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Towards the use of satellite-based tropical forest disturbance alerts to assess selective logging intensities

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Abstract

Illegal logging is an important driver of tropical forest loss. A wide range of organizations and interested parties wish to track selective logging activities and verify logging intensities as reported by timber companies. Recently, free availability of 10 m scale optical and radar Sentinel data has resulted in several satellite-based alert systems that can detect increasingly small-scale forest disturbances in near-real time. This paper provides insight in the usability of satellite-based forest disturbance alerts to track selective logging in tropical forests. We derive the area of tree cover loss from expert interpretations of monthly PlanetScope mosaics and assess the relationship with the RAdar for Detecting Deforestation (RADD) alerts across 50 logging sites in the Congo Basin. We do this separately for various aggregation levels, and for tree cover loss from felling and skidding, and logging roads. A strong linear relationship between the alerts and visually identified tree cover loss indicates that with dense time series satellite data at 10 m scale, the area of tree cover loss in logging concessions can be accurately estimated. We demonstrate how the observed relationship can be used to improve near-real time tree cover loss estimates based on the RADD alerts. However, users should be aware that the reliability of estimations is relatively low in areas with few disturbances. In addition, a trade-off between aggregation level and accuracy requires careful consideration. An important challenge regarding remote verification of logging activities remains: as opposed to tree cover loss area, logging volumes cannot yet be directly observed by satellites. We discuss ways forward towards satellite-based assessment of logging volumes at high spatial and temporal detail, which would allow for better remote sensing based verification of reported logging intensities and tracking of illegal activities.

1. Introduction

The globally increasing demand for timber is an important driver of forest loss in tropical countries (Bager *et al* 2020). An estimated 15%–30% of global logging is illegal, with tropical hardwood as the primary subject (Nelleman & INTERPOL Environmental Crime Programme 2012). Unsustainable timber extraction can turn tropical forests into a net carbon source for at least 10 years (Mills *et al* 2023). Consequently, there is a large interest in developing techniques that allow for tracing timber from the forest to the international market.

A large proportion of tropical forests has been designated for permanent production (FAO 2020). These forests are often governed under a concession system, which allows logging companies to extract pre-defined quantities of timber under long-term lease contracts. Concessions are commonly selectively logged, i.e. trees (larger than a minimum diameter) belonging to commercially valuable species are extracted, while the remaining forest is left standing. Selective logging is usually associated with prior development of logging road infrastructure, ranging from large and permanent logging roads to skid trails that are used to extract a few trees (Pereira *et al* 2002, Jackson and Adam 2020).

Companies are required to report their planned and realized logging intensities, defined as the harvestable wood volume, excluding branches and other parts of the tree that are not brought to the mill. Logging intensities are generally reported as the log volume (m^3) per forest management unit, and provide the basis for forestry taxes.

A wide range of organizations and interested parties wish to track selective logging activities and verify reported logging intensities. Timber companies not only wish to track the progress of logging operations for management purposes, but also want to prevent illegal third-party encroachments that are difficult to trace from the ground. The establishment of logging roads makes the forest more vulnerable to such illegal encroachments (Kleinschroth *et al* 2019). National forest services are interested to monitor whether logging companies have executed their concessions and complied with the parameters. Similarly, local and international watchdog organizations aim to hold governments and logging companies accountable for over-logging, logging without permit, or logging outside of the permitted area. International action plans such as the Forest Law Enforcement Governance and Trade officially require importers to verify the origin of wood to ensure it was produced legally and sustainably (European Commission 2020). Finally, Indigenous and local communities may want to monitor for illegal logging in their lands (Wells *et al* 2022).

Satellite-based remote sensing has been established as a cost-effective tool to track tree cover loss across landscapes with great accuracy (Shimabukuro *et al* 2012, Hammer *et al* 2014, Diniz *et al* 2015, Hansen *et al* 2016, Langner *et al* 2016). However, detection of small disturbances, such as those from selective logging, remains difficult since selective logging-related disturbances are often small and the remotely-sensed signal disappears quickly due to rapid canopy closure and understory regrowth (Asner *et al* 2004, Broadbent *et al* 2006, Souza *et al* 2013, Verhegghen *et al* 2015, Jackson and Adam 2020, Reiche *et al* 2021). Unmanned aerial vehicles (UAVs) and very high resolution satellite imagery at sub-meter scale allow for precise detection of small-scale changes in tree cover (Asner *et al* 2012, Mitchell *et al* 2017, Ota *et al* 2019, Jackson and Adam 2020). However, repeated acquisition of high resolution data required for tracking logging activities over time remains expensive and logistically infeasible when trying to cover large areas (Jackson and Adam 2020).

Recently, new opportunities for large-area detection of selective logging have emerged. The free availability of 10 m scale optical and radar Sentinel data has resulted in several satellite-based alert systems that can detect increasingly small-scale forest disturbances in near-real time (Hoekman *et al* 2020, Reiche *et al* 2021, Weisse *et al* 2021). For example, the RAdar for Detecting Deforestation (RADD) alerts provide weekly updated forest disturbance alerts for most of the humid tropics based on cloud-penetrating Sentinel-1 imagery, which is acquired every 6–12 d (Reiche *et al* 2021). A validation procedure in the Congo Basin showed that the RADD alerts reach an overall user's accuracy of 97.6 ($\pm$4.8) percent and a producer's accuracy of 95 ($\pm$25.8) percent for alerts larger than 0.2 ha (Reiche *et al* 2021). However, the detection of tree cover loss from selective logging has not been quantified separately.

The aim of this paper is to provide insight in the usability of satellite-based forest disturbance alerts to track selective logging in tropical forests. We use visually interpreted monthly 4.77 m resolution PlanetScope mosaics (NICFI 2020) as a reference source for the area of logging-related tree cover loss. We assess the relationship between this visually identified tree cover loss and the RADD alerts across 50 logging sites across the Congo Basin. We do this separately for various aggregation levels, and for tree cover loss related to felling and skidding, and roads. A demonstration case in the Republic of the Congo shows how this modelled relationship can be used to improve consistent estimates of logging-related tree cover loss over large-areas and in high temporal detail.

Besides offering the ability to track activities spatially, satellite imagery could be a promising tool for verification of reported logging intensities. As opposed to tree cover loss area, logging volumes cannot be directly observed by satellites. Remotely identified tree cover loss could be a proxy for verification of reported logging volumes when used with due care, as the logging volume is expected to increase with the area of tree cover loss. However, existing research has used the term 'logging intensities' inconsistently to refer to logged area (Grecchi *et al* 2017) or the number of trees logged per hectare (Keivan Behjou and Ghaffarzadeh Mollabashi 2017, Bourgoin *et al* 2020), rather than log volume. Additionally, logging intensity is often not reported in studies assessing logging impact. Awareness of the discrepancies between ground-based and satellite-based measurements is key to understand the limitations as well as the opportunities that remote sensing offers. We discuss how satellite-based forest disturbance alerting needs to evolve to further narrow the gap between ground-based and satellite-based assessment of logging intensities at high spatial and temporal detail.

2. Methods

The following sections explain the research components as summarized in the overview flowchart (figure 1). In brief, we identified actively logged areas in PlanetScope mosaics, and sampled 50 grids of 100 ha (1 × 1 km^2). PlanetScope mosaics were then used to annotate the presence of tree cover loss (Planet-TCL), and the associated disturbance type at the 0.01 ha (100 m^2) grid cell level. RADD alerts were obtained for the same areas, and assigned a disturbance type based on an overlay with the annotated disturbance type. We aggregated both RADD alerts and Planet-TCL at 1 ha, 6.25 ha, 25 ha, and 100 ha and obtained the percentage of grid cells affected by logging-related disturbances. For each aggregation level, we assessed the relationship between the RADD alerts and Planet-TCL. The modelled relationship was used to improve tree cover loss predictions from RADD alerts over large areas in near-real time.

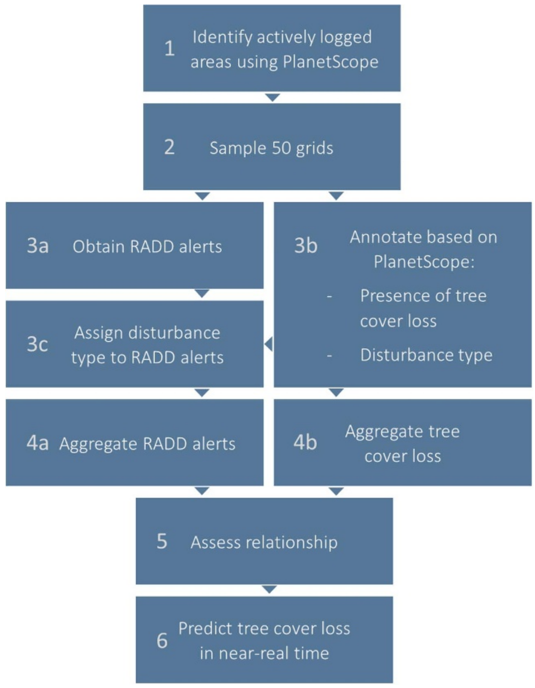

Figure 1. Overview of the research methods.

2.1. Study area and sampling

The study area is situated at the heart of the Congo Basin and spans across the borders of Cameroon, the Central African Republic, Gabon, the Republic of the Congo, and the Democratic Republic of the Congo. More than 30% of the dense tropical forest in the Congo Basin is governed under forestry concessions (Karsenty and Ferron 2017).

Grids were sampled in areas that were actively logged in the first 6 months of 2021, and where no tree cover loss was visible in the 6 months before and after that (figure 2). This approach ensures that the time period of annotated tree cover loss aligns with the RADD alerts. Grid samples were exclusively taken in areas with at least one cloud-free and clear PlanetScope mosaic that showed the maximum tree cover loss across the period of interest.

2.2. Data

The RADD alerts consistently provide information on small scale forest disturbances on a weekly basis. Forest disturbance is defined as 'complete or partial removal of tree cover within a 0.01 ha Sentinel-1 pixel' (Reiche *et al* 2021). For the purpose of this paper, we processed RADD alerts at a minimum mapping unit of 0.05 ha (figure 1 step 3a).

PlanetScope mosaics have been made openly available for the tropics at a spatial resolution of 4.77 m via Norway's Climate and Forest Initiative (NICFI 2020). Free availability of data with such high spatial and temporal resolution is unprecedented, and provides great opportunity to visually reference tree cover loss at scale, and across time. PlanetScope mosaics with a co-registration error were removed from the analysis.

We created a primary humid tropic forest baseline mask for 2020 by removing 2001–2020 forest loss (Hansen *et al* 2013) from the primary humid tropical forest mask from Turubanova *et al* (2018), similar to the forest mask used for the RADD alerts (Reiche *et al* 2021).

2.3. Annotating logging-related tree cover loss from PlanetScope data

We annotated the maximum visible tree cover loss over the first 6 months of 2021 using PlanetScope. We annotated Planet-TCL *presence* and *disturbance type* at the grid cell level (figure 3). Planet-TCL *presence* was defined as 'complete or partial removal of tree cover', which results in a binary indicator for each grid cell. In pixels with tree cover loss, the *disturbance type* distinguished whether this was associated with felling and skidding or logging roads, because these differ in their level and persistence of disturbances over time (Kleinschroth *et al* 2016), which may influence detection. Felling and skidding was defined as 'small-scale canopy disturbances related to selective tree harvesting and skid trailing'. It was recognized based on fragmented canopy disturbance and visibility of bare soil. Logging roads were defined as 'forest clearing mainly driven by infrastructure development related to facilitating selective tree harvesting'. They were recognized as forest clearings in connected linear shapes, where, full and spatially continuous canopy openings occur with visibility of bare

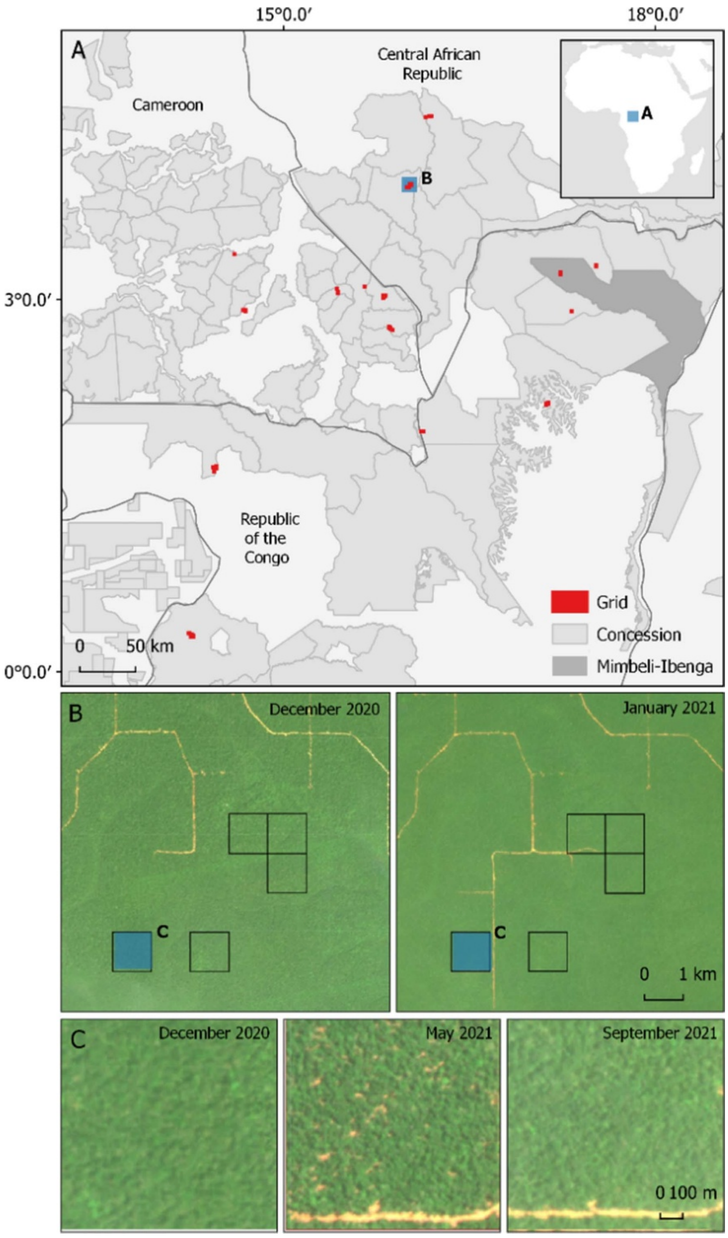

Figure 2. (A) Location of grid samples and the demonstration concession (Mimbeli-Ibenga). (B) Grid samples without active logging before the start of 2021 and after the first 6 months of that year. Changes are visible when comparing both images. (C) Tree cover loss though time in a grid sample. The blue squares indicate the extent of the map with the corresponding letter. Imagery © 2020/2021 Planet Labs Inc.

soil or road surface. Note that sub-canopy or discontinuous skid trails are not included under this definition, as they could not be distinguished. No other types of forest loss were perceived in the areas of interest.

2.4. Relationship between logging-related tree cover loss and RADD alerts

The disturbance type of the annotated Planet-TCL was used to relate each RADD alert to a disturbance type. To compensate for potential misalignments between the datasets, all RADD alerts within a 10 m buffer from Planet-TCL annotated as logging roads were given that same label (buffer sizes of 0, 20, and 30 m were also tested) (figure 1 step 3c). All other RADD alerts were attributed to felling and skidding.

We modelled the relationship between logging-related tree cover loss and RADD alerts at aggregation levels of 1, 6.25, 25, and 100 ha (figure 1 step 4ab). Aggregation is needed to balance misalignments that complicate comparison at the pixel level. For each aggregate area, we compared the percentage of grid cells with tree cover loss as defined using Planet-TCL and RADD. We excluded areas that were deforested before 2021 using the generated forest baseline map

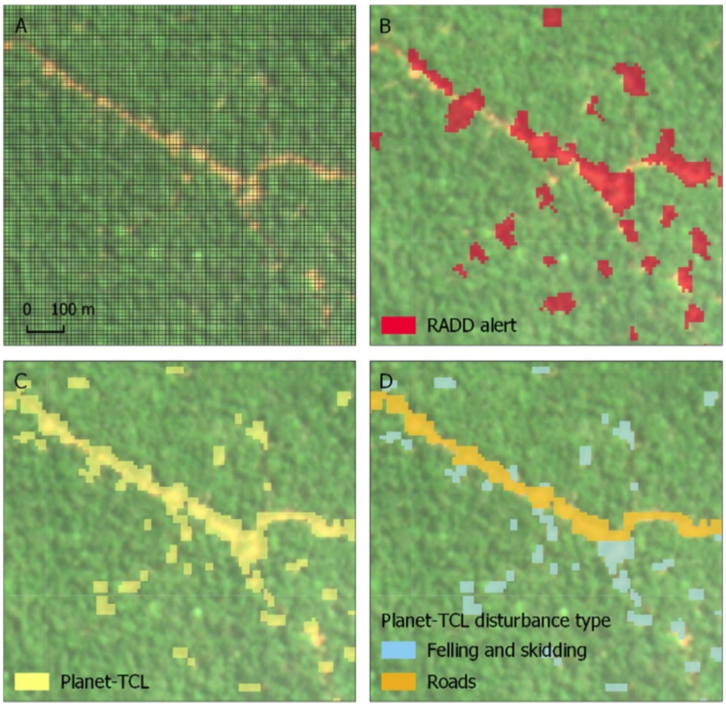

Figure 3. (A) Logging-related tree cover loss visible in a PlanetScope mosaic with grid overlay. (B) RADD alerts. (C) Annotated tree cover loss (Planet-TCL). (D). Disturbance type of Planet-TCL. Imagery © 2021 Planet Labs Inc. Centre coordinate: 2.91° N, 14.70° E.

for 2020. The percentage of Planet-TCL and RADD alerts was assessed individually for felling and skidding, and roads.

We used a linear fit to model the relationship between Planet-TCL and the RADD alerts separately for the various aggregation levels and disturbance types (figure 1 step 5). We forced the fit through the origin, because data points with an associated disturbance type never have zero tree cover loss. To avoid spatial autocorrelation, we grouped 8-connected grids to perform 'leave one group out' cross validation. To ensure a constant training sample size, we reduced the training set to the size it had when the largest group was left out. We assessed the strength of the relationship by the root mean square error (RMSE) and mean absolute error (MAE).

The relationship was separately assessed for the lower third of the Planet-TCL distribution to demonstrate differences in the fit at lower levels of tree cover loss. To demonstrate how the modelled relationships can be used for large-area estimates of logging-related tree cover loss based on RADD alerts, we mapped the area of tree cover loss from felling and skidding across the Mimbeli-Ibenga concession (650 000 ha in size) (figure 1 step 6). Roads were manually digitized and excluded from the RADD alerts to obtain tree cover loss estimates from felling and skidding.

3. Results

The relationships between RADD alerts and Planet-TCL were found to be different per aggregation level and per disturbance type (figure 4). At the finest aggregation level, small misalignments result in limited overlap. For coarser aggregation levels, the strength of the relationship increases and MAE and RMSE decrease. The same pattern holds when aggregations are subsampled to match n for 100 ha. The relationship is weak for low levels of Planet-TCL, as indicated by the relatively low R^2 for the third of the datapoints with the lowest Planet-TCL (table 1).

Felling and skidding was responsible for 84% of the total Planet-TCL, and 89% of the RADD alerts. The remaining 16% of Planet-TCL and 11% of the alerts were logging roads. Roads showed higher rates of omission than commission errors, while felling and skidding shows a more balanced spread around the 1:1 line. The maximum Planet-TCL in a grid was 83% of grid cells (at an aggregation level of 1 ha) (figure 4).

Figure 5 shows tree cover loss from felling and skidding estimated based on RADD alerts for the Mimbeli-Ibenga concession. The concession had a total RADD alert area of 3029 ha, of which 2131 ha were attributed to felling and skidding, and 898 ha to logging roads. These estimates were adjusted based on the fit for an aggregation level of 100 ha, because this resulted in the most robust fit. This adjustment resulted in an increase in the estimated tree cover loss of 217 ha; 10% on top of the area detected using RADD alerts. When considering monthly tree cover loss, strong intra-annual variability is visible, with the largest loss between December and April (figure 5).

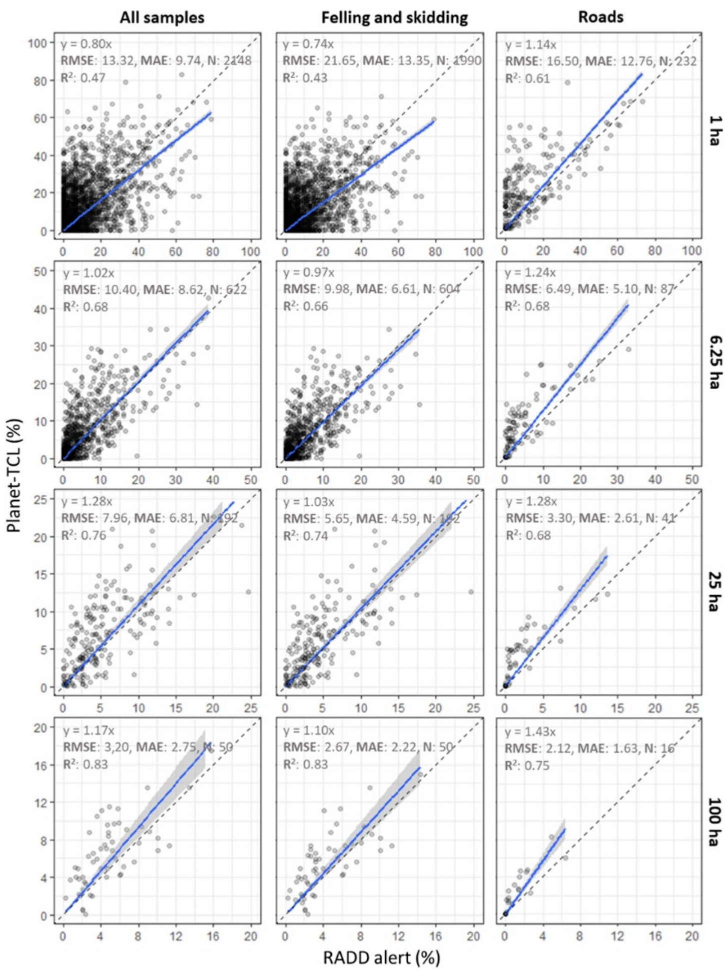

Figure 4. Relationship between RADD alerts and Planet-TCL for felling and skidding, roads, and both driver types combined at aggregation levels of 1 ha, 6.25 ha, 25 ha, and 100 ha. Each point represents the percentage of 10 × 10 m grid cells with tree cover loss as defined using Planet-TCL and RADD alerts in one aggregated area. For each graph, the linear fit through the origin is reported, along with the associated root mean squared error (RMSE), mean absolute error (MAE), the number of observations (N), and R^2. The reported RMSE, MAE, and R^2 values are based on leave one group out cross validation.

Table 1. Coefficient of determination (R^2) of the relationship between RADD alerts and Planet-TCL for all samples, selective logging, and logging roads at aggregation levels of 1 ha, 6.25 ha, 25 ha, and 100 ha. The R^2 associated with the third of the datapoints with the smallest Planet-TCL is reported separately. All results show statistical significance based on 95% confidence.

	All samples		Selective logging		Logging roads	
	All datapoints	Smallest third Planet-TCL	All datapoints	Smallest third Planet-TCL	All datapoints	Smallest third Planet-TCL
1 ha	0.47	0.09	0.43	0.08	0.61	0.43
6.25 ha	0.68	0.28	0.66	0.25	0.68	0.50
25 ha	0.76	0.49	0.74	0.43	0.68	0.58
100 ha	0.83	0.66	0.83	0.60	0.75	0.66

4. Discussion

4.1. Usability of satellite-based forest disturbance alerts to track selective logging

In this study, we successfully showed that logging-related tree cover loss identified from PlanetScope mosaics (Planet-TCL) and high spatio-temporal resolution satellite-based forest disturbance alerts (RADD) are related, and that this modelled relationship can be used to obtain improved estimates of tree cover loss from felling and skidding and logging roads based on satellite-based forest disturbance alerts.

Although satellite-based forest disturbance alerts may be used as a proxy to report the ecological and environmental impact of logging-related tree cover loss, the trade-off between aggregation level and accuracy requires careful consideration. Coarser aggregation levels result in more reliable tree cover loss estimations than finer levels. At finer aggregation levels, small spatial offsets between datasets will result in relatively high rates of error, both omission

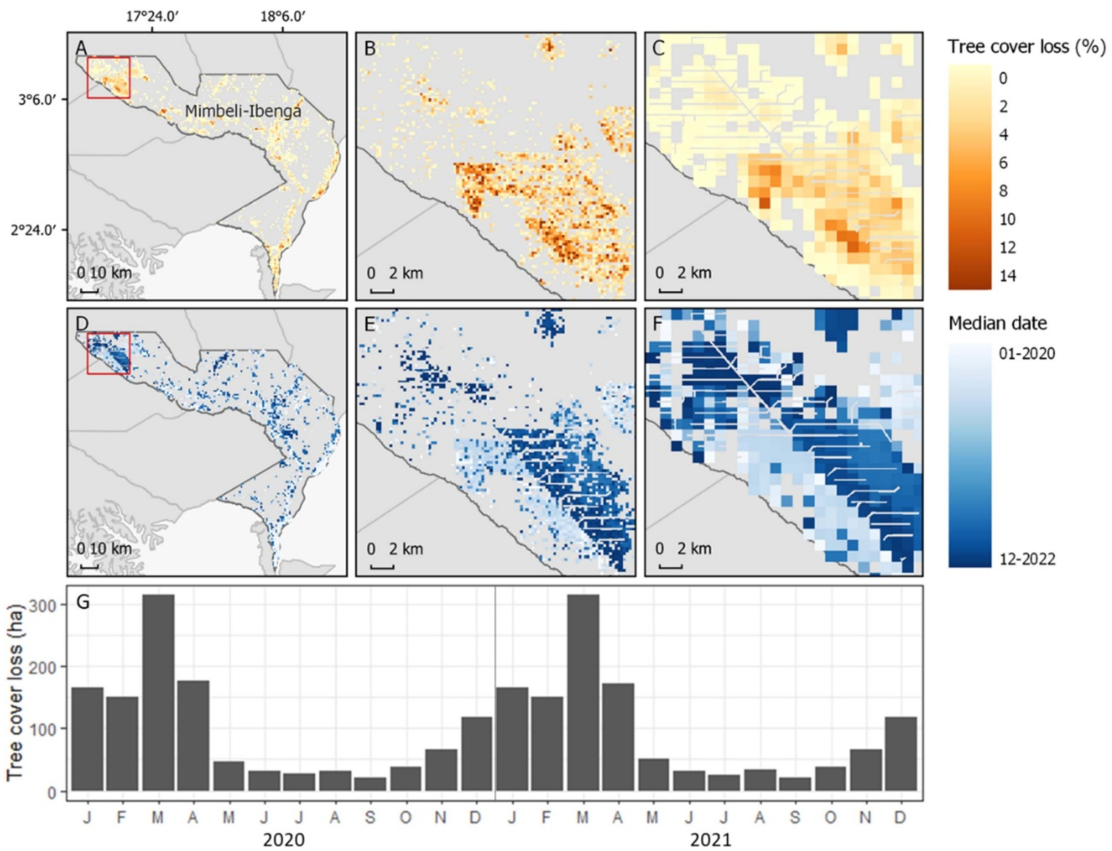

Figure 5. (A) Tree cover loss from felling and skidding in 2020–2021 in the Mimbeli-Ibenga concession mapped at 100 ha. Logging roads were manually digitized and excluded. Tree cover loss is mapped for the area within the red overview (B) at 6.25 ha and (C) at 100 ha. (D) The first date of logging-related tree cover loss mapped at 100 ha for the whole concession. The first date is mapped for the area within the red overview (E) at 6.25 ha and (F) at 100 ha. (G) Monthly tree cover loss over 2020–2021.

and commission. Users should consider this trade-off in their choice of aggregation level. While the area of tree cover loss may not be accurately estimated at the finest aggregation level, users may still use it to confirm whether logging of known density took place as authorized, since the presence or absence of logging activities is generally reliably captured.

Special care is required when tree cover loss is low, since the relationship has shown a relatively high uncertainty in these areas (table 1). Improvement in the detection of sparse tree cover loss is highly desirable, since (illegal) selective logging may happen at very low intensities in- or outside of concessions (Khai *et al* 2016).

The strong linear relationship between RADD and Planet-TCL confirms findings of a recent study relating drone imagery and canopy disturbances from selective logging that were retrospectively mapped by Sentinel-1 radar in Gabon (Carstairs *et al* 2022). However, we found a slightly lower R^2 compared to this earlier study. A key reason for this is the fact that the RADD alerts aim to detect various types of disturbances (including small-scale agriculture, mining, logging of various intensities and roads), which calls for a conservative approach regarding small-scale changes to avoid high commission errors.

The increasing availability of high spatial and temporal resolution data allows for the detection of strong intra-annual variability in logging patterns (figure 5), which contributes towards the traceability of logging activities over time. However, no operational national and continental-scale satellite forest disturbance alerts have been tuned specifically for selective logging yet (Reiche *et al* 2018, Hoekman *et al* 2020, Weisse *et al* 2021, Doblas *et al* 2022). Tuning satellite-based forest disturbance alerts for selective logging will benefit detection and monitoring of low intensity tree cover loss and small canopy gaps.

To improve verification of such small patches of tree cover loss, some of which may be invisible in the PlanetScope 4.77 m resolution mosaics, higher resolution data is needed. Nevertheless, some illegal activities may remain undetected, because informal extraction and skid trails are often under the canopy of adjacent trees, and may therefore be invisible for remote sensing (Kleinschroth *et al* 2019).

The results show differences in the relationship between Planet-TCL and RADD when comparing disturbances related to roads and selectively logging. This indicates a need for adjustments per disturbance type when estimating tree cover loss based on the RADD alerts. Roads showed a relatively high omission error across aggregation levels. This may be explained by the orientation of the Sentinel-1 radar, which results in frequent omission of linear shapes in line with the look angle. Integration of Sentinel-1 data with additional data sources may improve road detection. One third of tree cover loss in the Mimbeli-Ibenga concession was attributed to logging roads, emphasizing the environmental impact of logging road expansion (Kleinschroth *et al* 2019). In fact, damage from logging infrastructures is highly persistent compared to the damage caused by logging itself (Kleinschroth *et al* 2016).

Remote sensing could offer an opportunity to provide insight in the collateral damage from logging beyond the volume of processed wood. Slagter *et al* (submitted) have recently developed an automated methodology to classify the drivers of RADD alerts. Even though remote sensing approaches cannot completely rule out confusion between felling and skidding and other (natural) causes of forest loss, automated driver detection is key for application of the demonstrated results at scale and will aid concession-level assessments of the contributions of different disturbance types towards the total tree cover loss.

Analysis of the relationship between the RADD alerts and Planet-TCL has provided insight in the usability of these alerts as a proxy for logging-related tree cover loss for forest management purposes in the Congo Basin. However, patterns of selective logging may vary across geographies, and different types of forest respond differently to change (Mitchell *et al* 2017). Therefore, region-specific assessments are needed. The provided workflow, which was developed in Google Earth Engine, can be adopted in other geographies, and to assess different satellite-based forest disturbance alert systems.

4.2. Narrowing the gap between ground-based and satellite-based measurements

There is an urgent need to move from area based estimates of disturbance to other metrics that can be linked better to the data produced by forest managers. To better relate satellite-based measurements and logging intensities, information on logged volumes (in m^3) at the tree level or per management unit is required. While such information is measured consistently by logging companies across the tropics, public access to spatially explicit data is often limited as the information is considered sensitive.

Existing research has developed allometric equations that estimate biomass from tree height and crown size (Jucker *et al* 2017). Such metrics could potentially also be used to estimate logging intensities. Tree height information from GEDI is available globally, and existing research has quantified changes in forest height across time (Potapov *et al* 2022). UAV-based multi-spectral and height data are invaluable in the provision of data relating to the percentage of tree cover and tree height. Information on crown size is also commonly extracted from very high resolution drones or commercial satellites (Brovkina *et al* 2015, Wagner *et al* 2018, Tong *et al* 2021, Freudenberg *et al* 2022). When use of commercial data is not feasible, estimations could benefit from forest inventory data (e.g. tree density, species composition, and timber volume) (Cole and Ewel 2006).

In addition, the upcoming BIOMASS mission (https://earth.esa.int/eogateway/missions/biomass) will provide P-band SAR data from 2024 onwards, which could be combined with GEDI tree height information to obtain more accurate satellite-based approximations of biomass, and associated tree volumes. These data will be invaluable for remote estimation of logging intensities, and could be integrated with satellite-based forest disturbance alerts to obtain improved near-real time carbon emission estimates (Csillik *et al* 2022).

A final option is the collection of ground data to establish the relation between logging intensity and logging-related tree cover loss. Field techniques to do so are well-established in the forestry literature, and have been used to estimate for example CO_2 emissions from logging (Ellis *et al* 2019, Umunay *et al* 2019). The disadvantage of this approach is that the relationship is likely to vary with forest type, topography, and biogeographic region. On the other hand, combining different satellite-based information with ground truth data will allow us to gain more in-depth knowledge on logging disturbances and their detection through satellite-based measurements.

The use of novel data sources in combination with an improved understanding of the relationship between alerts and logging-related tree cover loss offers great potential for improved tracking of logging activities and verification of logging intensities, and will improve our understanding of uncertainty at different aggregation levels and for different disturbance types.

5. Conclusion

This paper has assessed the relationship between tree cover loss visually identified based on PlanetScope imagery and the RADD alerts for different disturbance types and spatial aggregation levels. The strong linear relationship in tree cover loss identified from these two data sources can be used to obtain improved tree cover loss estimates over aggregated areas separately for felling and skidding, and logging roads. The results provide insight in the usability of satellite-based forest disturbance alerts as a proxy for tree cover loss in areas under forest management. Users should be aware that the reliability of estimations is highly dependent on the aggregation level and the intensity of tree cover loss. Forest characteristics may further impact the relationship between satellite-based alerts and tree cover loss.

Tuning satellite-based forest disturbance alerts for selective logging could reduce omission of small disturbances and improve the modelled relationship in areas with small canopy gaps. Additionally, adjustments per disturbance type could improve tree cover loss estimates, and provide insight in the collateral damage from logging roads.

An urgent need remains to move from area based estimates of disturbance to other metrics which can be linked better to the data from forest concessions. To narrow the gap between ground-based and satellite-based measurements, forest disturbance alerts should be combined with additional data sources that provide information on volume-related metrics. This will contribute to the development of affordable and consistent logging volume estimates to not only track logging activities spatially, but also verify reported logging intensities.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors have no conflicts of interest to declare.

Ethics statement

The article does not contain any studies involving human or animal participants.

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