DETER-RT: The new INPE-TropiSCO deforestation monitoring system in the Amazon biome

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Abstract

The Amazon biome, undergoing significant deforestation, requires robust monitoring systems for effective management and conservation. This study introduces DETER-RT, a novel deforestation detection system that combines the Synthetic Aperture Radar (SAR)-based DETER-R and the TropiSCO systems to enhance detection capabilities using Sentinel-1 satellite data. DETER-RT utilizes a double-threshold technique to optimize the detection of deforestation by balancing detection accuracy and minimizing false positives across different forest types and conditions in the Amazon. The new system modulates detection thresholds based on the proximity of new disturbances to previously detected deforestation, incorporating a dynamic, regionalized threshold adjustment to cater to the variable characteristics of the Amazon's diverse forest cover. Initial results indicate that DETER-RT provides more timely and accurate warnings compared to existing methods, especially during the fire season, where its performance is less impacted by smoke and haze that typically hinder optical sensors. This approach exemplifies the integration of advanced remote sensing technologies and analytical techniques in environmental monitoring.

1. Introduction

Deforestation rates and hotspots vary in space and time in the Brazilian Amazon (Schielein and Börner, 2018). Near real-time (NRT) information about the forest cover has been proven a crucial tool for the inspection and control of deforestation events (Assunção et al., 2019; Finer et al., 2018; World Resources Institute, 2021). Due to the need for continued vigilance and intervention for forest protection, many agencies worldwide have developed NRT deforestation detection systems able to monitor the region throughout the year, based on different detection methodologies.

Brazil has developed a pioneer NRT deforestation detection system aptly called Near Real-Time Deforestation Detection System (DETER), which has been operated by the National Institute for Space Research (INPE) since 2004. DETER is the official governmental system monitoring the Amazon biome (Diniz et al., 2015) and was implemented as part of the Plan of Action for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). Created as a single system based on the visual interpretation of medium spatial-resolution optical remote sensing, DETER has evolved into a family of systems that encompasses different remote sensing data and detection methodologies (Soler et al., 2021), as well as biomes (National Institute for Space Reseach, 2024) and types of vegetation within the Amazon (Messias et al., 2023). The main system currently monitoring forest vegetation within the Amazon is known as DETER-B (Diniz et al., 2015).

DETER-B operates based on the visual interpretation of optical images. However, methodologies capable of automatically detecting deforestation events are of particular interest to the Brazilian government. This fostered the development of the Synthetic Aperture Radar (SAR) system of the DETER family, called DETER-Radar (DETER-R) (Doblas et al., 2022). DETER-R automatically monitors forests in the Amazon biome by applying thresholds on change metrics calculated from time series of C-band backscatter of the Sentinel-1 (S1) constellation. DETER-R uses flexible thresholds based on the distance of previously detected deforestation events and the local backscatter time series. In its three years of operation (from 2021-04-21), DETER-R has issued around 1.6 million ha of warnings, evaluated to have a false positive rate lower than 0.50% (0.46% in number and 0.26% in area of warnings). This low commission rate comes with the need to use very restrictive thresholds, which leads to omission errors (Reis et al., 2023).

Other available systems, as for example TropiSCO, have shown the potential to avoid this omission problem. The TropiSCO system (Mermoz et al., 2021) was originally developed by the *Centre National d'Études Spatiales* (CNES), Global Earth Observation (GlobEO) and the *Centre d'Etudes Spatiales de la Biosphère* (CESBIO) through the Space Climate Observatory (`https://spaceclimateobservatory.org`). This system is also based on the automatic processing of Sentinel-1 time series, with the advantage of flagging areas of deforestation in two steps: 1) first by detecting radar shadows caused by deforestation events, and then 2) delineating the deforested area that has also changed (Bouvet et al., 2018). This approach, based on the Radar Change Ratio (RCR) index, has the advantage of allowing for higher thresholds without increasing the commission rates of the system.

Although implemented based on different methodologies and architectures, DETER-R and TropiSCO show remarkable synergy potential. As such, this research presents the proposal for merging these systems into the herein-presented DETER-RT framework.

2. Materials and Methods

DETER-RT has been designed by combining elements of both DETER-R and TropiSCO systems and by adding additional features produced by joint INPE/CNES/GlobEO/CESBIO research. The three systems are based on the same collection of S1 images, detailed in Section 2.1. Sections 2.2 and 2.3 detail the DETER-R and TropiSCO systems, respectively. Section 2.4 presents the merging process and the resulting characteristics of DETER-RT. The following sections present the experiments designed to calibrate DETER-RT: the initial comparison of TropiSCO modulated results to other state-of-the art systems (Section 2.5); analysis of the spatial optimization of thresholds per ecoregion (Section 2.6); computation of the distance of recent deforestation events and consolidated deforested areas (Section 2.7); and DETER-RT performance assessment (Section 2.8).

2.1 Imagery

DETER-R, TropiSCO and, subsequently, DETER-RT are based on S1 data acquired in the Interferometric Wide Swath (IW) mode and polarization VH. Whereas DETER-R uses only data acquired in descending orbits, TropiSCO and DETER-RT uses data acquired in both ascending and descending orbits. Furthermore, DETER-R is based on the S1 images loaded and processed by the Google Earth Engine (GEE), in the Ground Range Detected (GRD) format. TropiSCO and DETER-RT are based on similar images hosted and processed by CNES' *Plateforme d'Exploitation des Produits Sentinel* (PEPS).

2.2 DETER-R

DETER-R was formulated and runs based on GEE capabilities, following the steps detailed in Doblas et al. (2022). Basically, DETER-R:

1. Selects S1 images from the GEE catalog;
2. Preprocesses these images to correct variations in backscatter intensity due to the local incidence angle, speckle effect, and seasonal variations on canopy;
3. Computes warning rasters of anomalies based on the Adaptive Linear Thresholding (ALT) technique (Doblas et al., 2020), with thresholds modulated by the distance of previously detected deforestation events;
4. Vectorizes the detected anomalies to generate deforestation warning polygons. DETER-R only issues warnings for polygons that surpass a set of filters to check for the Minimum Mapping Unit (MMU) (currently, 0.4 ha) and recurrence of detection;
5. Issued warnings are further subjected to a validation process encompassing the cross-validation with DETER-B deforestation warnings and the visual interpretation of optical images of near dates;
6. Warnings of interest are then sent to partner agencies.

2.3 TropiSCO

Differently from DETER-R, which uses Google's proprietary technology, TropiSCO uses the open-source PANGEO paradigm and the computational capabilities of the *Centre National d'Études Spatiales* High-Performance Computing (CNES-HPC) to process and analyze large time series of S1 data. Maps generated by CESBIO's system are part of the TropiSCO project and are available on its dedicated website (`https://tropisco.org`). Details about the project can be found at the Space Climate Observatory's page for TropiSCO Amazonia (`https://www.spaceclimateobservatory.org/tropisco-amazonia`). TropiSCO's methodology is detailed in Mermoz et al. (2021). In a nutshell, TropiSCO:

1. Selects S1 images from the PEPS archive;
2. Preprocesses these images using the open source package S1-Tiling (`https://github.com/CNES/S1Tiling`). Images are orthorectified, cut in tiles defined by the 110 km × 110 km Military Grid Reference System (MGRS), normalized using incidence and local incidence angles, and then filtered based on previously processed images;
3. Computes the features known as Radar Change Ratio (RCR) and synthetizes the minimum value of a RCR time series into the RCRmin attribute;
4. Computes anomaly rasters based on a double thresholding approach that considers radar shadows and drops in brightness caused by deforestation events. This detection respects an MMU of 0.1 ha;
5. Freely divulges the results on its dedicated website.

2.4 Development of the DETER-RT system

DETER-RT uses the core detection system proposed by TropiSCO, therefore based on CNES-HPC capabilities and the double-threshold methodology proposed by Bouvet et al. (2018). As a novelty, thresholds are regionalized and vary spatially, following changes in the type of vegetation in the Amazon biome, as presented in Section 2.6. These thresholds, however, are modulated by the distance of the analyzed pixel to the previous deforestation (Section 2.7), following the DETER-R detection paradigm. In the near future, DETER-RT detections will be further vectorized and evaluated following the DETER-R quality assessment approach and divulged to monitoring and control agencies once it is fully operational. We also expect to divulge DETER-RT results on the DETER dedicated web page (`https://terrabrasilis.dpi.inpe.br/`). Figure 1 synthesizes the main elements of DETER-RT, in comparison to DETER-R and TropiSCO.

The following section presents the methodology used to determine if the improvements applied to the input systems were producing the desired results, in terms of detection accuracy and timeliness.

2.5 Initial comparison with other systems

First, we investigated if adjusting the original thresholds used in TropiSCO could improve the accuracy of detection. We then compared these values with other well-known NRT forest deforestation detection systems: RAdar for Detecting Deforestation (RADD) (Reiche et al., 2021) and optical system Global Land Analysis & Discovery (GLAD) (Pickens et al., 2020).

2.6 Spatial optimization of thresholds per ecoregion

As part of a joint research effort INPE-CESBIO, we performed a basin-wide test to elucidate whether the optimal thresholds vary as a function of the variations in the forest types. To do so, we applied the TropiSCO algorithm to a set of 19,256 deforestation samples, produced by INPE, and then refined by the Mapbiomas Alerta (MBA) initiative (https://alerta.mapbiomas.org/). The added value of the MBA-refined alerts consists of 1) the validation of the warnings by external interpreters over very high-resolution images and 2) the addition of two-time stamps to every warning: the last date when vegetation was seen and the first date when deforestation was seen. This double refinement allowed us to choose areas that were precisely deforested in a given year.

We ran the deforestation detection algorithm using different levels of thresholds for all the MBA polygons deforested in the year 2020. To do so, we applied a multiplicative threshold correction factor ranging from 0.8 to 1.2 with a 0.05 step. A threshold correction factor >1 would lead to a stricter system with potentially fewer detections, and <1 results in more detections but more false alarms. We also varied the time range of the analyzed images, using 2020 S1 images to evaluate the true positives vs. omissions and 2019 images to evaluate commissions vs. true negatives. This procedure allowed us to compute confusion matrices for every threshold level and ecoregion.

2.7 Threshold modulation as a function of the distance to deforestation areas

We used the same reference dataset from the previous section to update the deforestation probability vs. distance curve used in DETER-R for DETER-RT. Then we measured the effect of different degrees of variation of the threshold with distances over a subset of the reference polygons. To help calibrate this feature, we added to the validation dataset a set of polygons manually drawn over unaltered, distant forest areas. An effective calibration of the probability vs. distance curve allows to lower the warnings in these deep-forest areas while maintaining accuracy in the closer-to-deforestation areas.

2.8 Preliminary timeliness assessment

We also evaluated the DETER-RT temporal performance by computing the date of detection of all the deforestation warning polygons detected by its optical counterpart (DETER-B) over three Brazilian municipalities (Feliz Natal, Lábrea and São Félix do Xingu) between 2018 and 2023 (n=17,033). We then computed the percentage of warnings that could be detected by DETER-RT before DETER-B.

3. Preliminary results

DETER-RT calibration and preliminary validation performances are presented in this section.

3.1 Initial comparison with other systems and threshold adjustment

Figure 2 shows the variation in accuracy indexes in TropiSCO given variations in the used thresholds. Straight horizontal lines illustrate the accuracy indexes for other monitoring systems. As can be seen in this figure, adjusting the threshold can optimize TropiSCO results and overpass other, state-of-the-art deforestation detection methods.

3.2 Thresholds regionalization

Regarding the regionalization of thresholds, we verified that there were substantial differences in the accuracy vs. threshold curves over the different ecoregions covering the Amazon biome (Appendix 1). Most (but not all) moist forest regions need a low threshold correction level (around 0.85) to maximize global accuracy, whereas *várzea* forests need higher corrections (around 1.05). Open forest formations have different behaviors, with overall lower performance than denser forests.

The accuracy charts obtained at this point of the research will guide the choice of the final, operational thresholds for every ecoregion. They allow the users of the system (in this case, INPE) to make an informed decision on the operational threshold as a function of their needs in terms of frequency of commission and omission errors.

3.3 Curve of probability of deforestation

Another result of the DETER-RT preparation phase was the update of the curve of probability of deforestation, and its corresponding analytical model. These results are illustrated in Figure 3.

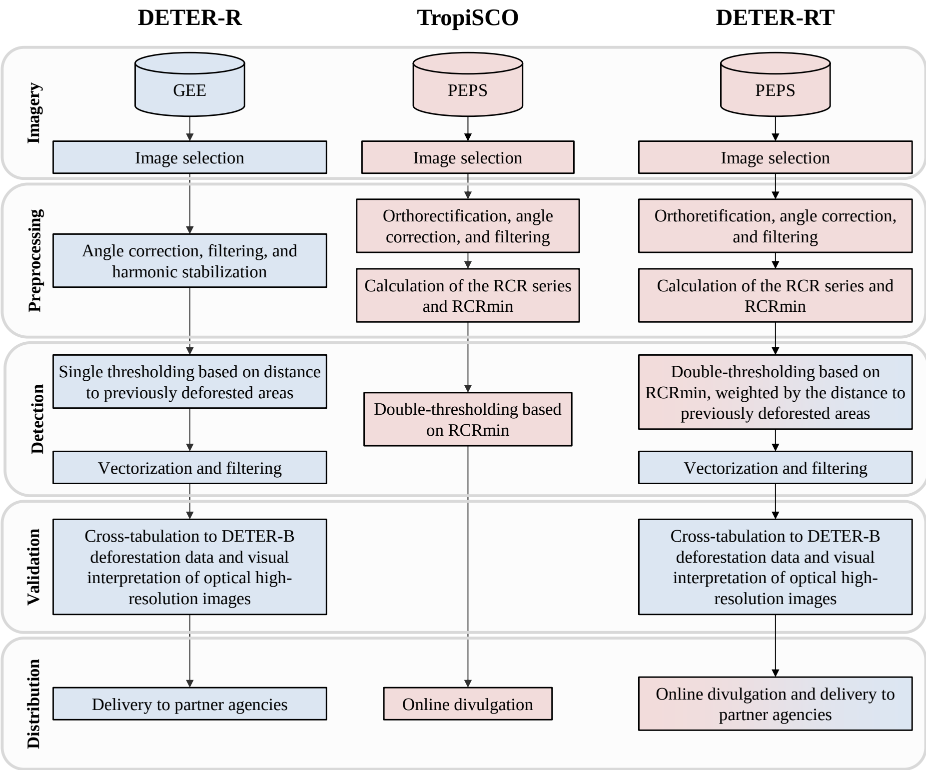


Figure 1. Combination of DETER-R and TropiSCO main elements into DETER-RT.

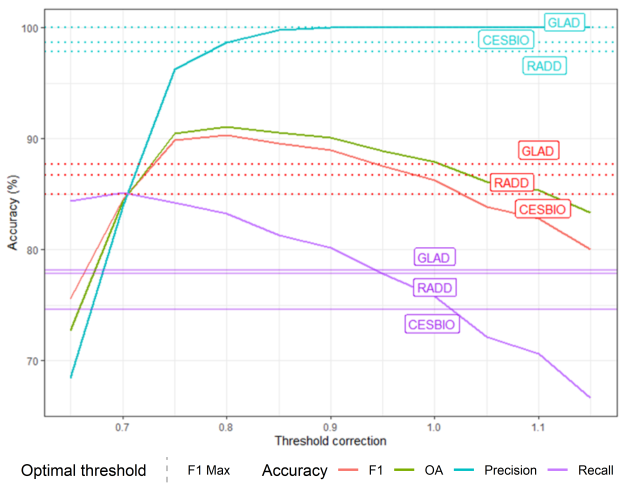


Figure 2. Updated TropiSCO accuracy vs. NRT deforestation dectection operational systems. ’CESBIO’ stands for Tropisco original system, GLAD refers to the latest GLAD-S2 system.

After the collection of data (Figure 3, A), we modelled the normalized probability (P_n) vs. distance to previous deforestation (d) using a 7-degree polynomial function with the form $P_n(d) = \sum_{i=1}^{7} a_i log^i(d)$. The experimental curve peaks at d = 89 m ($P_n = 1$) and then decreases to reach a minimum approximately at d = 10,000 m ($P_n = 0$) (Figure 3, B). Following these results, we assigned a “near” threshold τ_n to areas lying less than 89 meters from previous deforestation, and a “far” threshold τ_f to areas further than 10,000 m. Then we applied the polynomial function to be able to compute the threshold at any given d, following the expression $\tau(d) = \tau_n + (\tau_f - \tau_n)(1 - P_n(d))$. Varying the values of near and far thresholds showed that the use of a high τ_f (1.15) coupled with a lower-than-usual τ_n (0.9) allowed us to markedly raise the F1-score of the method while diminishing the commissions on dense forest by a factor of almost 4.

3.4 Timeliness of detections

One of the main issues related to the SAR-based deforestation detection systems is the temporal delay between the deforestation event and its detection, which most of the time is longer than the delay of detection of their optical counterparts (Doblas et al., 2023; Mullissa et al., 2024). In order to determine the exact delay attributed to the DETER-RT system, we ran the prototype DETER-RT algorithm over the full DETER-B warnings (n=17,033) detected in three municipalities (Feliz Natal, Lábrea and São Félix do Xingu) in the Brazilian Amazon from 2018 to 2023. The results of DETER-RT over these municipalities (Table 1) show that in many cases the DETER-RT system may be used to detect deforested areas before they appear in optical images. This is especially true during the Amazonian fire season, due to: 1) the occurrence of smoke and haze, which impairs optical images, and 2) the easier detection of deforested areas if they are burned right after their clearing.

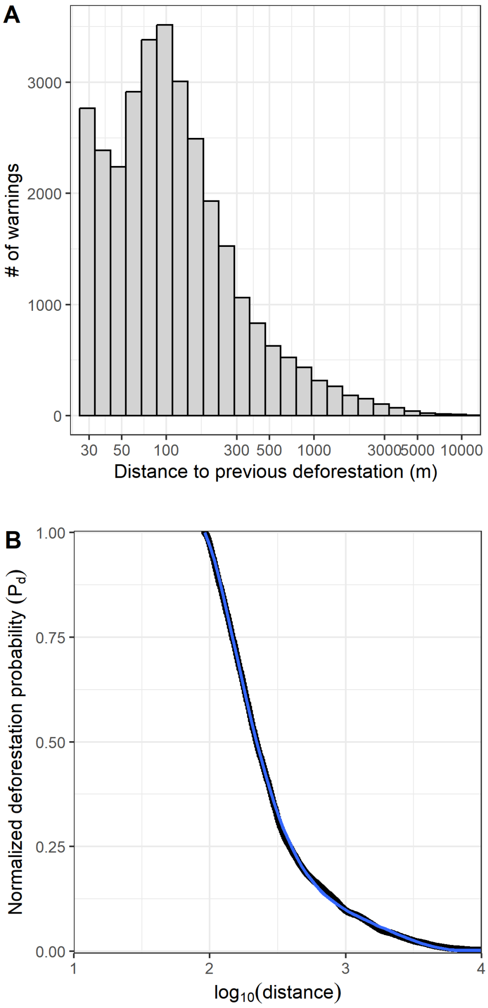


Figure 3. A) Histogram of the mean distance to previous deforestation (National Institute for Space Reseach, 2024). B) Normalized experimental deforestation probability function used in the DETER-RT system.

4. Operationalization

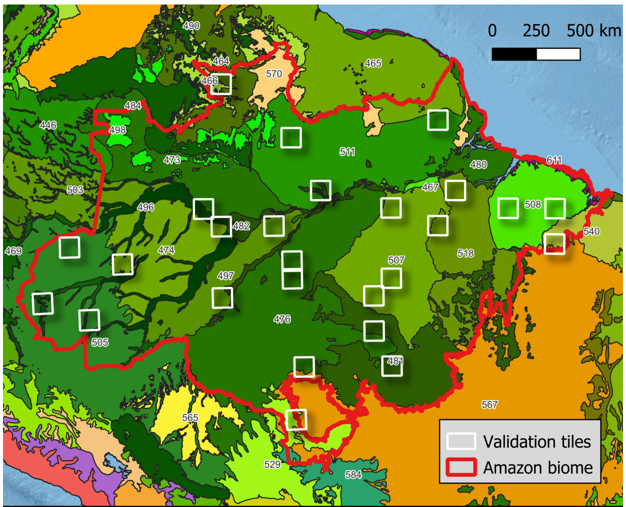
Up to date (July 2024), DETER-RT calibration and preliminary validation procedures are completed, and the prototype of the system will be tested in full operational mode over of 26 MGRS tiles representative of the main ecoregions and deforestation patterns of the Brazilian Amazon (Figure 4). During this phase, the output of the system will be validated by a team of INPE experts, following the well-established flow of DETER-R validation. If needed, the system will receive a final fine-tuning and then will be made operational over the entire Brazilian Amazon biome. We expect to make the system results publicly available in 2025.

5. Conclusions

The improved DETER-RT system will be operational in late 2024, using the design and optimization detailed above. It will deliver public deforestation warnings on a

Municipality	Season	Anticipated warnings (%)
Feliz Natal	Fire season	47.1
	Outside fire season	29.1
Lábrea	Fire season	19.6
	Outside fire season	6.8
São Félix do Xingu	Fire season	29.6
	Outside fire season	18.4

Table 1. Percentage of 2018-2023 DETER-B warnings anticipated by the DETER-RT prototype over three municipalities in the Amazonian basin.



ID	ECO_NAME	ID	ECO_NAME
611	Amazon-Orinoco-Southern Caribbean mangroves	496	Purus várzea
584	Pantanal	490	Pantepui forests & shrublands
570	Guianan savanna	484	Negro-Branco moist forests
567	Cerrado	482	Monte Alegre várzea
565	Beni savanna	481	Mato Grosso tropical dry forests
540	Maranhão Babaçu forests	480	Marajó várzea
529	Chiquitano dry forests	476	Madeira-Tapajós moist forests
518	Xingu-Tocantins-Araguaia moist forests	474	Juruá-Purus moist forests
511	Uatumã-Trombetas moist forests	473	Japurá-Solimões-Negro moist forests
508	Tocantins/Pindare moist forests	469	Iquitos várzea
507	Tapajós-Xingu moist forests	467	Gurupa várzea
505	Southwest Amazon moist forests	466	Guianan piedmont moist forests
503	Solimões-Japurá moist forests	465	Guianan lowland moist forests
498	Rio Negro campinarana	464	Guianan Highlands moist forests

Figure 4. Sentinel-2 tiles used in the pre-operational validation of the DETER-RT system and corresponding eco-regions.

daily basis. Initially, it will comprise all the forest formations in the Brazilian part of the Amazon biome. Our results indicate that DETER-RT should be able to detect deforestation events during the fire season before its optical counterpart, configuring DETER-RT as an important inclusion in the DETER family.

6. Acknowledgements

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National Institute for Space Research (INPE).

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Appendix 1

Results from the optimization of the threshold correction coefficient (alpha) throughout the most representative eco-regions of the Brazilian Amazon basin are synthesized in Figure 5.

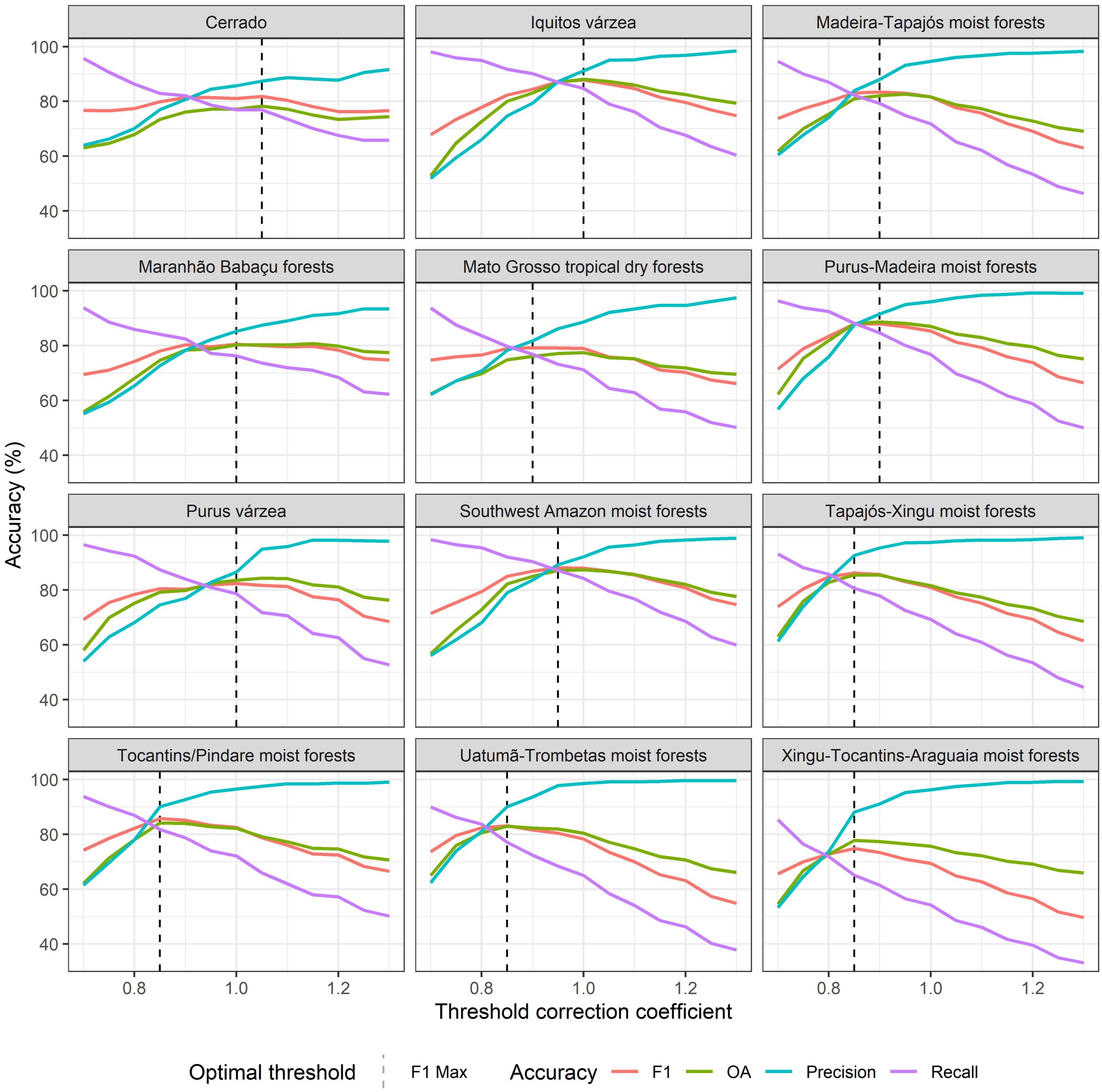

Figure 5. DETER-RT accuracy vs. Threshold correction coefficient throughout the most representative ecoregions of the Brazilian Amazon basin.