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Monitoring lianas from space: Using Sentinel-2 imagery to observe liana removal in logged tropical forests

C. Finlayson [a,b,*], M.G. Hethcoat [b,c], P.G. Cannon [d], R.G. Bryant [e], K.M. Yusah [f], D.P. Edwards [g], R.P. Freckleton [b]

[a] Center for Natural Climate Solutions, Conservation International, Arlington, VA, USA
[b] Ecology and Evolutionary Biology, School of Biosciences, University of Sheffield, UK
[c] Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, Edmonton, Canada
[d] School of Biological Sciences, University of Reading, UK
[e] Department of Geography, University of Sheffield, UK
[f] Tropical Biology and Conservation, Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia
[g] Department of Plant Sciences and Conservation Research Institute, University of Cambridge, UK

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ABSTRACT

Liana removal – the cutting of over-abundant woody climbing plants (lianas) – has the potential to substantially increase tree growth and biomass accumulation across millions of hectares of degraded tropical forest. Satellite imagery could provide data capable of observing the effect of liana removal on the forest canopy, enabling the large-scale monitoring and validation of liana removal, which remains a key hurdle to its widespread implementation. Using a 320-ha liana removal experiment in Sabah, Malaysian Borneo, we tested whether a time series of Sentinel-2 images could observe the canopy signature of liana removal. Calculating a range of metrics derived from the Normalized Burn Ratio – a vegetation index based on spectral reflectance that differentiates leaf from non-leaf – we quantified satellite-derived canopy disturbance and fragmentation across a range of liana removal intensities and examined how canopy disturbance changed in the 12-months following removal treatments. We find that liana removal significantly increases canopy disturbance and fragmentation metrics one month after removal, with partial removal having a smaller effect than complete removal. The impact of liana removal on the canopy metrics declined over time, with measures of canopy disturbance and fragmentation largely indistinguishable from control forest within 12-months of treatment. Our findings evidence that freely available satellite imagery can be used to efficiently monitor large-scale liana removal applied at a range of intensities and suggest that partial liana removal could significantly reduce canopy disturbance of this restoration method.

1. Introduction

Logging has a profound impact on tropical forests globally. Over 400 million ha of tropical forest are currently designated for timber production (FAO, 2020), with global timber demand increasing (Malhi et al., 2014). While logging threatens some biodiversity (Gibson et al., 2011), alters forest structure (Gatti et al., 2014), and reduces carbon stocks (Pan et al., 2011), logged forests are still instrumental in biodiversity conservation (Edwards et al., 2011; Fisher et al., 2011; Gilroy et al., 2014), carbon sequestration (Erb et al., 2018; Putz et al., 2012), and for local economies (Edwards et al., 2021). Protection of logged forests from conversion to non-forest uses is therefore a global priority (Edwards et al., 2014, 2011).

One option to protect logged forests is to enhance their ecological or economic value (Cerullo and Edwards, 2019). This can be achieved by restoring tree composition, timber volume, or carbon stocks towards that of primary forests (Putz et al., 2023; Toledo-Aceves et al., 2021). Restoration methods include enrichment planting, which aims to replenish tree seedling stocks (Cerullo and Edwards, 2019). However, large-scale implementation of planting initiatives is costly, requiring substantial carbon payments to offset initial costs (Philipson et al., 2020). Passive restoration, in which forests recover naturally, can be less expensive, but success depends on environmental conditions and protection from human activities (Zahawi et al., 2014).

* Corresponding author at: Center for Natural Climate Solutions, Conservation International, Arlington, VA, USA.
E-mail address: cfinlayson@conservation.org (C. Finlayson).

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An alternative restoration solution involves the removal of woody, climbing plants (called lianas) that proliferate in disturbed forests and limit their recovery. Lianas compete intensely with trees and are sometimes referred to as "structural parasites", climbing the stems of trees to deploy their leaves in the canopy rather than investing in their own supportive trunk. Liana removal accelerates forest recovery (César et al., 2016; Marshall et al., 2016) significantly enhancing tree growth, carbon stocks (Estrada-Villegas et al., 2022; Finlayson et al., 2022), and other tree-based metrics including tree reproduction and survival (Estrada-Villegas and Schnitzer, 2018). Recent estimates suggest liana removal could sequester up to 7.4 Gt CO_2 per decade across the tropics at comparatively low cost (Finlayson et al., 2022). However, various obstacles hinder the widespread implementation of this emerging technique.

Liana removal is already implemented extensively in logged forest in Malaysian Borneo (Sabah Forestry Department, 2020) and is poised for expansion across millions more hectares globally (Finlayson et al., 2022; Putz et al., 2023). Verifying liana removal ("validation") and monitoring forest responses are vital to ensure proper treatment, quantify carbon and tree growth outcomes, and secure carbon credits and payments from initiatives such as REDD+ and Verra (GOFC-GOLD, 2016). However, traditional field-based monitoring and validation over large, remote areas are logistically problematic and requires high labour costs (Camarretta et al., 2020; Murcia et al., 2016). Remotely-sensed data, which can be accessed freely at high spatial and temporal resolutions, could address these challenges and may be particularly relevant to liana management (de Almeida et al., 2020; van der Heijden et al., 2022).

Previous studies demonstrate the potential of remote-sensing to distinguish between tree crowns and over-topping lianas based on distinct spectral reflectance (Chandler et al., 2021; Meunier et al., 2021; van der Heijden et al., 2022), and to quantify decreases in canopy vegetation one year after enrichment planting and liana removal (Wu et al., 2020). However, these studies do not determine the spectral signal of liana removal as a stand-alone method, nor evaluate the nuanced spatial-temporal aspects in this specific signal. A time-series of images could facilitate observing the initial loss and browning of canopy leaves after liana removal, identifying when satellite data can best verify treatment application. A time series could also track the recovery of the canopy, for example informing forest managers of when the canopy re-closes after liana removal (Martínez-Izquierdo et al., 2016; Perez-Salicrup, 2001). Moreover, the spatial pattern of changes in the canopy, due to the variable abundance of lianas within a forest (Campanello et al., 2007; Campbell et al., 2018), could aid in the quantification of any canopy disturbance and fragmentation (here defined as the process by which a closed canopy becomes disturbed, resulting in smaller patches of contiguous closed canopy) caused by liana removal.

It is also opportune to investigate the utility of remote sensing data to refine the process and management of liana removal. Lianas are a key component of tropical forests, constituting 20% of the woody plant diversity, providing food and nesting resources, facilitating animal locomotion, and buffering the understory from extreme temperatures (Arroyo-Rodriguez et al., 2015; Magnago et al., 2017; O'Brien et al., 2019; Putz et al., 2001; Schnitzer and Bongers, 2002). Hence, there are concerns about the negative consequences of large-scale liana removal, prompting recommendations to retain some lianas in target areas ("partial removal" hereafter) (Estrada-Villegas and Schnitzer, 2018; Finlayson et al., 2022). Partial removal could cause less canopy disturbance and fragmentation, for example, causing a smaller reduction in liana resources and fewer restrictions on the movement of arboreal animals. Thus, targeted use of remotely-sensed data could compare canopy disturbance and fragmentation between partial and complete removal, evidencing whether partial liana removal mitigates impacts on the forest. To date, however, the impact of partial removal on biodiversity and ecosystem functioning has not been experimentally tested.

Differentiating the spectral signals of partial compared to complete removal could also be useful in the monitoring of liana removal that is required for certification (e.g. Verra carbon credits (Verra, 2023)). This could provide an inventory of areas with incomplete liana removal, such as the 30% of climbing plants missed during commercial liana removal in Belize (Mills et al., 2019), identifying where removal crews need to re-visit or adjusting the expected tree growth and carbon sequestration outcomes of removal treatment. A robust remote sensing methodology for assessing liana removal could substantially enhance the climate mitigation potential of this emerging restoration method.

Here, we experimentally applied varying intensities of liana removal to 320 ha of logged forest in Malaysian Borneo and used a time series of satellite images to determine whether Sentinel-2 can monitor restoration activity. Specifically, we test: (1) whether Sentinel-2 can be used to observe and quantify canopy degradation and fragmentation caused by liana removal; (2) whether Sentinel-2 can differentiate varying intensities of liana removal; and (3) how long the signal of liana removal remains visible via Sentinel-2.

2. Methods

2.1. Study area

We set up the liana removal experiment in the Ulu Segama-Malua Forest Reserve (USMFR), within the Yayasan Sabah (YS) logging concession, Sabah, Malaysian Borneo (Fig. 1). The study site is an aseasonal lowland dipterocarp forest. Between 2018 and 2020, mean annual rainfall was 2651 mm year^{-1} and mean maximum temperature was 29.1 °C (SEARRP, 2020).

The USMFR forest reserve underwent two rounds of selectively logging using a modern uniform system, employing tractors and high-lead cable extraction techniques: firstly from 1976 to 1991 (extracting ~120 m^3 ha^{-1} of timber), and then from 2001 to 2007 (extracting an additional 15–72 m^3 ha^{-1} of timber) (Edwards et al., 2011). By 2018, the site had an average tree basal area of 4.85 m^3 ha^{-1} ($\pm$ 1.56) and was dominated by fast-growing, early successional species. Lianas infested 82% of adult trees, and lianas covered an average of 46% of infested trees' crowns (Cannon, 2021).

2.2. Liana removal experiment and field data

In 2019, we established five independent 800 × 800 m sites at least 1 km apart and 100 m from the nearest logging road (Fig. 1C). We divided each site into sixteen 200 × 200 m treatment blocks (80 blocks in total) (Fig. 2A). Between September and November 2019, we applied one of three liana removal intensities or a control to each treatment block. The intensities were achieved by leaving different proportions of the block untreated and lianas were cut in strips to align with the methods used by commercial liana removal teams in the region. Treatments were as follows: 0% area treated (control), 60% area treated (two 40 m strips uncut), 80% area treated (two 20 m strips uncut), and 100% area treated (removal across whole block). 60% and 80% removal were chosen since the effect of liana removal can be small (see Finlayson et al., 2022) and lower intensity removal could have been hard to observe, and to maintain a high number of replicates within the experiment. We kept the number of uncut strips consistent between partial treatments, thus limiting difference in the amount of uncut edge between blocks. We arranged treatments in a 4 × 4 Latin square design (Fig. 2A), totalling 20 replicates of each treatment across the five sites.

Liana removal was carried out by a team of local contractors with experience of liana removal and forest management within USMFR. Climbing plant stems (including lianas, climbing bamboo, and rattan) were cut near to the floor and at shoulder height using machetes to prevent stems from re-connecting (Putz et al., 2023). Cut climbers were allowed to decompose in situ to avoid damaging tree crowns.

To account for initial liana abundance, we recorded pre-treatment canopy liana load in two to five 20 × 20 m subplots randomly located in the central 100 m^2 of each treatment block (Cannon, 2021). Canopy

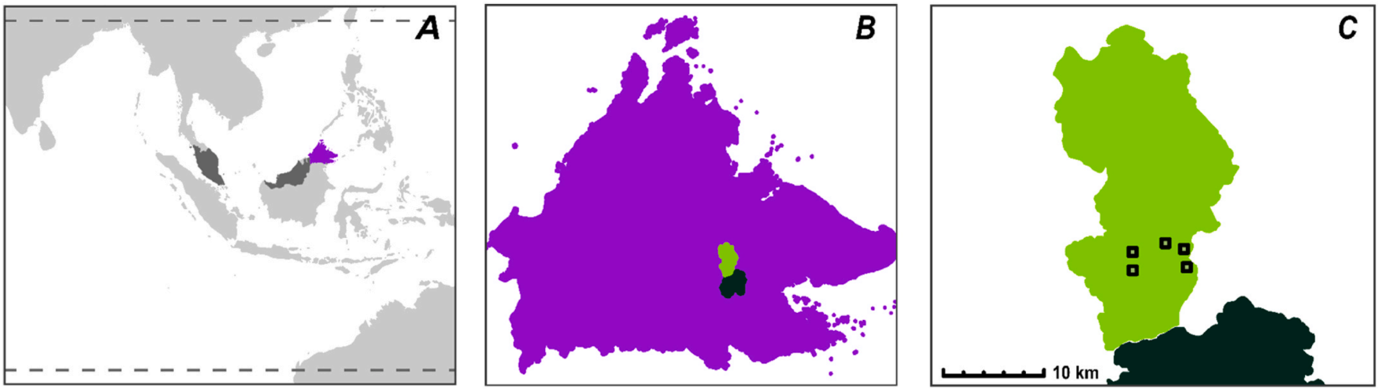

Fig. 1. Study site location. Map of SE Asia with Malaysia highlighted in dark grey and Sabah in purple (A), map of Sabah with Danum Valley Conservation Area in dark green and Malua Forest Reserve in light green (B), and locations of the five 800 × 800 m experimental sites within the Malua Forest Reserve (C).

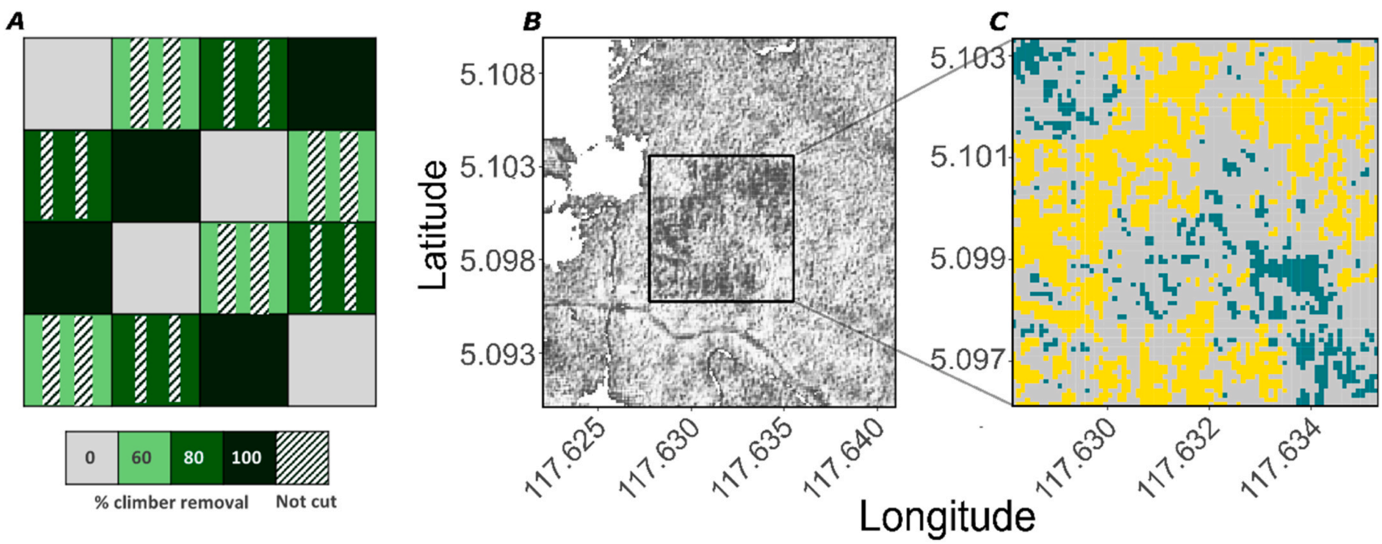

Fig. 2. Impact of liana removal on NBR in one site four weeks post-treatment. Latin-square design of liana cutting treatments (A), raw NBR values across one experimental site (inside the black square) and the surrounding forest (B), change in pixel-level NBR values compared to median for the year pre-treatment (C). Darker pixels in (B) represent lower NBR values (minimum = −1), lighter colour represents higher NBR values (maximum = 1), and white pixels are masked. Blue pixels in (C) indicate those with > 5% increase in NBR compared to pre-treatment, yellow indicates pixels with > 5% decrease in NBR, and grey indicate < 5% change in NBR.

liana load estimates the proportion of liana coverage in each adult tree crown (Muller-Landau and Visser, 2019), following a five-point scale (0 = no lianas in the canopy, 1 = 1–25% coverage, 2 = 26–50% coverage, 3 = 51–75% coverage, 4 = 76–100% coverage). Canopy liana load was averaged within each subplot, and then averaged across all subplots within each treatment block. Rainfall data were also collected at the Malua Forest Research site, twice daily where possible (accessible at: http://www.searrp.org/scientists/available-data/).

2.3. Remote-sensing data

To capture potentially fine-scale and temporally dynamic changes in canopy structure following liana removal, we used high spatial (10 ×10 m) and temporal (every 5 days) resolution imagery from the Sentinel-2 (S2) MSI data (MultiSpectral Instrument, Level 2 A). Imagery is orthorectified and atmospherically corrected to surface reflectance. This instrument acquires reflectance data in 12 spectral bands, ranging from aerosols (443.9 nm) to short-wave infrared (2202.4 nm).

We used all available S2 images acquired across our experimental sites from December 2018 (the first surface reflectance corrected images available over the study region at time of writing) to November 2020, totalling 78 images spanning nearly one year before and one year after treatment (Table S1). To minimise noise from atmospheric effects that could obscure subtle canopy disturbances, clouds, cloud shadows, and non-forest artefacts were removed using the in-built S2 cloud mask, which determines presence of clouds based on several spectral bands (European Space Agency, 2023), and fine-tuned thresholds in the aerosol, blue, red, and green bands.

2.4. Quantifying canopy disturbance and fragmentation

To quantify canopy disturbance and fragmentation resulting from liana removal, we derived the Normalized Burn Ratio (NBR: García and Caselles, 1991) from the Sentinel-2 images. We used NBR as it detects a loss of photosynthetically active leaves, directly quantifies canopy openness, and has recently been used to detect small-scale canopy disturbance (Langner et al., 2018). Initial data exploration also demonstrated that liana removal treatment blocks were more clearly distinguishable using NBR than Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Greenness Index (GI) (see Supplementary Information section *'Other satellite imagery and metrics'*). We calculated NBR thus:

$$\mathrm{NBR} = (\mathrm{NIR} - \mathrm{SWIR2})/(\mathrm{NIR} + \mathrm{SWIR2}) \quad (1)$$

Where letters indicate spectral reflectance bands: NIR = near-infrared (832.8 nm); SWIR2 = short-wave infrared 2 (2202.4 nm).

We calculated NBR for each pixel in each S2 image and summarised the NBR values in each treatment block using four metrics representing canopy disturbance and fragmentation. We excluded pixels within 5 m of the edge of each block to account for GPS error and excluded data when more than 15% of pixels in a treatment block were masked due to clouds or other artefacts. We calculate four metrics of canopy disturbance and fragmentation for each treatment block:

1. Median NBR: lower NBR suggests fewer photosynthetically active leaves in the canopy, more bare earth, or greater canopy openness.
2. Proportion of canopy disturbed: we quantified the proportion of S2 pixels in each treatment block that had more than 5% reduction in NBR compared to the median NBR value for each pixel during the year pre-treatment.
3. Mean area of intact canopy patches: we classed pixels as 'intact' when they had less than 5% reduction in NBR compared to the median value for the pixel for a year pre-treatment. We then calculated the mean area of adjoining intact pixels (an 'intact patch').
4. Aggregation of intact canopy patches: we quantified how aggregated (clumped together) intact canopy patches were.

Metrics 2–4 were devised following landscape ecology theory (Hesselbarth et al., 2019; Senior et al., 2019) and calculated using *landscapemetrics* and *landscapetools* packages in R (Hesselbarth et al., 2019; Sciaini et al., 2018). A 5% NBR change served as a threshold to differentiate liana removal effects from natural variation in NBR. We used a 10% threshold in supplementary analyses. To verify conclusions about the influence of liana removal on canopy disturbance we also calculated metrics 1 and 2 using NDVI, EVI, and GI (Zeng et al., 2022). Additional satellite-derived metrics explored are detailed in the Supplementary Information *Other satellite imagery and metrics* section.

2.5. Statistical analyses

To test whether liana removal caused canopy disturbance that could be observed by satellite (objective 1), we initially visualised pixel-level NBR and percentage change in NBR in one experimental site for one S2 image that had no cloud-masked pixels. We then statistically compared the median NBR, proportion of pixels with decreased NBR, mean area of intact patches, and aggregation of intact patches in treated compared to control blocks across all sites. We performed these analyses on S2 images within one-month post-treatment, when we expect the impact of liana removal to be largest (O'Brien et al., 2019), and on images within 12-months post-treatment.

We analysed the one-month time-series using linear fixed effects models. Treatment (0, 60, 80, or 100% liana removal) and experimental design (row and column of treatment blocks) were included as fixed effects, alongside rainfall and mean liana load, when significant. These models were run using the *nlme* package in R (Pinheiro et al., 2018). We analysed the 12-month time series using generalized additive models (GAMs). We followed a similar structure as the one-month models, including a smoothing term for an interaction between site and date to account for seasonality and temporal non-independence. Analyses were run using the *mgcv* package in R (Wood, 2011). We set the reference treatment level in all models to 0% removal (control), hence a significant positive coefficient for 60, 80, or 100% removal treatment indicated that liana removal significantly increased the disturbance or fragmentation metric compared to control. To determine whether Sentinel-2 could differentiate between removal intensities (objective 2), we calculated the estimated marginal means for all combinations of removal intensities (i.e., 60% vs 100% removal) from all models.

To determine how long Sentinel-2 could identify canopy degradation and fragmentation post-treatment (objective 3), we compared the coefficients for liana removal treatments between the one-month and 12-month analyses. We also plotted the canopy disturbance and fragmentation metrics in the treated blocks relative to control blocks for each month post-treatment. All analyses and figures were produced using R statistical software (R Core Team, 2020).

3. Results

3.1. Canopy disturbance and fragmentation observed by Sentinel-2

We found that liana removal caused canopy disturbance that was clearly visible using Sentinel-2 (S2) imagery. Firstly, Fig. 2 shows that treatment blocks with any level of liana removal were visually distinct from surrounding forest and control blocks in one experimental site. This is based on raw NBR (Fig. 2B) and the change in NBR compared to pre-treatment (Fig. 2C) from one image at one-month post-treatment. Secondly, across all five experimental sites and all S2 images within a month post-treatment, all liana removal intensities (60%, 80%, and 100%) significantly reduced median NBR compared to control blocks and pre-treatment levels, and increased the proportion of the canopy that was disturbed (the proportion of the canopy with decreased NBR) compared to control blocks (Fig. 3A, p-values < 0.01, Table S3). There was also a significant increase in canopy disturbance according to these metrics on average across 12-months post-treatment (Fig. 3B, p-values < 0.001, Table S3).

Liana removal also significantly increased canopy fragmentation metrics, with smaller and less aggregated intact patches in liana removal treated blocks than control blocks during the first month post-treatment, irrespective of removal intensity (Fig. 3A, p-values <0.01, Table S3). However, across the full 12-months post-treatment, only 100% removal blocks had significantly higher canopy fragmentation than control blocks (p-values < 0.001, Fig. 3B, Table S3). There was minimal impact of pre-treatment liana load on the canopy disturbance and fragmentation signals of liana removal: liana load only decreased the area and aggregation of intact canopy patches, and only when metrics were calculated using the 10% reduction threshold (Table S4).

Additional analyses found that liana removal increased canopy disturbance and fragmentation irrespective of whether the metrics were calculated using a 5% or 10% reduction threshold (Table S4). In general, liana removal also caused a decrease in minimum NBR, median GI, NDVI, and EVI, and increased the proportion of the canopy with a decrease in these vegetation indices (Table S5; Fig S1).

3.2. Complete liana removal causes greater canopy disturbance and fragmentation

We were able to differentiate between some intensities of removal (60%, 80%, and 100%) using Sentinel-2 imagery. Blocks treated with complete (100%) removal had significantly greater canopy disturbance metrics (lower median NBR and greater proportion of the canopy with decreased NBR) compared to control blocks than partial (60% and 80%) removal treatments (Fig. 3, p-values < 0.05, Table S3). Complete removal also caused significantly more canopy fragmentation (smaller and less aggregated intact patches) compared to control blocks than partial removal, but this was only significant when assessing all S2 images within 12-months of treatment (Fig. 3B, p values <0.05, Table S3). Greater canopy disturbance and fragmentation in complete than partial removal blocks were also observed when metrics were calculated using a 10% rather than a 5% reduction in NBR threshold (p-values < 0.05, Table S4).

Conversely, it was not possible to determine whether 60 or 80% removal had a greater impact on canopy disturbance and fragmentation metrics. While 80% removal caused a greater proportion of the canopy to be disturbed than 60% across 12-months post-treatment, 80% removal had a smaller effect on the aggregation of intact canopy patches

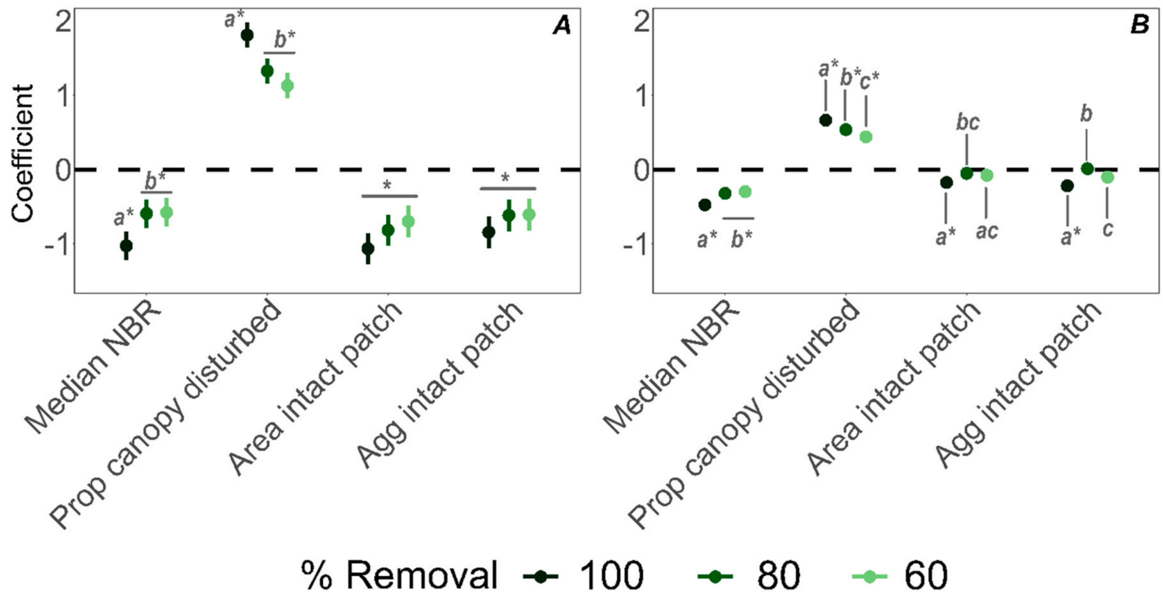

Fig. 3. Effects of different intensities of liana removal (60%, 80%, and 100% removal) on canopy disturbance and fragmentation during one month (A) and 12-months (B) post-treatment. Points show coefficients of treatment intensities from linear models in (A), and from GAMs in (B) and error bars show standard error; response variables are normalized before running models. The dotted line shows control (0% removal), coefficients below the line indicate a decrease compared to control, and above the line indicate an increase compared to control. Different grey letters indicate a significant difference between percentage removal treatments, calculated using the estimates marginal means, and "* " indicates removal treatments that are significantly different from control (zero).

(Fig. 3B, p-values <0.05, Table S3) and on median EVI (Fig S1B, p-value = 0.001, Table S5) than 60%. Moreover, partial removal treatments were indistinguishable when disturbance and fragmentation metrics were calculated using 10% rather than 5% reduction in NBR (Table S4).

3.3. Canopy disturbance and fragmentation signals decline over a year post-liana removal

The impact of liana removal on the canopy appeared to reduce across the year post-treatment. Liana removal had a greater effect on all disturbance and fragmentation metrics across the one-month than the 12-month time-series (represented by larger coefficients in Fig. 3A than 3B). The temporal trend, presented in Fig. 4, also showed that by month

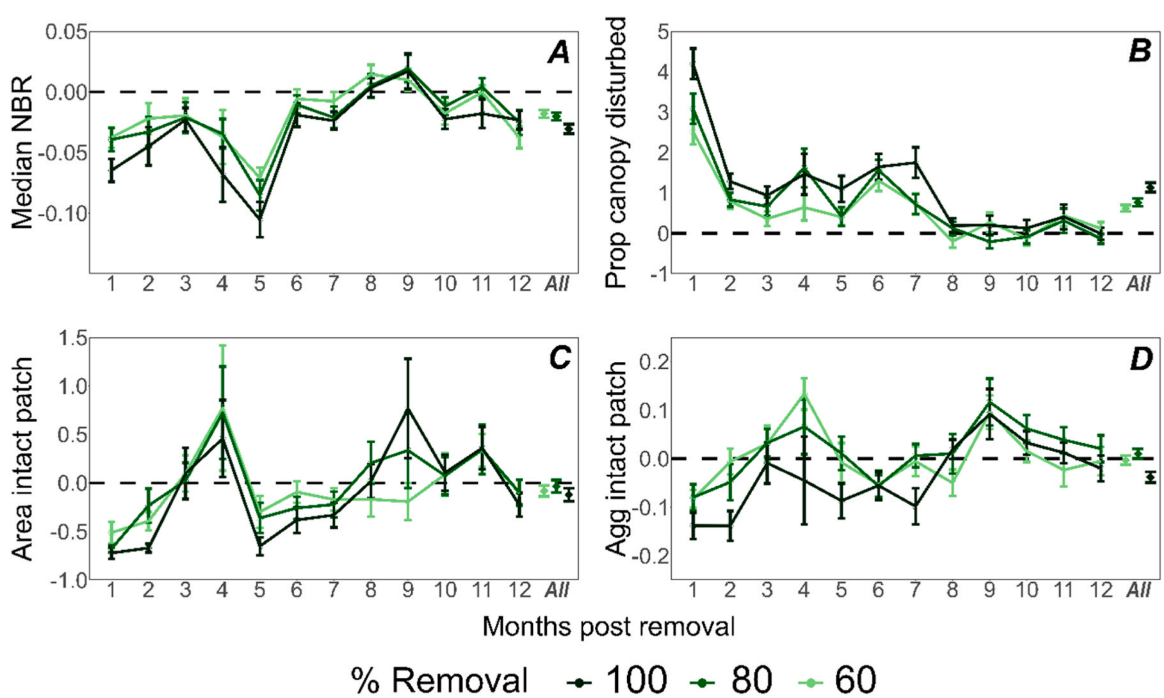

Fig. 4. Effect of liana removal on canopy degradation and fragmentation over 12-months post-treatment. Lines represent the mean degradation and fragmentation metric for each treatment intensity relative to the mean value in control blocks at each month (dotted black line at zero). Values above the dotted line indicate that the metric was higher in treated than control blocks. Points on the right of each panel represent mean value for each treatment intensity across the whole 12-months, relative to control. Error bars show standard error.

12 post-treatment, minimum NBR, proportion of canopy disturbed, and fragmentation metrics were all similar in treated and control blocks. The large drop in median NBR in treated compared to control blocks at month five (Fig. 4A) results from a sharp increase in the median NBR in control blocks (Fig S2), likely caused by an artefact in the imagery and fewer images in this month due to cloud cover. Fig. S3 shows that while there was considerable variation in median NBR pre-treatment, there was a clear and sustained decrease in median NBR in treated compared to control plots for the five months immediately following liana removal.

Liana removal treatment was distinguishable from control forest for longest when using the proportion of the canopy with decreased NBR (Fig. 4B), with all intensities of removal causing canopy disturbance for more than seven months using this metric compared to less than six months for median NBR and the area and aggregation of intact pixels (Fig. 4A, C & D). In general, complete removal had a larger influence on canopy disturbance and fragmentation than partial removal throughout 12-months post-treatment (Fig. 4), but all intensities of removal became indistinguishable from control at a similar time for each metric. Recovery of the canopy over 12-months is consistent across additional canopy metrics (GI, NDVI, EVI, minimum NBR indices), and when using a 10% threshold for calculating the proportion of disturbed canopy and fragmentation metrics (Tables S4-S5, Fig S1 & Figs S4-S6).

4. Discussion

The use of remote sensing to quantify the effects of liana removal is a powerful tool for large-scale monitoring and validation. We show that remote-sensing data can observe the impact of varying intensities of liana removal on the canopy over large spatial and temporal scales. Specifically, our results suggest that: liana removal fragments and disturbs the canopy; these impacts may be minimised with partial removal; and the Sentinel-2 signal of liana removal is strongest during the first months post-treatment.

4.1. Liana removal and canopy dynamics

The satellite signal of liana removal provides insight into the influence of lianas on the canopy and in tropical forests. Consistent with other studies, our results indicate that liana removal increases canopy browning or openness (O'Brien et al., 2019; Perez-Salicrup, 2001; Wu et al., 2020). Observing these canopy changes using relatively coarse 10 m resolution imagery supports studies evidencing that lianas are a substantial component of the canopy, one that that maintains cool, low-light, and low-wind understory conditions (Meunier et al., 2021). Hence, this study emphasises that liana removal could subject fauna and flora to more extreme climatic conditions (Scheffers et al., 2014). The apparent fragmentation of the canopy after liana removal also highlights the role of lianas in canopy connectivity that is critical for the movement of arboreal animals (Adams et al., 2019; Putz et al., 2001). We echo the views of others that safeguarding the functional role of lianas is, therefore, critical when implementing liana removal in tropical forests (Putz et al., 2023).

Partial removal of lianas is proposed to counteract potential negative consequences for biodiversity (Estrada-Villegas and Schnitzer, 2018; Finlayson et al., 2022). As anticipated, partial removal appeared to significantly reduce canopy disturbance compared to complete removal, but, interestingly, our results suggest that 60% and 80% liana removal may cause similar disturbance. Research should explicitly measure the impact of partial removal on biodiversity and forest function, but we show that leaving 20–40% of the target area untreated could substantially reduce canopy openness, fragmentation, and any harmful consequences. Research should also explore alternative partial removal configurations. For example, treating a proportion of future crop trees rather than using the strip-cutting technique, as proposed by Putz et al. (2023), could preserve the functions of lianas throughout a treated area and may also result in larger differences between partial removal treatments.

The recovery of the canopy disturbance signals within a year post-treatment, consistent with field-based data from the same region (O'Brien et al., 2019), highlights canopy dynamism. Determining whether recovery is driven by trees or lianas, however, is challenging. While other studies quantify liana abundance using airborne hyper-spectral and trained satellite data (Chandler et al., 2021; Waite et al., 2019), Sentinel-2 imagery alone lacks the resolution for precise estimation of tree and liana proportions in the canopy (van der Heijden et al., 2022). The significant positive correlation between pre-treatment liana load and median NBR was also relatively weak so could not be used to accurately quantify liana load post-treatment (Fig S7; $R^2 = 5\%$). Theory suggests that lianas may regrow faster than trees due to lower investment in woody stems (Alvira et al., 2004; Campanello et al., 2012; Phillips et al., 2005; Schnitzer et al., 2014), but a recent study found that leaf turnover in aseasonal forests is similar between lianas and trees (Medina-Vega et al., 2021). Regardless, the recovery of canopy disturbance signals observed herein imply that canopy closure and the associated microclimate buffer could recover within a year, benefitting understory fauna. Moreover, if canopy closure is driven by lianas, the negative impacts of liana removal on food, nesting, and locomotion resources may also be temporary. It is important to note, however, that our study only monitors changes in canopy cover since Sentinel-2 cannot observe the vertical distribution of plant material.

4.2. Monitoring liana removal

This study introduces a method to observe liana removal using freely available Sentinel-2 imagery. We build on work by Wu et al. (2020), demonstrating the length and spatial pattern of the liana removal signal using simple spectral indices. Once operational, quantification of NBR within the first months following treatment could provide evidence that liana removal activities have taken place, thereby helping land managers to secure income from carbon accreditation programs such as Verra (Verra, 2023). Compared to ground verification, using a S2 imagery-based method is demonstrably faster, cheaper, can cover larger extents, and is independently verifiable (Camarretta et al., 2020; Murcia et al., 2016; Zahawi et al., 2015). We recommend assessing the proportion of Sentinel-2 pixels with decreased NBR to observe liana treatments for this purpose since median NBR is highly variable.

The apparent re-closure of the canopy within 12-months also suggests that land managers could use a time-series of NBR metrics to determine this key stage in the effect of liana removal on the forest. However, since the impact of liana removal is expected to persist for more than 10 years (Finlayson et al., 2022), re-closure of the canopy does not indicate the end of the effect of liana removal. We also show that Sentinel-2 imagery could be used to identify areas of incomplete removal, addressing large-scale implementation issues (e.g., Mills et al., 2019) that may reduce tree growth and carbon sequestration. However, research is needed to determine factors other than intensity of liana removal that influence the signal.

4.3. Next steps for operational remote-sensing of liana removal

Despite advances noted herein, the liana removal signal we identified will require additional verification before further roll-out and being operational elsewhere. Importantly, the magnitude and spatial arrangement of the NBR-derived signal may differ in large-scale commercial treatments, such as whole forest compartments in Malaysian Borneo (Sabah Forestry Department, 2020), as these may use different removal methods and achieve different removal intensities (Mills et al., 2019).

Forest structure and liana abundance may also impact the NBR-derived signal. We expect liana removal to cause canopy changes throughout disturbed forests of the tropics but liana removal may be harder to observe with satellite in areas of lower liana abundance, for example those that are less intensely disturbed or have less seasonal rainfall (DeWalt et al., 2010; Schnitzer et al., 2014; Yorke et al., 2013). Without a global dataset on liana prevalence or canopy occupancy index (the metrics used to quantify liana abundance in our study) it is hard to predict whether the liana removal signal will be greater or smaller in other sites. Moreover, the patchy canopy influence of liana removal we identified may be specific to forests dominated by tree species that tend to have lower liana infestation, such as Dipterocarps (Brearley et al., 2016; Wright et al., 2015).

While Sentinel-2 imagery benefits from high spatial and temporal resolution and free access, other remote-sensing sources with higher spatial resolution, such as Planet CubeSats (Roy et al., 2021) or drone imagery (Waite et al., 2019; Zahawi et al., 2015), may offer more detailed signals of liana removal. Notably, the potential of GEDI for quantifying forest structure and carbon storage (Ngo et al., 2023; Potapov et al., 2021) should be explored for generating carbon credits without extensive ground data. However, the next Landsat mission ("Landsat Next"), due to launch in 2030, will be closely aligned with Sentinel-2 in terms of spatial and temporal resolution and spectral bands (NASA, 2023), meaning that liana-removal monitoring protocols using methods presented in this study will be possible with future generations of satellite data. Further work assessing the changes in individual Sentinel-2 bands, such as Near Infrared (NIR) and Short-Wave Infrared (SWIR) that can differentiate low and high liana infestation (Visser et al., 2021), may also contribute to our understanding of how (best) to observe liana removal using remote sensing.

5. Conclusion

Sentinel-2-derived NBR provides a strong basis for widespread observation of liana removal. With further development and testing, this approach could be used to validate and monitor liana removal, assisting large-scale application of the technique to restore tree growth and carbon sequestration in logged tropical forests. Further work is required to assess the impact of partial liana removal, but we recommend leaving at least 20% of the target forest untreated to safeguard the various roles of lianas for fauna and forest function.

Authors' statement

All authors on the manuscript have seen and approved the submitted version of the manuscript, all authors have substantially contributed to the work, and all persons entitled to co-authorship have been included.

CRediT authorship contribution statement

R.P. Freckleton: Conceptualization, Supervision, Writing – review & editing. **K.M. Yusah:** Conceptualization, Supervision, Writing – review & editing. **P.G. Cannon:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **M.G. Hethcoat:** Conceptualization, Supervision, Writing – review & editing. **C. Finlayson:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Funding acquisition. **D.P. Edwards:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **R.G. Bryant:** Supervision, Writing – review & editing.

Authors' contributions

C.F., R.P.F., D.P.E., P.G.C., and **K.M.Y.** designed the study; **C.F.** and **P.G.C.** conducted the fieldwork; **C.F.** conducted analyses with support from **M.G.H., R.P.F., D.P.E.**, and **R.G.B.; C.F.** produced figures; **C.F.** wrote the manuscript with feedback from **M.G.H., R.P.F., D.P.E., P.G.C., R.G.B.**, and **K.M.Y.** We bring together authors from a number of different countries, including scientists based in the country where the study was carried out. Where possible, our research was discussed with local stakeholders.

Declaration of Competing Interest

The corresponding author confirms on the behalf of all authors that there are no competing interests.

Data availability

All data necessary to reproduce the results presented in this study are available on Data Dryad at https://doi.org/10.5061/dryad.v15dv4234.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2023.121648.

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