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Liana cutting accelerates the structural recovery of once-logged tropical forests at a fraction of the cost of tree planting

Highlights

- Forest restoration experiment in Borneo covering 500 ha over 18 years
- Laser scanning revealed a ~50% reduction in tree mortality following liana cutting
- Liana cutting increased growth and carbon storage 3× faster than tree planting
- Liana cutting was also cost effective and 10× cheaper than tree planting

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In brief

Jackson et al. focus on forest restoration in logged dipterocarp-dominated forests using an 18-year, 500-ha experiment in Borneo. This study demonstrates that liana cutting reduces tree mortality and increases growth and carbon storage while remaining ten times cheaper than tree planting.

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Liana cutting accelerates the structural recovery of once-logged tropical forests at a fraction of the cost of tree planting

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SUMMARY

We urgently need to restore degraded tropical forests to mitigate the climate and biodiversity crises, but how to do so rapidly and cost-effectively remains an open question. Here, we provide a long-term, landscape-scale assessment of the effectiveness of enrichment tree planting and liana cutting, the two most common restoration interventions used across many tropical regions. Leveraging one of the world's largest and longest-running forest restoration experiments, we used repeated airborne laser scanning to track the 3D structural recovery of 500 ha of once-logged rainforest in Borneo. Over an 18-year period, enrichment planting increased mean canopy height by 1.6 m relative to unplanted controls. Remarkably, liana cutting increased canopy height more than four times faster (3.7 m over just 9 years). This recovery was jointly driven by accelerated tree growth and a 50% reduction in tree mortality. Given that liana cutting is around 10 times cheaper to implement than enrichment planting, our results suggest it provides a cost-effective, scalable solution to accelerate the structural recovery of logged tropical forests.

INTRODUCTION

Over the past century, vast portions of the world's tropical forests have been fragmented and selectively logged, leaving more than half of all remaining tropical forests in a degraded state.[1] Restoring these degraded forests is essential to limit global warming to 2°C and prevent further biodiversity loss.[2,3] Indeed, tropical forest restoration is widely recognized as one of the most impactful actions we can take to slow climate change,[4,5] and it is central to global initiatives like the UN Decade on Ecosystem Restoration. A major threat to the recovery of these degraded forests are lianas (woody vines), which often proliferate after disturbance and can outcompete trees for light, water, and nutrients.[6] Cutting lianas is therefore increasingly seen as a promising way to restore degraded tropical forests, especially as it is relatively cheap to implement[7] and has been shown to be effective in Central and

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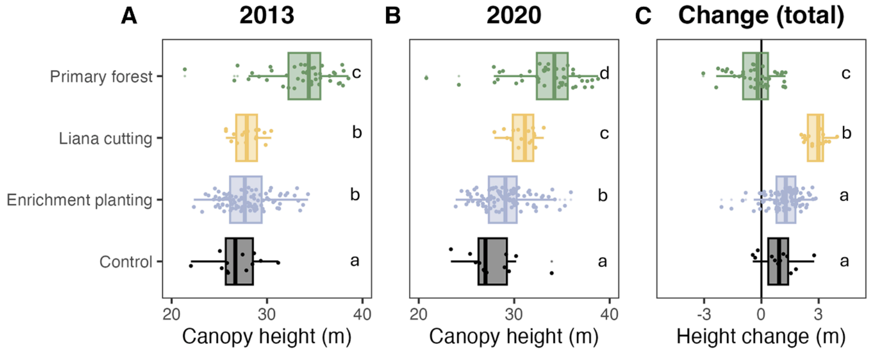

Figure 1. Liana cutting accelerates canopy height growth in once-logged forests in Borneo

Panels show the canopy height for each treatment in 2013 (A) and 2020 (B) and the change over time (C). The boxplots show the median (central line) and interquartile range (boxes) of the 4-ha plots with the data points overlaid. The letters indicate classes that are statistically different (at the $p < 0.05$ level) within each panel. A comparison of all mixtures of enrichment planting separated by block is given in Figure S1.

See also Figure S4 and Tables S1 and S2.

South America.[8–10] However, the effectiveness of liana cutting may not transfer to the forests of Southeast Asia because they are biologically distinct and dominated by a single family of trees, the Dipterocarpaceae.

Selective logging in Southeast Asia generally targets large mature dipterocarps, thus dramatically reducing seed production. Dipterocarp seeds do not survive in the soil, meaning that there is no seed bank once mature trees have been removed, putting these forests at risk of regeneration failure.[11] Therefore, the restoration of these selectively logged forests often focuses on enrichment planting with dipterocarp seedlings.[12,13] However, enrichment planting is expensive (US\$1,500–2,500 ha^{-1}), and many seedlings die in the first few years after planting.[13] Given that financial resources for restoration are limited, we urgently need to compare the effects of enrichment planting and liana cutting in Southeast Asia's dipterocarp-dominated forests.

The dipterocarps of Borneo can grow up to 100 m tall,[14] creating a unique forest structure and storing vast amounts of carbon (C).[15] Enrichment planting and liana cutting are likely to have distinct impacts on this 3D structure by altering tree growth and mortality at different layers of the forest canopy. For example, liana cutting may partially release canopy trees from competition for light, water, and nutrients, enabling them to grow faster and so increasing canopy height.[16] By contrast, the effects of enrichment planting are likely to be confined to the forest understory for many years before the seedlings begin reaching the height of the canopy.[13] The 3D canopy structure is widely recognized as an essential biodiversity variable[17] owing to its relationship with forest C storage, habitat complexity, and biodiversity.[18] However, we currently have no comparison of the impacts of different restoration interventions on the 3D structure of forests in Southeast Asia.

To address this major knowledge gap, we acquired repeated airborne laser scanning (ALS) data from one of the world's largest and longest-running tropical forest restoration experiments, the Sabah Biodiversity Experiment (SBE). Established in 2002, SBE encompasses 500 hectares (ha) of once-logged dipterocarp forest in Malaysian Borneo.[19] Its experimental design enables direct comparison of enrichment planting and liana cutting against untreated control plots. Using the repeated ALS data, we tracked how key attributes of the 3D canopy structure recovered over time across each of these restoration treatments. This helped us disentangle different components of forest recovery following restoration, distinguishing between understory growth, canopy gap recovery, and canopy growth and disturbances due to tree mortality and branch falls. We further compared these measurements to a nearby primary forest to provide a reference for pre-logging conditions. Using this approach, we address the following research questions:

(Q1) How do liana cutting and enrichment planting impact the recovery of canopy height and aboveground C storage?
(Q2) What are the demographic processes driving structural recovery in the different restoration treatments?
(Q3) How is the 3D canopy structure affected by enrichment planting and liana cutting?

RESULTS

Additional growth and C storage due to restoration

In the absence of logging, the forest at SBE would be similar to the nearby primary forest at Danum, which had a mean canopy height of 33.64 ± 0.53 m (mean ± standard error) that did not change significantly between 2013 and 2020 (Figure 1). As expected, the mean canopy height of the control plots in the logged forest was substantially lower than that of the primary forest in 2013 (26.90 ± 0.31 m) and steadily increased to 27.80 ± 0.21 m by 2020. Enrichment planting started in 2002, and these plots were 1.43 ± 0.65 m taller than the controls in 2013 (p = 0.03) and 1.61 ± 0.68 m taller in 2020 (p = 0.03). The additional canopy height growth between 2002 and 2020 due to enrichment planting was therefore 9 ± 4 cm per year.

Liana cutting started in 2011 in the southern block and 2014 in the northern block. In 2013, the mean canopy height of the liana cutting plots was 1.86 ± 0.81 m taller than that of controls (p = 0.02) but not significantly different from the enrichment planting plots. However, by 2020, the impact of liana cutting was clear, with these plots now 3.73 ± 0.85 m taller than the control plots ($p < 0.001$). This sharp increase in height due to liana cutting is particularly clear in the growth between 2013 and 2020 (Figure 1C). Since the liana cutting occurred in plots that had previously undergone enrichment planting, we estimated the additional canopy height growth due to liana cutting as the difference between liana cutting and enrichment planting plots, giving 2.12 ± 0.60 m ($p < 0.001$). Accounting for the different periods in the northern and southern blocks, the additional mean canopy height growth due to liana cutting was therefore 27 ± 8 cm per year. All the stated differences in mean canopy height were calculated after accounting for the modulating effects of elevation (see Table S1).

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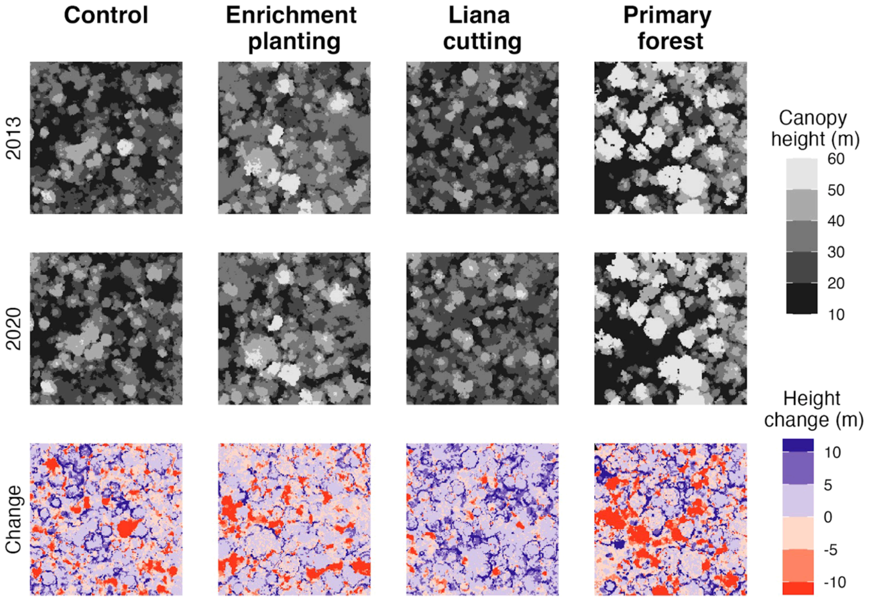

Figure 2. Tracking canopy dynamics using repeated ALS

Each panel shows an example 4-ha plot. The top row shows the canopy height models in 2013, the second row shows 2020, and the bottom row shows the change between them. Note that the effect of liana cutting is determined by comparison with the enrichment planting plots.

Previous work in Sabah[15] indicates that an increase in mean canopy height of 1 m represents approximately 5.19 ± 0.11 Mg of additional aboveground C storage per hectare (see Figure S1). Liana cutting therefore led to an additional gain of -+1.40 ± 0.42 Mg C ha^{-1} year^{-1}, three times greater than that of enrichment planting (+0.47 ± 0.21 Mg C ha^{-1} year^{-1}). Liana cutting is also substantially cheaper to implement than enrichment planting. In Malaysia, liana cutting costs approximately US$140–330/ha, while enrichment planting is an order of magnitude more expensive at US$1,500–2,500/ha.[12] Based on this, and assuming the impacts remain constant over time, we estimate that the cost per additional ton of CO$_2$ sequestered between 2030 and 2050 would be around US$2 (range: US$1–8) for liana cutting, compared with US$58 (US$23–593) for enrichment planting (see Table S2). The dramatic disparity between the two treatments is so large that even if our assumptions are out by a factor of 10, the general conclusions would still hold. We note that these estimates represent only the cost of implementing the restoration treatment and exclude other management and monitoring costs.

Impacts of restoration on canopy dynamics

To explore the demographic processes driving the mean canopy height growth after restoration (Q2), we tracked the canopy dynamics through the repeated ALS data covering SBE. The visualization of the ALS data (Figure 2) clearly shows that the liana cutting plots experienced less canopy disturbance (fewer and smaller red areas representing decrease in canopy height). To quantify this, we classified canopy disturbance events as a decrease in canopy height of at least 5 m over a contiguous canopy area of at least 25 m^2. We found that the proportion of canopy area disturbed in the liana cutting plots was 3.61% ± 0.27% (mean ± standard error; Figure 3A). This was significantly smaller ($p < 0.001$ in all cases) for the enrichment planting (9.86% ± 0.30%), the control plots (11.20% ± 0.98%), and the primary forest (12.64% ± 0.56%). The canopy height change visualizations (Figure 2) clearly shows that much of this disturbance represents canopy tree mortality. If we assume that each event represents a single tree mortality event (see Figure S2), we estimate that 5.3 ± 0.3 trees/ha died in the liana cutting plots. This was significantly lower ($p < 0.001$ in all cases) for the enrichment planting (10.1 ± 0.2), the control plots (10.8 ± 0.5), and the primary forest (10.8 ± 0.2). Given the experimental setup of SBE, the additional impact of liana cutting is the difference between the liana cutting and enrichment planting treatments. Our results therefore suggest that liana cutting reduced tree mortality by 4.8 ± 0.2 trees/ha.

In addition to the lower disturbance rates, plots with liana cutting had noticeably faster height growth rates in both recovering canopy gaps and in the remaining intact canopy (Figure 3B). The mean height growth in recovering canopy gaps was 1.39 ± 0.05 m year^{-1} in the liana cutting plots. This was significantly faster ($p < 0.001$ in all cases) than in the enrichment planting plots (1.07 ± 0.03 m year^{-1}), the logged controls (0.89 ± 0.09 m year^{-1}), and the primary forest (0.89 ± 0.04 m year^{-1}; Figure 3B). Similarly, mean height growth rates of the intact canopy was faster ($p < 0.001$ in all cases) in the liana cutting plots (0.50 ± 0.02 m year^{-1}) than in the enrichment planting (0.41 ± 0.01 m year^{-1}), the control plots (0.41 ± 0.03 m year^{-1}), or the primary forest (0.38 ± 0.01 m year^{-1}; Figure 3B). The additional height growth due to liana cutting (calculated as the difference between liana cutting and enrichment planting) was 0.32 ± 0.05 m year^{-1} in the recovering gaps and 0.09 ± 0.02 m year^{-1} in the intact canopy. As most of the canopy remained intact between the two ALS surveys (90% in the liana cutting plots; Figure 3A), these seemingly small differences in height growth have a substantial impact on the canopy at the plot level (Figure 3C).

Our results show that the difference in additional canopy height growth between liana cutting and enrichment planting was due to a combination of faster canopy growth and reduced mortality. To quantify the relative importance of these two processes, we used a counterfactual approach to simulate a treatment with the growth rate of the enrichment planting and the mortality rate of the liana cutting. This approach demonstrated that 46% of the difference in canopy height and C storage between treatments was due to faster growth in the liana cutting plots, and 54% was due to avoided tree mortality (see Figure S3 and Table S3).

Changes in forest 3D structure after restoration

To understand the impacts of each treatment on 3D canopy structure (Q3), we calculated the total leaf area index and the

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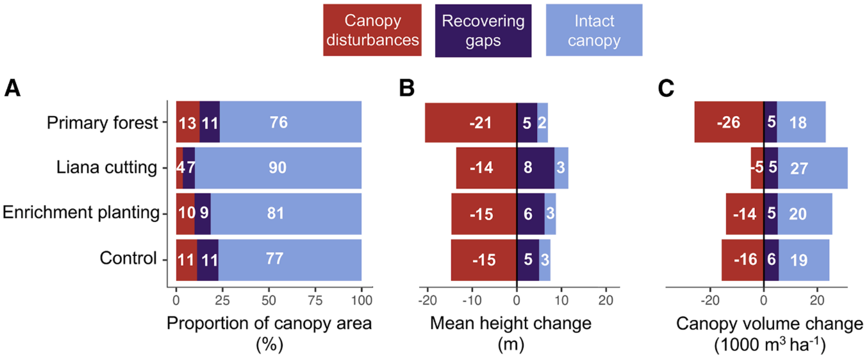

Figure 3. Liana cutting increased growth and reduced disturbance

Panels show (A) the area, (B) the mean height change, and (C) canopy volume change (area × height) in each canopy dynamics class across the experimental treatments between 2013 and 2020. Figure S3 shows the counterfactual approach used to determine the contribution of avoided mortality.

See also Figure S2 and Table S3.

vertical profiles of leaf area from the ALS data. The control, enrichment planting, and liana cutting plots all had a similar total leaf area index (4.13–4.24) and 3D distribution of leaf area in 2013 (Figures 4A and 4D). As we would expect, the primary forest had a larger total leaf area index (4.40 ± 0.03; $p = 0.02$), concentrated at greater heights, due to the presence of taller trees (Figures 4D and 4E). Between 2013 and 2020, the leaf area of the control and enrichment plots increased in the upper canopy (35–45 m), suggesting that the canopy trees are still growing after logging in the 1980s (Figure 4F). Over the same period, their leaf area decreased in the mid-canopy (10–30 m), suggesting that the enrichment seedlings planted in 2002 had not yet reached these heights in sufficient density. These two effects balanced out so that the total leaf area index of the control and enrichment plots did not change significantly between 2013 and 2020. By contrast, the leaf area of the liana cutting plots increased substantially across all heights and all tree size classes from 10 to 45 m, reflecting the faster growth and lower mortality described above. The increase was a decrease in leaf area between 0 and 10 m and a particularly strong increase between 10 and 20 m height (Figure 4F). Together, these changes reflect the accelerated gap recovery observed in Figure 3E. Overall, this resulted in a leaf area index of 4.54 ± 0.03 in the liana cutting plots in 2020. This was higher than that of the enrichment planting plots (4.26 ± 0.02, $p < 0.001$) and even than the primary forest (4.28 ± 0.03, $p < 0.001$). The additional leaf area index due to liana cutting was therefore 0.29 ± 0.03.

DISCUSSION

We assessed the structural recovery of once-logged tropical forests in Borneo by using repeated ALS data collected over a 500-ha forest restoration experiment that had been running for 18 years. Our study demonstrates that liana cutting provides a cost-effective opportunity to accelerate the structural recovery of these once-logged forests. Liana cutting increased canopy growth rates and reduced the mortality rates of large canopy trees. This resulted in a marked change in 3D canopy structure, with taller, denser, and more vertically complex canopies, compared with the control and enrichment planting plots. While enrichment planting had only a limited impact on the structural recovery of these forests during the first two decades of restoration, we emphasize that it still has an important role to play in promoting the recovery of dispersal-limited dipterocarps—especially when in heavily degraded forests subjected to multiple rounds of selective logging.

Liana cutting is a cost-effective way to accelerate canopy growth and C accumulation

We found that liana cutting accelerated additional net canopy height growth three times faster than enrichment planting. Given that it is around 10 times cheaper to implement than enrichment planting, liana cutting represents a cost-effective way to restore some of the C lost during logging. For example, if the increased growth remains stable over a 20-year period, this would sequester CO_2 at a cost of US\$2 per ton (range: US\$3–23). For context, the average price to offset a ton (1,000 kg) of CO_2 equivalent on the voluntary C market was US\$6.34 in 2024.[20] Liana cutting may therefore present a cost-effective opportunity to extend management over large areas of at-risk forests that might otherwise be cleared and replaced with oil palm.[21] We note that C sequestration was estimated from mean canopy height growth, and although this relationship is based on a range of local plot measurements,[15] it does not account for the specific combination of tree species at this site.

Previous work has shown that liana cutting prior to logging reduces the impact of the logging process on the surviving trees, increasing their future growth. This has been shown in Borneo[22] and across the tropics.[9] However, the effectiveness of liana cutting after logging as a way to restore degraded forests has rarely been tested outside of the Americas.[8–10] Given the unique biogeography of Southeast Asia, it was unclear whether results from the Americas would be transferrable, especially given that severe liana infestations are less common in dipterocarp forests.[23–25] Our results are therefore highly relevant to forest management in the region, especially given the SBE's scale and duration. However, we caution that SBE is a once-logged forest that was relatively intact prior to restoration and is not representative of all logged forests in the region. We also note that liana cutting occurred in plots that had previously been planted with seedlings, although the timing of treatments and our analysis of the processes driving mean canopy height change allow us to largely disentangle the effects of liana cutting from seedling growth.

Our results show that after 18 years, the impact of enrichment planting on the canopy structure was considerably smaller than that of liana cutting. This contradicts previous results derived from multispectral satellite data at SBE, which suggested that enrichment planting was accelerating the recovery of canopy

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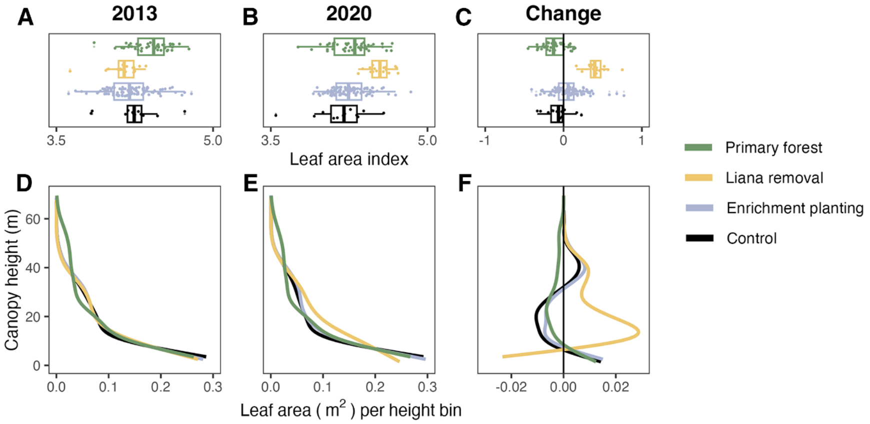

Figure 4. Liana cutting alters 3D forest structure

The top row (A–C) shows the variation in leaf area index for each 4-ha plot. The bottom row (D–F) shows vertical leaf area profiles of leaf area. The columns show the values in 2013 (A and D) and 2020 (B and E), and the difference between them (C and F).

See also Table S4.

cover and aboveground biomass as early as 2012.[26,27] The higher spatial resolution of our ALS surveys and their ability to accurately reconstruct changes in the 3D canopy structure revealed this to be an overestimation, emphasizing the real challenge of mapping tropical forest structure using satellite archives such as Landsat.[15] Our ALS results also align with the 2015 field measurements that showed that the mean basal diameter of surviving seedlings was 3.2 cm,[28,29] making them still too small to have reached the canopy.

Liana cutting increased growth and reduced tree mortality

To understand the ecological impacts of liana cutting, we must examine the processes driving forest recovery. Multiple studies in central America have shown that liana cutting releases trees from competition, enabling them to grow faster.[8,9,16] We found a similar response in Borneo, with liana cutting leading to both greater height growth rates of mature trees that make up the intact canopy and faster regeneration in canopy gaps, compared with enrichment planting plots and logged forest controls. However, this accelerated growth only accounted for around half of the increased aboveground C accumulation following liana cutting, a similar proportion as reported in Panama.[16] The remaining difference between restoration treatments was linked to the reduction in tree mortality that we observed in the liana cutting plots. Based on the disturbed area, we estimate that liana cutting reduced tree mortality by 5 trees/ha, compared with the enrichment planting, the control plots, and even the nearby primary forest. If this effect endures, then the reduced mortality due to liana cutting would be sufficiently large to mitigate the climate impacts of a round of selective logging, which generally targets between 4 and 10 mature trees/ha every 30-year cutting cycle.[30]

There are several mechanisms through which liana cutting could lead to reduced tree mortality.[31] Lianas can physically suppress trees and outcompete them for light.[32] Beyond competition with trees, lianas can also enhance the risk of tree mortality by lightning,[33] wind gusts during storms,[34] and as collateral damage during tree falls.[31] Their greater hydraulic efficiency can also reduce a tree's access to water and could exacerbate the effects of drought.[35] This hydraulic mechanism seems plausible in this case because our study overlapped with a severe drought in Borneo that was caused by the 2015–2016 El Niño.[36] It is therefore possible that liana cutting alleviated the hydraulic stress sufficiently to reduce tree mortality. Of course, liana cutting may have simply delayed tree mortality, rather than reducing it in the long term. Between 2013 and 2020, the canopy in the liana cutting plots at SBE became increasingly closed and dense, to the point where the leaf area index was higher than that of the primary forest. This has not been reported in other long-term liana removal experiments[37] and could potentially lead to enhanced competition for light followed by self-thinning in the future. Our results provide a snapshot of the first decade following liana cutting, but understanding the long-term implications of this restoration intervention will require continued monitoring both at SBE and across the tropics.

Seeking a balanced approach to forest restoration in Borneo

Assuming the goal of restoration is to enhance both nature recovery and C capture, then striking a balance between enrichment planting and liana cutting is likely to be key. Given the high costs associated with enrichment planting, it is important that these resources are targeted toward areas likely to benefit most. Previous work in Southeast Asia has shown that in highly degraded forests that have undergone multiple rounds of selective logging or clearcutting, enrichment planting with dipterocarps is critical to restore the composition of the tree community.[13] By contrast, in forests that have undergone a single round of selective logging (such as the SBE landscape), our results suggest that liana cutting by itself may promote the compositional recovery of the forest. This is because liana cutting accelerates the growth and reduces the mortality of trees that survive the logging, including many small and medium-sized dipterocarps. The increase in dipterocarp basal area is therefore likely to be greater due to liana cutting rather than enrichment planting over the 10- to 20-year timescales of this experiment.

While it is tempting to think of lianas simply as structural parasites of trees, it is important to remember that they are also integral components of the forest ecoystem.[23] For instance, lianas generally promote greater bird abundance and diversity,[38,39] and they serve as important food resources and canopy pathways for numerous fauna, including keystone species such as orangutans.[40] Moreover, lianas contribute significantly to overall plant diversity, and their removal may thus result in a net loss of species richness.[10] The fact that lianas adopt very different functional strategies to trees, geared toward more acquisitive leaf and root traits,[35,41,42] suggests that their removal could also have knock-on impacts on forest biogeochemical cycling.[43] While lianas typically only make up a small fraction of the aboveground biomass in a tropical forest, they contribute disproportionately to the total leaf area and therefore presumably to primary productivity.[44,45] Systematically removing lianas could therefore have unforeseen impacts on C and nutrient cycling in the litter and soil that have so far been almost completely unexplored. These impacts could potentially be mitigated by partial cutting of lianas (e.g., cutting 60%–80% of stems as opposed to all of them), which is currently being trialed in the Ulu Segama-Malua Forest Reserve near SBE.[46] This work will hopefully shed light on how best we can achieve the structural recovery benefits of liana cutting without compromising biodiversity and ecosystem function.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Toby Jackson (tobydjackson@gmail.com).

Materials availability

This study did not generate any new materials.

Data and code availability

- The ALS data have been deposited on Zenodo and are publicly available at 10.5281/zenodo.14917550.
- All original code has been deposited on Zenodo and is publicly available at 10.5281/zenodo.19692749.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.D.J., L.V.J.B., and T.J.; data curation, T.D.J., M.J.O., D.A.C., F.J.F., and T.J.; formal analysis, T.D.J., L.V.J.B., and T.J.; funding acquisition, A.H., M.J.O., D.A.C., D.F.R.P.B., and T.J.; investigation, T.D.J., L.V.J.B., and F.J.F.; methodology, T.D.J., L.V.J.B., and M.J.O.; project administration, T.D.J. and T.J.; resources and software, T.D.J. and F.J.F.; supervision, T.J.; validation, A.H., M.J.O., G.C., E.G., C.J.W., M.S., M.D., and W.S.W.M.J.; visualization, T.D.J.; writing – original draft, T.D.J. and L.V.J.B.; and writing – review and editing, A.H., E.E.J., M.J.O., G.C., D.A.C., D.F.R.P.B., F.J.F., C.D.P., E.G., C.J.W., M.S., M.D., W.S.W.M.J., and T.J.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
- METHOD DETAILS
    - Enrichment planting
    - Liana cutting
- QUANTIFICATION AND STATISTICAL ANALYSIS
    - Airborne laser scanning acquisition and processing
    - Additional canopy height growth
    - Additional carbon accumulation
    - Disturbance and recovery dynamics
    - Vertical leaf area index profiles

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2026.04.056.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Airborne laser scanning data collected over the Sabah Biodiversity Experiment in 2013 and 2020	Ground Data Solutions Gmbh	https://zenodo.org/records/14917551
Software and algorithms		
R version 4.5	CRAN	https://cran.r-project.org/bin/windows/base/
Terra package for R version 1.8.42	CRAN	https://cran.r-project.org/web/packages/terra/index.html
Marginaleffects package for R	CRAN	https://cran.r-project.org/web/packages/marginaleffects/index.html
LeafR package for R	Github	https://github.com/cran/leafR/
Canopy dynamics and analysis software	This study	10.5281/zenodo.19692749

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

The Sabah Biodiversity Experiment (SBE) is a forest restoration and tree biodiversity experiment in Sabah, Malaysian Borneo, that has been running since 2002.[19] The region is characterized by a tropical climate, with a mean annual temperature of around 27°C and mean annual rainfall exceeding 3000 mm. SBE covers a 500 ha area of lowland dipterocarp forest that was selectively logged in the 1980s and has since been allowed to recover. The area is divided into two blocks (north and south) separated by an old logging road and is topographically heterogeneous, with elevation ranging between 150-350 metres above sea level. The protected primary forest of Danum Valley is located approximately 50 km southeast of SBE and has a similar climate and topography.

METHOD DETAILS

Enrichment planting

SBE consists of 124 plots (200×200 m in size, or 4 ha, see Figure S4), randomly allocated to different experimental treatments (64 in the southern block and 60 in the north). 12 plots were designated as controls and were allowed to recover without any post-logging intervention. All remaining plots received understory enrichment planting with varying combinations of 16 dipterocarp species. Specifically, 32 plots were planted with a single dipterocarp species, 32 plots with a mixture of four species, and a further 32 plots with all 16 species. Seedlings were planted in parallel lines 10 m apart, with a 3-m spacing between seedlings along the lines. Initial planting occurred in 2002-2003, with a second cohort planted in 2008-2009 to replace any seedling that had died. In total, around 100,000 seedlings were planted (approximately 900 per 4-ha plot, excluding the controls). We found no statistical difference between the canopy height of the three different enrichment planting treatments (see Figure S4). For the purpose of our analysis, we therefore grouped all three enrichment planting treatments together.

Liana cutting

Liana cutting targeted all climbers (including bamboos) across the entire 4-ha plot with no minimum size limit. Liana cutting was implemented in 16 plots which had previously been planted with the full mixture of 16 species. Liana cutting in the 10 plots in the southern block was undertaken in 2011 and repeated in 2014. In the remaining 6 plots in the north block, liana cutting occurred initially in 2014 and was repeated in 2017. Due to field constraints, the 6 plots in the northern block were not randomly allocated but located close to the access road and therefore at relatively low elevation (see Figure S4). We included elevation and experimental block as a factor in the model to account for these differences. We note that the impact of liana cutting was slightly larger in the southern block where plot location was randomized (see Figure S4).

Our analysis compares three categories: logged forest controls (n = 12 plots, 48 ha), enrichment planting only (n = 96 plots, 384 ha) and liana cutting with enrichment planting (n = 16 plots, 64 ha). It is important to note that the SBE design does not fully separate the effects of liana cutting from enrichment planting, as all plots (except the controls) were planted. However, we can still infer the effect of liana cutting by comparing the enrichment planting plots with and without liana cutting. We note that the enrichment planting lines were also kept clear of lianas (following standard practice) using multiple rounds of targeted liana cutting. This excludes the possible interaction effect whereby the planted seedlings in the liana cutting plots grow faster due to reduced competition.

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QUANTIFICATION AND STATISTICAL ANALYSIS

Throughout this study we report the mean ± standard error and report significance based on post-hoc pairwise comparisons among restoration treatments calculated using the *marginaleffects* package.[47] No plots were excluded from our analyses.

Airborne laser scanning acquisition and processing

Airborne laser scanning (ALS) data were collected in November 2013 and February 2020 by the survey company Ground Data Solutions using a Riegl scanner mounted on a helicopter. Both ALS surveys covered the entire SBE landscape, as well as 180 ha of primary forest at nearby Danum Valley. To enable comparisons between the two sites, we gridded the data over Danum into 4-ha plots (45 plots). Data acquisition followed similar flightlines and specifications in both surveys (see Table S4), with the 2013 data collected from an altitude of 350 m and achieved a density of 26 pulses m^{-2}, while the 2020 data were flown at 250 m and a density of 32 m^{-2}. Ground points were classified using the LASground function in LAStools[48] and the point cloud was normalized by subtracting the ground elevation from the remaining points. We then used the point cloud data to build 1-m resolution digital terrain models (DTM) and canopy height models (CHM) using a locally adaptive spikefree algorithm which is highly robust to variation in ALS pulse density in the range of our data.[49]

Additional canopy height growth

To assess the net effect of restoration (Q1) we extracted the 2020 mean canopy height from the CHM using the *terra*[50] package in R v4.5.[51] We then modelled canopy height as a function of elevation, treatment and experimental block using the following linear model.

$$\textit{canopy height } 2020 \sim \textit{elevation} + \textit{treatment} + \textit{block}$$

Restoration treatment was included as a factor with 3 levels (logged forest controls, enrichment planting and liana cutting) and experimental block as a factor with two levels (north and south). Initial results showed that the canopy height was taller at higher elevations, so we accounted for this by including elevation in the model (see Table S1). The additional canopy height growth due to enrichment planting is therefore given by the coefficient of the enrichment planting term in the model output (see Table S1). The additional canopy height growth due to liana cutting was calculated as the difference between the mean canopy height of liana cutting and enrichment planting plots. This is because liana cutting happened in plots which had already undergone enrichment planting.

Additional carbon accumulation

To convert the additional canopy height growth into additional carbon accumulation we used a simple allometric equation developed specifically for Sabah.[15] We found that both linear and power law models gave very similar carbon estimates (see Figure S1) so chose to use the linear model for simplicity. This linear model simply predicts that each additional meter of growth in mean canopy height equates to 5.2 Mg Carbon per hectare (see Figure S1). We then multiplied the tons of carbon by 3.67 to calculate the tons of CO_2, which is the unit usually used in the global carbon market.

To compare the cost effectiveness of liana cutting and enrichment planting we estimated the cost of sequestering a ton of CO_2 by 2050, assuming the intervention takes place in 2030. To make this calculation, we first assumed that the treatment effect was linear over 20 years. This seems justified for the enrichment planting since we already have 18 years of data but is a larger extrapolation from the 9-years of liana cutting. We then combined the 20-year carbon accumulation estimates with the cost of the restoration treatment in SBE. These costs were derived from the contracts used to implement the restoration and ranged from USD$140-330 per hectare for the liana cutting and USD$1500-2500 per hectare for the enrichment planting. We took the central value from these ranges and also calculated the best- and worst-case scenarios by combining the lowest cost with the highest effectiveness and vice-versa (see Table S2).

Disturbance and recovery dynamics

To disentangle the processes driving canopy dynamics (Q2), we used a recently developed framework[52] that classifies repeat ALS data into three classes of canopy dynamics: new disturbances, recovering canopy gaps, and intact canopy. Disturbances were defined as contiguous areas larger than 25 m^2 which decreased in height by more than 5 m between scans. Recovering gaps were defined as contiguous areas larger than 25 m^2 which had a canopy height lower than 10 m in the initial 2013 scan. Intact canopy is the remaining area of the CHM that was not classified as a recovering gap in 2013 and was not subjected to a disturbance between the two scans. This classification makes full use of the repeat ALS data and helps tease apart the processes driving forest recovery, such as tree mortality, understory growth in gaps, and mature tree growth. For each 4-ha plot at SBE and Danum, we calculated the proportion of the canopy classified as either disturbed, recovering gap or intact, and then quantified the mean canopy height change in each of these three classes. We then multiplied these together to get the change in canopy volume over time attributed to new disturbances, recovering gaps and intact canopy growth. We used a multiple linear regression to quantify the effect of treatment on the area of disturbed canopy and the height growth in intact canopy and recovering gaps.

Our initial results showed that the net increase in mean canopy height was due to a combination of faster growth in the intact canopy and gaps, as well as a lower rates of canopy disturbance (avoided mortality). We used a counterfactual approach to estimate the relative contributions of these two demographic processes and how these contributions differ between treatments (see Figure S3 and Table S3). Specifically, we simulated a counterfactual treatment with the same area of intact canopy, gaps and disturbances

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as the enrichment planting plots. To this we then applied the height change rates of the liana cutting plots, giving us an estimated canopy volume change due solely to the effects of liana cutting on height growth (i.e., removing any effects associated with differences in disturbance rates between treatments). This allowed us to calculate how much the total canopy volume would have increased in this counterfactual scenario. By comparing this counterfactual to the observed canopy volume increase in the liana cutting treatments, we were able to estimate what proportion of the difference between treatments was due to avoided mortality.

Vertical leaf area index profiles

To explore the impact of restoration on different canopy layers (Q3), we used the *leafR* package[53] to generate vertical LAI canopy profiles of each SBE plot in 1-m height bins. Leaf area profiles were generated from the normalized point clouds by estimating the transmittance of laser pulses through the canopy. Since ALS samples the canopy from above, the lower levels of the canopy are likely to be occluded. The *leafR* package therefore applies a Beer-Lambert transformation to the transmittance profiles to estimate leaf area in each 1-m height bin. This transformation assumes homogeneous volume filling through the canopy, which is rarely the case in a forest. However, as we were not interested in the absolute values of LAI, but rather the difference between treatments, this approach allowed us to compare the vertical canopy profiles of enrichment planted and liana cutting plots and pinpoint where they differ in 3D space.

Specifically, for each restoration treatment we calculated the mean vertical LAI profile across all plots. We calculated the vertical distribution of leaf area for the 2013 ALS survey, which occurred 11-years after the first round of enrichment planting and at around the same time as the liana cutting (2011-2014) and therefore likely too early to detect any differences between treatments. We also calculated the vertical distribution of leaf area for the 2020 scan which took place 6-9 years after liana cutting. Additionally, we also calculated the total LAI of each plot in 2013 and 2020 by summing the leaf area across all height layers. Finally, we calculated the change in total LAI as well as in the vertical distribution of leaf area as the difference between 2020 and 2013 values. We used a multiple linear regression to test the effect of treatment on total LAI between treatments.