Enhanced Near Real-Time Forest Loss Monitoring with a Bayesian Change Detection Method and Sentinel-1 SAR Imagery: Application to the Cerrado Biome

Marta Bottani, Laurent Ferro-Famil, Thuy Le Toan, Juan Doblas, Stéphane Mermoz, Thierry Koleck

Forests worldwide have experienced significant transformations due to ongoing deforestation. The United Nations Food and Agriculture Organization (FAO) estimates an annual loss of approximately 10 million hectares. In Brazil, which accounts for about 12% of the world's forests, over 1.8 million hectares were deforested in 2023 alone. Alarmingly, 98% of this deforestation exhibited signs of illegality, as reported by MapBiomas Alerta in its 2023 annual report [1]. Recent trends reveal that the Cerrado, the world's most biodiverse woodland savanna, has emerged as the biome with the highest increase in deforestation rates. Additionally, there has been a reduction in the maximum size of deforested areas, likely due to illegal activities being conducted more rapidly to evade legal consequences. These alarming patterns highlight the critical need for near real-time forest monitoring to prevent further vegetation loss and facilitate prompt interventions, particularly targeting the monitoring of savanna-like biomes.

Traditionally, forest loss monitoring has relied on optical imagery, with GLAD-L [2] developed by the University of Maryland serving as a notable precursor in this field. However, the effectiveness of optical imagery is often hampered by cloud coverage, which limits the availability of usable images and potentially delays responses to illegal activities. In recent years, Synthetic Aperture Radar (SAR)-based systems have emerged, offering the advantage of all-weather operability. Notably, Sentinel-1 data has proven to be a valuable resource due to its extensive coverage, open-access policy, and high revisit frequency of six days over tropical regions, facilitated by two operational satellites. Several forest loss monitoring systems, including RADD [3] developed by Wageningen University in the Netherlands, TropiSCO [4] from the Centre Nationale d'Études Spatiales (CNES) and CESBIO in France, and DETER-R [5] from the Instituto Nacional de Pesquisas Espaciais (INPE) in Brazil, are based on Sentinel-1 imagery.

However, SAR-based approaches utilizing C-band data face several challenges in the context of forest loss monitoring. These challenges include the low contrast between forested and deforested areas, which can be further reduced by factors such as variations in soil moisture and the presence of residual biomass on the ground following deforestation activities. Furthermore, accurately detecting small-scale disturbances—recently reported as a growing trend in illegal deforestation practices—remains problematic for existing SAR-based systems. This difficulty arises partly due to the spatial filtering techniques used to mitigate speckle variations, which can degrade the spatial resolution of measurements, leading to omissions and sometimes over-detections in the change monitoring process. Additionally, monitoring forest loss in regions characterized by pronounced seasonality in backscatter signals, such as dry forests and savannas, presents further limitations. As a result, the Cerrado biome in Brazil, known for being an extensive carbon sink, is significantly under-monitored. At present, monitoring efforts for the Cerrado are largely dependent on optical-based methods, with the exception of a single supervised SAR-based approach, the LUCA dataset [6].

This study presents BOCD, an innovative unsupervised methodology for detecting forest loss, utilizing SAR data, and employing Bayesian inference through a hidden infinite-state Markov chain. This approach conceptualizes forest loss as a change-point detection problem within a Radiometrically Terrain Corrected (RTC) Sentinel-1 single polarization (VH or VV) time series. A significant advantage of this method is its ability to maintain the native resolution of Sentinel-1 RTC products, eliminating the need for spatial filtering, which often compromises data quality. Each new observation is integrated into the model, contributing to the probability of deforestation by leveraging prior information alongside a robust statistical data model [7]. The method's sequential adaptation process is designed to be resilient against variations and trends, enabling effective forest loss monitoring not only in dense forests, as demonstrated in previous studies validating our approach in regions like the Brazilian Amazon [8], but also in areas affected by seasonal fluctuations, thereby addressing limitations associated with traditional methods.

Since savanna-like biomes are often characterized by a diverse composition of land cover types—including forest formations, savannas, and grasslands—we aim to enhance detection accuracy in these mixed land cover areas by leveraging the distinct sensitivities of VH and VV channels of Sentinel-1. Specifically, we extend the BOCD methodology to the dual-polarimetric case (Pol-BOCD) by modeling our data with a bivariate distribution and deriving a suitable Bayesian inference model that exploits conjugacy between the data likelihood and the prior. Pol-BOCD enables the use of specific channel characteristics, such as the sensitivity of VH to volume scattering and that of VV to double-bounce effects, thereby improving forest loss monitoring in mixed land cover regions.

The BOCD and Pol-BOCD methods are evaluated for true detections, omissions, and false alarms using the MapBiomas Alerta validation dataset [9], including small-scale (<1 hectare) deforestation polygons detected in the Cerrado woodland savanna in 2020. This assessment considers varying the evaluation threshold, defined as the percentage of a detected polygon required to confirm or reject a detection based on user-defined needs. Additionally, we compare the performance of our methods with GLAD-L, a fully automated and readily available monitoring system for the Cerrado. No comparison was made with the LUCA dataset, despite its operational coverage of the Cerrado, as its forest loss products are not freely available and its accuracy metrics are reported at the continental level rather than by biome.

Our research unveils significant progress in detecting small-scale disturbances, accompanied by remarkable robustness to false alarms in comparison to GLAD-L. Single-polarization VH-BOCD demonstrates greater suitability for detecting forest loss than VV-BOCD due to its higher backscatter contrast between intact vegetation and deforestation, as well as its sensitivity to volume scattering. Nonetheless, VV-BOCD performs better in specific contexts where ground visibility is prominent. Ultimately, Pol-BOCD improves true positive detections compared to the single-polarization algorithms while maintaining resilience to false alarms, especially at high evaluation thresholds. This indicates that forest loss occurring over the mixed land cover types typical of the Cerrado benefits from a dual-polarimetric approach that exploits the distinct sensitivities of Sentinel-1 VH and VV channels. Regardless, all BOCD systems attain an F1-score greater than 95%, distinctly surpassing the 75.5% obtained by GLAD-L.

In conclusion, our adaptive approaches significantly improve the timely detection of forest loss with low false alarm rates, demonstrating efficacy in monitoring the Cerrado biome, where seasonal variations challenge existing systems and, in most cases, limit their monitoring capabilities. Furthermore, a focused comparison highlights a reduced over-detection of small-scale forest loss by the BOCD systems compared to GLAD-L, likely due to the avoidance of spatial filtering, which preserves the resolution of Sentinel-1 data.

References

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