Novel Bayesian Approach Based on Infinite State Markov Chains for Prompt Detection of Forest Loss Using Sentinel-1 Time Series

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Abstract

Forests globally are facing substantial changes due to forest loss, emphasizing the urgent need for real-time forest surveillance to mitigate further vegetation loss [1]. Traditional forest monitoring relied heavily on optical imagery, hindered by cloud coverage, particularly in tropical areas [2]. Synthetic Aperture Radar (SAR) systems have emerged as a promising alternative due to their all-weather operability [3, 4, 5], although they face challenges such as:

- Changes in backscatter caused by soil conditions;
- Filtering hampering small-scale detections;
- Forest loss monitoring in seasonality-prone areas.

This study presents an unsupervised SAR-based technique utilizing Bayesian inference based on infinite state Markov chains for identifying forest loss, addressing limitations of existing methods. Evaluation against Near Real-Time (NRT) forest loss monitoring systems showed significant improvements, with our adaptive approach achieving higher accuracy and lower false alarm rates in two different Brazilian biomes, demonstrating efficacy in regions with seasonal variations that challenge existing monitoring systems.

Keywords: Forest Loss, Change Detection, Bayesian Inference, Sentinel-1, Time-Series.

Study Area

The selected study area is Brazil, where 6.5 million hectares were deforested between 2019 and 2022. 90% of this deforestation occurred within two biomes.

Amazonia
Rainforest
40% of Brazil

Largely monitored

Cerrado
Savanna
20% of Brazil

Under-monitored

Validation Data

The reference dataset was produced by MapBiomas Alerta. Particularly, the validation campaign focused on small-scale deforestation (i.e., < 1ha) for the monitoring year 2020 [7].

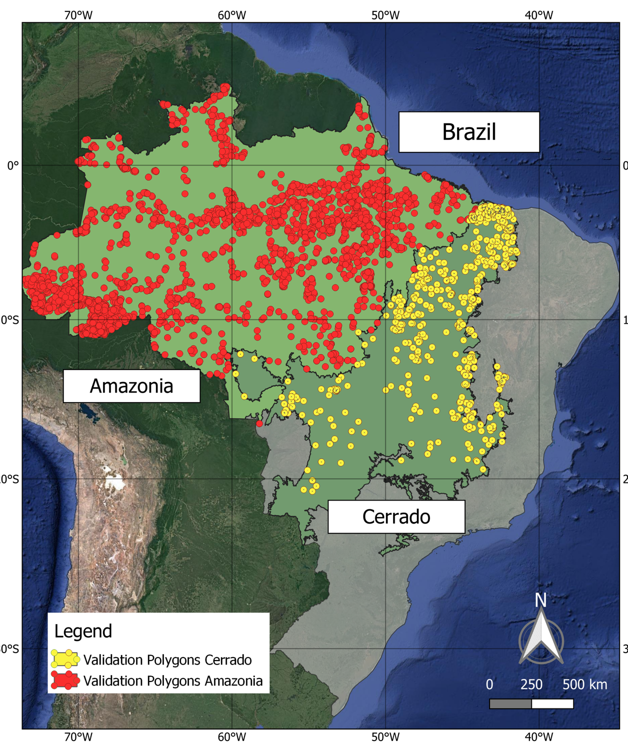


Figure: MapBiomas Alerta validation dataset

Conclusions

This work offers some key contributions: (**1**) A novel method for NRT forest loss detection, exhibiting enhanced detections and reduced false alarms compared to existing systems. (**2**) Application of the method in a seasonality-sensitive biome (i.e., Cerrado), showcasing its adaptability to varying patterns. (**3**) A filtering-free approach preserving spatial resolution, and mitigating deforestation overestimation.

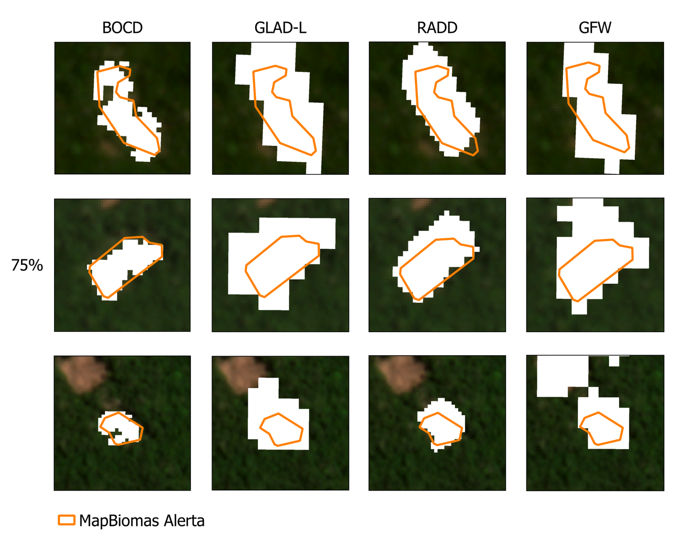


Figure: Example of small-scale deforestation over-estimation of existing NRT systems compared to BOCD.

Method

Bayesian Online Changepoint Detection (**BOCD**) is a statistical method that partitions a time series into segments by tracking the posterior distribution over the most recent change point, thus inferring the run length, r_t, of the current segment. As the time series can be partitioned in infinite ways, the model resembles an infinite state Markov chain.

Hypotheses

- Sequence of Sentinel-1, single polarization observations partitioned by change points;
- Data in each segment are independent identically distributed samples from p_θ via:

$$\theta \sim \pi(\theta) \quad \text{Parameter prior}$$
$$x_t|\theta \sim p_\theta(x_t) \quad \text{Data model}$$

- Conditional prior on r_t: $r_t|r_{t-1} \sim H(r_t|r_{t-1})$.

Quantity of interest

$$p(r_t|\mathbf{x}_{1:t}) = \frac{p(r_t, \mathbf{x}_{1:t})}{\sum_{r_t=0}^{t} p(r_t, \mathbf{x}_{1:t})}$$

The posterior over the run length is tractable in case the joint distribution is also tractable [6]:

$$p(r_t, \mathbf{x}_{1:t}) = \sum_{r_{t-1}=0}^{t-1} p(x_t|\mathbf{x}_{t-1}^{(r_t)}) \cdot H(r_t|r_{t-1}) \cdot p(r_{t-1}, \mathbf{x}_{1:t-1})$$

From the latter, the posterior predictive is:

$$p(x_t|\mathbf{x}_{t-1}^{(r_t)}) = \int_\Theta p_\theta(x_t) \cdot \pi(\theta|\mathbf{x}_{t-1}^{(r_t)}) d\theta$$

The integral is tractable only in case of conjugate likelihood-prior pairs.

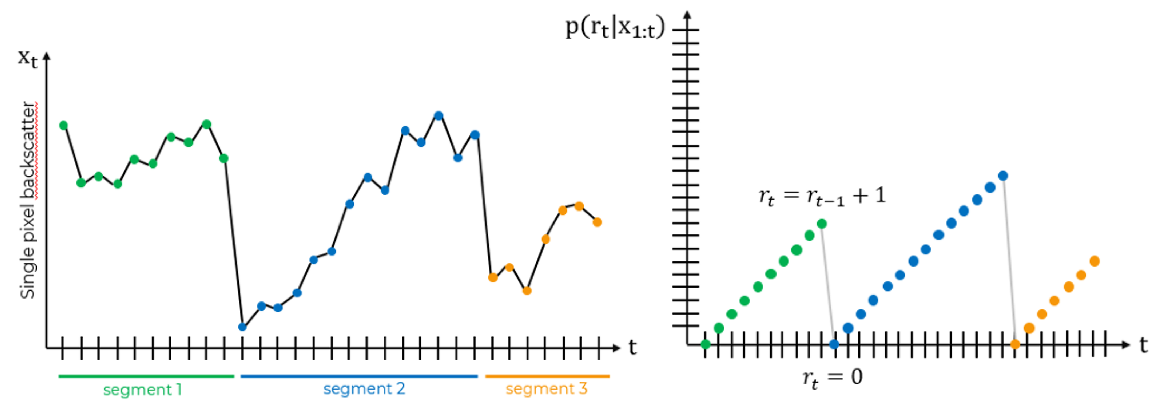


Figure: Example of time series and associated run length.

Spatial Results

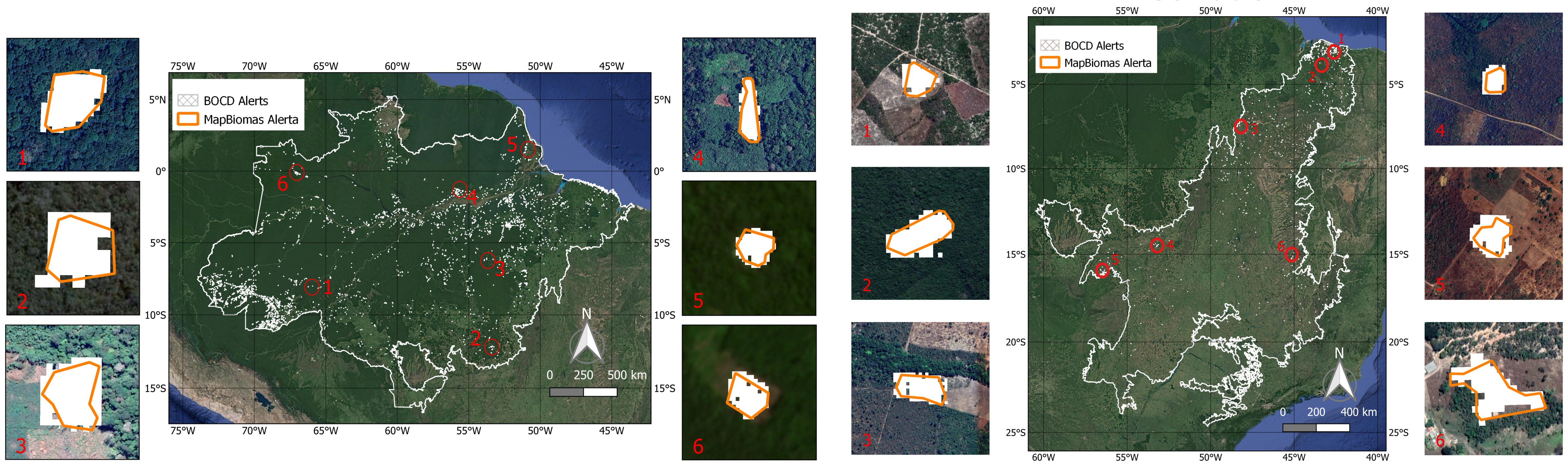
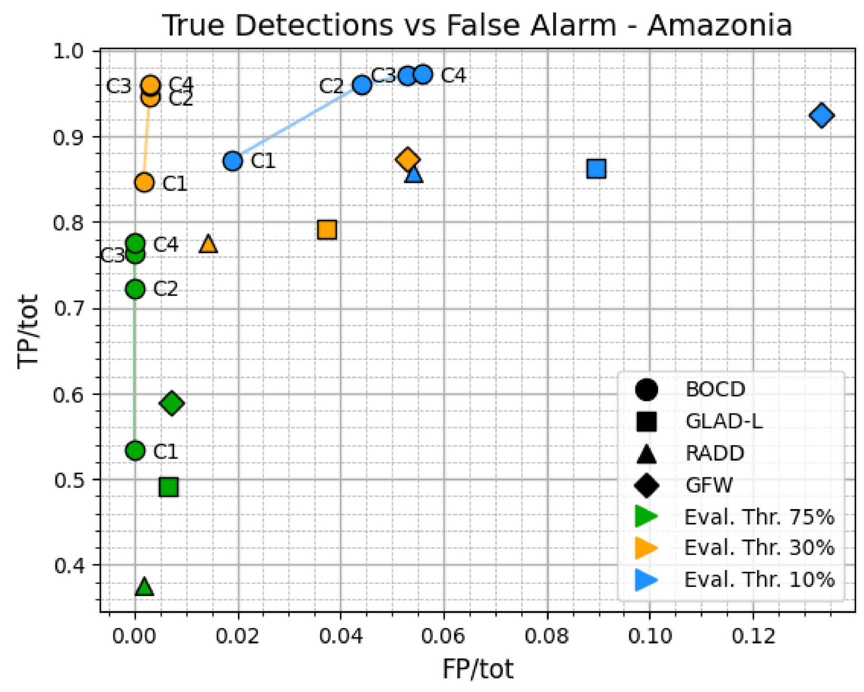


Figure: Small-scale forest disturbance for 2020 generated by BOCD over the Amazon (**left**) and the Cerrado (**right**), in comparison with MapBiomas Alerta reference data. Optical background image from Google Earth (©2023 Google)

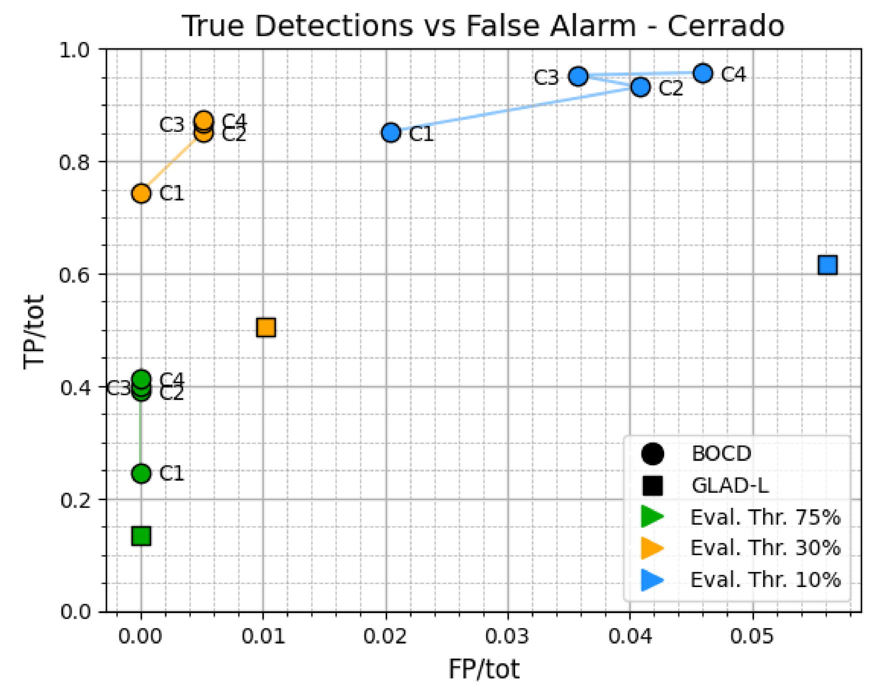
Performance Metrics & Comparison with other NRT systems

Performance metrics were assessed for the BOCD method across different configurations, each representing varying levels of conservatism, and compared with existing operational NRT systems. The NRT systems included in the comparison are GLAD-L ([2], optical-based), RADD ([3], SAR-based), and GFW (an ensemble of optical and SAR-based alerts).

Amazonia



Cerrado



Figures: Normalized true positives vs normalized false positives of the different systems for the Amazon (**left**) and the Cerrado (**right**) biomes. The labels C1, C2, C3, and C4 denote various configurations the BOCD method, each representing distinct degrees of conservatism.

	BOCD-C1	BOCD-C4	GFW
F1, thr=75%	69.6%	87.4%	74.1%
F1, thr=30%	91.6%	97.9%	92%
F1, thr=10%	92.7%	97.3%	93.1%

	BOCD-C1	BOCD-C4	GFW
F1, thr=75%	69.6%	87.4%	74.1%
F1, thr=30%	91.6%	97.9%	92%
F1, thr=10%	92.7%	97.3%	93.1%

Tables: F1-score comparison between systems for varying evaluation thresholds. (**left**) Amazon, (**right**) Cerrado.

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