requires an improvement of their signal quality [65,66].

Finally, it was seen that a non-parametric breakpoint algorithm behaved better in our case than parametric algorithms. Apparently, the absence of assumptions of data normality in the ECP package seemed to improve our results. This is also becoming an important research field, since non-parametric algorithms in remote sensing are more flexible for solving tasks where data quality and quantity are not exceptional [67,68]. However, as other assumptions could exist, knowledge is a must for proper implementation of these algorithms.

7.3. Some Advice for Improved Optimization of Complex Functions with GA

As GA constitutes our innovative contribution to this body of research, some advice regarding its implementation should be considered. First, splitting the search space into modules is a useful strategy to avoid becoming stuck in local optimization and to produce relatively quickly. This is corroborated by Garibay et al. [69], who indicate the benefits of splitting a search space into small modules instead of analyzing large and complex search spaces as a single module.

Regarding calibration, we found that GA was sped up when a higher mutation rate was applied. This condition predefines a more diverse population, consequently producing more diverse combinations of parameters. This conclusion is also supported by References [70,71], wherein exhaustive GA experiments were conducted and similar results, i.e., where mutation rate and crossover probability significantly influenced GA success, were found. However, as calibration of GAs implies many other parameters, the authors recommend implementing other approaches, such as those analyzed by El-Mihoub et al. [72], which can simplify this task.

Finally, because GA is computationally demanding, it is obvious but nonetheless important to mention that the workload introduced by the objective function and its training data should be carefully examined. If any of these elements introduce bottlenecks or code bugs during execution, GA will result in an overflow. This condition can limit calibration to small population sizes and lead to premature convergence [61] and less than satisfactory results. Therefore, processing time should be evaluated with different training data sizes and the objective function should be optimized as much as possible.

8. Conclusions

This research demonstrated that breakpoint detection should be carefully evaluated before its appliance for monitoring forest dynamics in the Andean Amazon using LTS, since insufficient data availability, inaccurate co-registration, radiometric variability in sensor calibration, and unmasked cloud and shadow pixels compromise its implementation in most areas of the Andean Amazon. Moreover, since landscape diversity in the Andean Amazon includes heterogeneous conditions, which require specific calibrations for breakpoint detection, its optimization could be compromised as more processing chains will be required for each specific landscape configuration. This is certainly costly in terms of software development and processing but also inefficient for large scale monitoring projects in the region. Therefore, users should consider these limitations and suggestions before implement breakpoint detection in similar landscape conditions.

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Author Contributions: F.S. conceived, developed, and executed the experiments and manuscript. O.D. contributed to the manuscript preparation and discussion. G.M. supervised the design of the research and participated in the field survey.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

| | |
|--------|--|
| BDA | breakpoint detection algorithms |
| PCG | processing chain generator |
| GA | genetic algorithms |
| LTS | Landsat time-series |
| LCCM | land cover change map |
| REF | surface reflectance |
| TOPO | topographic correction |
| NREF | radiometric normalization of surface reflectance |
| NTOPO | radiometric normalization of topographic correction |
| ECP | Non-Parametric Multiple Change-Point Analysis of Multivariate Data package |
| LOF | local outlier factor algorithm |
| NBR | Natural Burn Ratio |
| GEMI | Global Environmental Monitoring Index |
| TCTB | Tasseled Cap brightness |
| TCTG | Tasseled Cap greenness |
| TCTW | Tasseled Cap wetness |
| MSAVI | Modified Soil Adjusted Vegetation Index |
| AFRI16 | Aerosol Free Vegetation Index 1.6 μm band |
| AFRI21 | Aerosol Free Vegetation Index 2.1 μm band |

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