Active restoration accelerates the carbon recovery of human modified-tropical forests

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Abstract: More than half of all tropical forests are degraded by human impacts, leaving them threatened with conversion to agricultural plantations and risking substantial biodiversity and carbon losses. Restoration could accelerate recovery of Aboveground Carbon Density (ACD), but adoption of restoration is constrained by cost and uncertainties over effectiveness. We report a long-term comparison of ACD recovery rates between naturally regenerating and actively restored logged tropical forests. Restoration enhanced decadal ACD recovery by more than 50%, from 2.9 to 4.4 megagrams per hectare per year. This magnitude of response, coupled with modal values of restoration costs globally, would require higher carbon prices to justify investment in restoration. However, carbon prices required to fulfil the 2016 Paris climate agreement (US$40–80 per tCO_2 e) would provide an economic justification for tropical forest restoration.

One Sentence Summary:

Active restoration of logged tropical forests would be incentivised by carbon prices consistent with the 2016 Paris agreement

Main Text

Tropical forests contain 55% of global stores of aboveground forest carbon (1), but the size of these stocks is declining rapidly because of forest loss and degradation (2). Across the tropics, primary forests continue to be degraded by numerous human impacts such as timber harvesting, agriculture, and fire. Consequently, more than half of all tropical forests have some human impact, even though many disturbed sites retain high tree cover (3). Loss of tropical forest cover is particularly acute in Southeast Asia, which has the highest deforestation rate in the tropics and where the intensity of logging is increased by the high densities of commercially important dipterocarp trees (4). These forests, which are no longer pristine, may still support numerous ecosystem services, including timber production, sequestration of carbon, maintenance of biodiversity, and hydrological services (5–8).

Despite their ecological value, degraded forests remain vulnerable to conversion to agroecosystems possessing substantially lower carbon stocks and biodiversity (5, 9, 10). Alternatively, carbon stocks in degraded tropical forests can recover, particularly if accelerated by active restoration and if financial compensation mechanisms encourage avoided deforestation projects. However, these mechanisms require verification of aboveground carbon density (ACD) baseline values and recovery rates (11), which are currently lacking. Mean and maximum ACD values are higher in Southeast Asian forests than in other tropical forests, and the highest values occur in Malaysia (12). For example, in the Malaysian state of Sabah, where selective logging has been one of the main forms of habitat degradation, unlogged lowland forests show consistently high ACD values averaging over 200 Mg C ha^{-1}, whereas in logged forests, ACD varies from 60 to 140 Mg C ha^{-1} (10). The difference in ACD between logged and unlogged forests in Sabah shows the potential carbon gain if logged forests were allowed to recover, which is estimated at 362.5 Tg C (10). At current carbon prices [typically between \$2 and \$10 (USD) t CO_2 e), the potential value of this sequestered carbon would total between \$0.725 billion and \$3.625 billion for Sabah alone (13–15). Similar values could be calculated for any territory that has a comprehensive map of forest carbon and information on land-use history, but such data are not widely available across the globe.

Carbon sequestration rates in degraded tropical forests are highly variable. Long-term studies indicate that post-logging carbon recovery rates are between 0.30 and 4.3 Mg C ha^{-1}year^{-1} in Southeast Asia (11) and 0.04 and 2.96 Mg C ha^{-1} year^{-1} in Amazonia (16), whereas naturally regenerating pasture and abandoned agricultural land accumulate ACD at a mean rate of 3.05 Mg

C ha^{-1} year^{-1} in the Neotropics (17). These rates could be enhanced by implementing active restoration measures, which include tree planting, cutting of climbers such as lianas, and liberation of sapling trees from competing vegetation by thinning. Enrichment planting is especially important in the logged forests of Southeast Asia because selective logging affects the ecologically and economically important dipterocarp trees that are dispersal limited and mast fruit at irregular intervals (18, 19). Such measures are, however, expensive to implement; for example, enrichment planting of lowland forest in Sabah costs ~$1500 to $2500 ha^{-1} over the implementation period, consistent with estimates of restoration costs for other tropical forests globally (table S1). Carbon offset schemes could provide a potential financing mechanism for these restoration costs, but evidence of restoration treatment efficacy with respect to ACD recovery in degraded forests exists for very few sites globally (table S1). The likelihood that such measures will be adopted is critically dependent on the operational costs over the lifetime of the stand relative to the additional value in terms of enhanced ACD accumulation.

Here, we report estimates of the response of ACD accumulation rates to active restoration using a combination of climber cutting and enrichment planting in a logged tropical forest over decadal time scales. We compare the fiscal benefits of this restoration across a range of potential carbon prices. Using detailed information on logging history and repeated in situ measurements from 257 forest plots from three different plot networks in Sabah, Malaysia, we compared recovery rates for naturally regenerating forest with recovery rates for areas that had been actively restored (20). During the 30 to 35 years after logging, naturally regenerating forest accumulated aboveground carbon at a rate of 2.9 Mg ha^{-1} year^{-1} (Fig. 1 and fig. S2) [confidence interval (CI): 2.1 to 3.7], whereas those areas with active restoration recovered at the considerably higher rate of 4.4 Mg ha^{-1} $year^{-1}$ (Fig. 1 and fig. S2) (CI: 3.6 to 5.2). These values suggest that the reduction in ACD associated with a single logging event would be recovered to the ACD of unlogged forest (mean of 203 Mg ha^{-1}) (Fig. 1) and fig. S2) (95% CI: 157 to 247) through natural regeneration after ~60 years, but that this could be reduced to 40 years if restoration treatments are applied.

We validated the distribution of ACD spanned by our plots using a fine–spatial-resolution ACD map of the study landscape that was generated using an airborne LIDAR (light detection and ranging) survey in 2016 and calibrated with independent ground surveys (10, 21). Remote estimates showed a mean ACD of naturally regenerating forests in 2016 to be 135 Mg ha^{-1} (Fig. 2) (CI: 123 to 148), whereas that of forest that had been subjected to restoration treatments was 166Mg ha^{-1} (Fig. 2) (CI: 152 to 176), confirming a substantial difference in ACD in response to restoration (Fig. 2).We inferred remote estimates of ACD accumulation rates based on the 2016 LIDAR-derived carbon map and baseline ACD values derived from plot data (the intercepts in Fig. 1), which gave values of 3.5 and 4.8 Mg C ha^{-1} $year^{-1}$ without and with restoration treatments, respectively, consistent with the results from ground surveys alone. Together, these results suggest that our estimates of carbon recovery are robust and scalable across the whole study area.

To estimate the economic feasibility of applying restoration treatments, we modeled the carbon price required to offset the cost of restoration, assuming carbon credits are released every 5 years for a project life span of 30 years and adjusting for the time value of money through nominal discount rates of 1, 5, and 10% (Fig. 3 and fig. S3). Carbon prices on the voluntary market fluctuate widely, and our analyses suggest that only values close to the top of those seen in recent years (around \$10 per tCO_2 e) approach the minimum value required to offset the cost of restoration by tree planting and maintenance (13–15). Accounting for variation in ACD recovery rates suggests that implementing restoration uniformly across the logged forest landscape would require carbon prices 2- to 10-fold greater than those that currently exist in the voluntary carbon market (Fig. 3). Independent reports suggest that carbon prices in the range of \$40 to \$80 per tCO_2 e by 2020 are required to fulfill the obligations of signatories to the Paris Climate Agreement for maintaining a global temperature rise of less than 2°C (22), and a value in this range would be sufficient to offset the costs of tropical forest restoration in our model (Fig. 3).

We report the long-term gains in tropical forest ACD after restoration of logged forest using interventions such as enrichment planting, climber cutting, and liberation thinning. These methods contribute differentially to ACD recovery. Climber cutting is likely effective because lianas compete with trees and substantially reduce carbon accumulation in tropical secondary forests (23–25). Enrichment planting eliminates the constraints of dispersal limitation for large canopy trees and may have resulted in a more uniform distribution of trees than in areas regenerating naturally, thus filling canopy gaps more quickly and reducing light competition from other species (18). The tree species that were planted, mostly in the Dipterocarpaceae family, have a potential for rapid growth rates (26, 27) and include the tallest trees recorded in the tropics (28), yielding high biomass when mature. Our findings support previous claims that rates of ACD accumulation in formerly logged Southeast Asian tropical forests are among the highest in the tropics [e.g., (11)] and reinforce the value of logged forests with respect to carbon storage potential in addition to maintenance of biodiversity and other ecosystem functions and services (5–8, 10, 29). We also show that targeted restoration treatments, initiated an average of 9 years after logging, generate substantially higher rates of ACD over the following two decades, which has important implications for the conservation and management of logged forests.

The breakeven carbon price can be estimated for any combination of ACD accumulation rate attributable to restoration and restoration costs for a specific set of economic assumptions (Fig. 4). Restoration programs have a lower breakeven carbon price if they achieve a higher additional ACD accumulation rate (over and above natural regeneration) or if the costs are reduced (Fig. 4). To our knowledge, only two other studies have reported both the costs and additional carbon benefits of tropical forest restoration (30–32). In Uganda, for lands dominated by grasses that were degraded by agricultural encroachment, an additional ACD gain of 1.62 Mg ha^{-1} year^{-1} was achieved through protection from fire and tree planting at a cost of \$1200 ha^{-1}, and abandoned pastures in Costa Rica gained an additional ACD of 1.17 or 2.48 Mg ha^{-1} year^{-1} through tree planting at costs of \$297 or \$1100 ha^{-1}, respectively, depending on planting strategy. The mean cost of tropical forest restoration (except Australia) across more than 50 published examples was \$1596 ha^{-1} (95% CI: \$1338 to \$1854 ha^{-1}) (Fig. 4 and table S1). Most of these examples were derived from projects in tropical developing countries where restoration costs are less than \$5000 ha^{-1}, whereas restoration costs of Australian forests are in the range of \$6000 to \$15,000 ha^{-1} (table S1).

This review of previously published costs suggests that the range of carbon prices available on the voluntary market during 2017 and 2019 would be sufficient to incentivize investment in widespread active restoration in about half the settings where restoration costs have been reported, as long as the additional ACD gains from this investment are equivalent to those achieved by the three case studies in Fig. 4. Conversely, current carbon prices may be insufficient to support restoration in the logged forests of Southeast Asia despite the high rates of recovery reported in this study, unless financing to accept a low (1 to 3%) nominal discount rate is available (fig. S3). An additional constraint is that the infrastructure and labor force required to implement this large-scale restoration across the global tropics are lacking in many sites, particularly in Southeast Asia, where mast fruiting necessitates greater investment in seedling nurseries (33). Under these circumstances, an alternative approach is to implement generic low-cost measures such as climber cutting, combined with selective tree planting in accessible parts of the degraded forest landscapes where the density of mature trees is insufficient to ensure adequate natural regeneration. This strategy may be attractive to investors in the carbon market, even at current carbon prices, and would leverage recent investments in a new generation of space-borne sensors designed to deliver global high-resolution maps of forest biomass (34–36). Varying the type and intensity of restoration treatments according to the residual ACD of the stand has the potential to reduce the net costs of implementation, help bridge the gap to financial sustainability, and therefore enable much larger areas of forest to be restored.

Carbon stocks and future carbon sequestration are not the only valuable services provided by forest ecosystems (37), and climate change mitigation is not the single goal of restoration, particularly for local stakeholders. The multiple co-benefits of restoration, such as biodiversity conservation (8, 38), flood protection, provision of clean drinking water, and support for the livelihoods of local communities and stakeholders, provide additional justification for legislation and financing mechanisms that incentivize tropical forest restoration.

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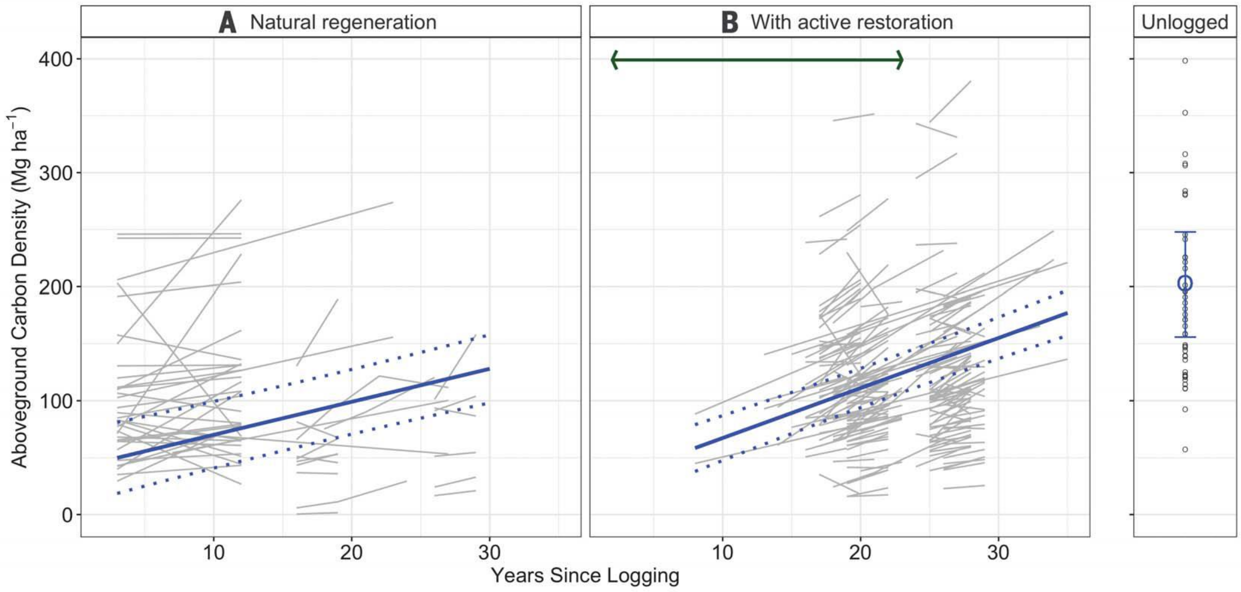

Fig. 1. ACD as a function of time since logging. (A and B) The recovery of ACD in (A) naturally regenerating logged forest and (B) forest with active restoration using climber cutting and enrichment planting. Blue solid lines represent the mean recovery rate, and blue dashed lines represent the 95% CI. Each gray line represents the recovery for an individual plot between measurement intervals. The plot on the far right displays the mean (±95% CI) ACD of unlogged forest and therefore highlights the potential for ACD recovery. The green arrow represents the time frame in which restoration activities took place.

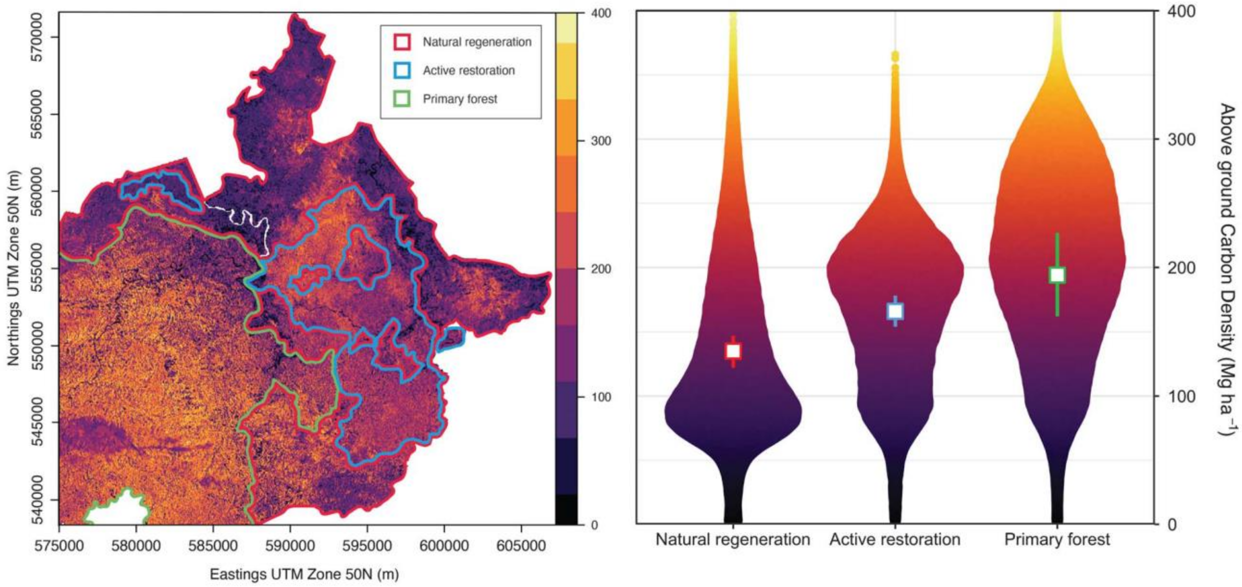

Fig. 2. ACD across the entire study area. **(Left)** ACD (Mg ha^{-1}) across the study landscape in 2016 derived from an airborne LIDAR-derived carbon map (30 m resolution). Naturally regenerating logged forest (225 km^2) is outlined in red, logged forest that underwent active restoration (124 km^2) is outlined in blue, and the primary forest (449 km^2) is outlined in green. The color bar indicates low (dark) to high (light) values of ACD. Universal Transverse Mercator **(Right)** Violin plots indicating the distribution of ACD (Mg ha^{-1}) from logged forest allowed to regenerate naturally (left, red outline), actively restored (middle, blue outline), and from primary unlogged forest (right, green outline). The data presented on the right correspond to the full study area shown on the left and are independent of those used in the analysis of forest regrowth (Fig. 1).

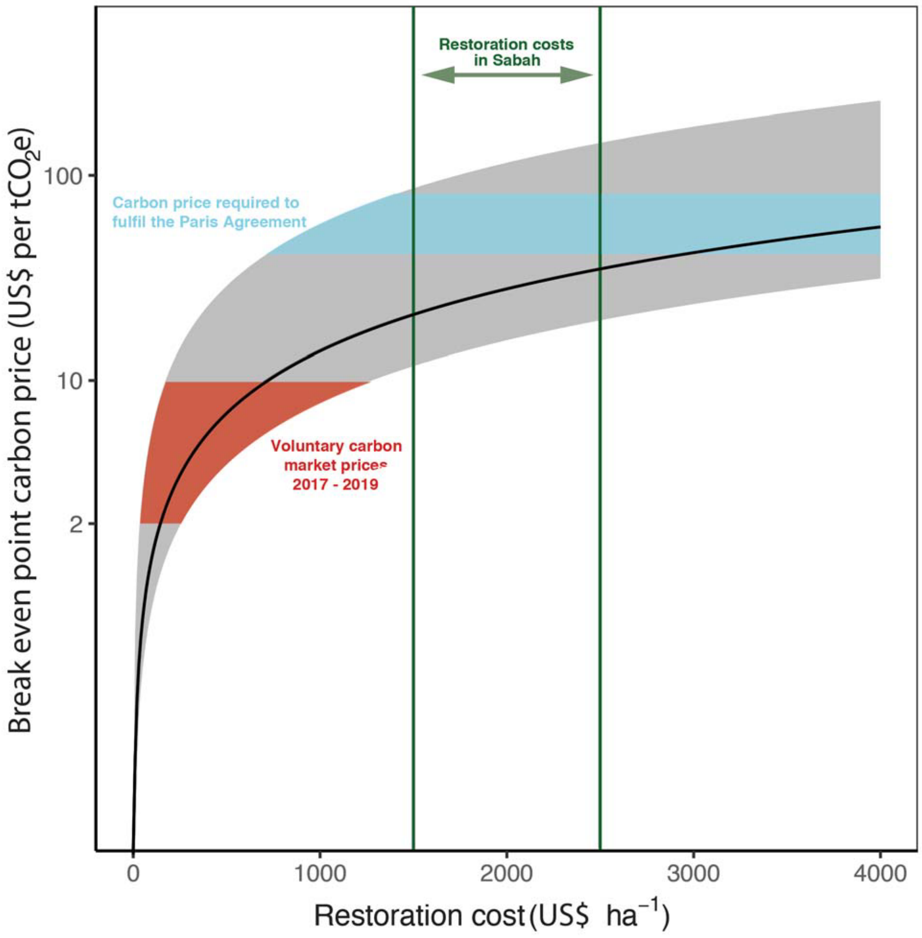

Fig. 3. Carbon price breakeven point as a function of restoration costs. Estimates of carbon price breakeven point for the increase of 1.5 Mg ha^{-1} year−1 (CI: 0.4 to 2.6) in ACD recovery attributed to restoration over a 30-year period with discounted revenues accrued at 5-year intervals, assuming a nominal 5% discount rate. The envelope shows a CI propagated from the ACD recovery model. The breakeven carbon price represents the threshold price required to offset restoration costs. Dark green lines highlight the typical range of enrichment planting costs in Malaysia at the present time. The red region within the confidence envelope highlights the current (2017 to 2019) range in the voluntary carbon market prices ($2 to $10 per tCO$_2$ e), and the blue region highlights the estimated range in carbon price required to fulfill the Paris Agreement and limit global temperature increases to less than 2°C ($40 to $80 per tCO$_2$ e).

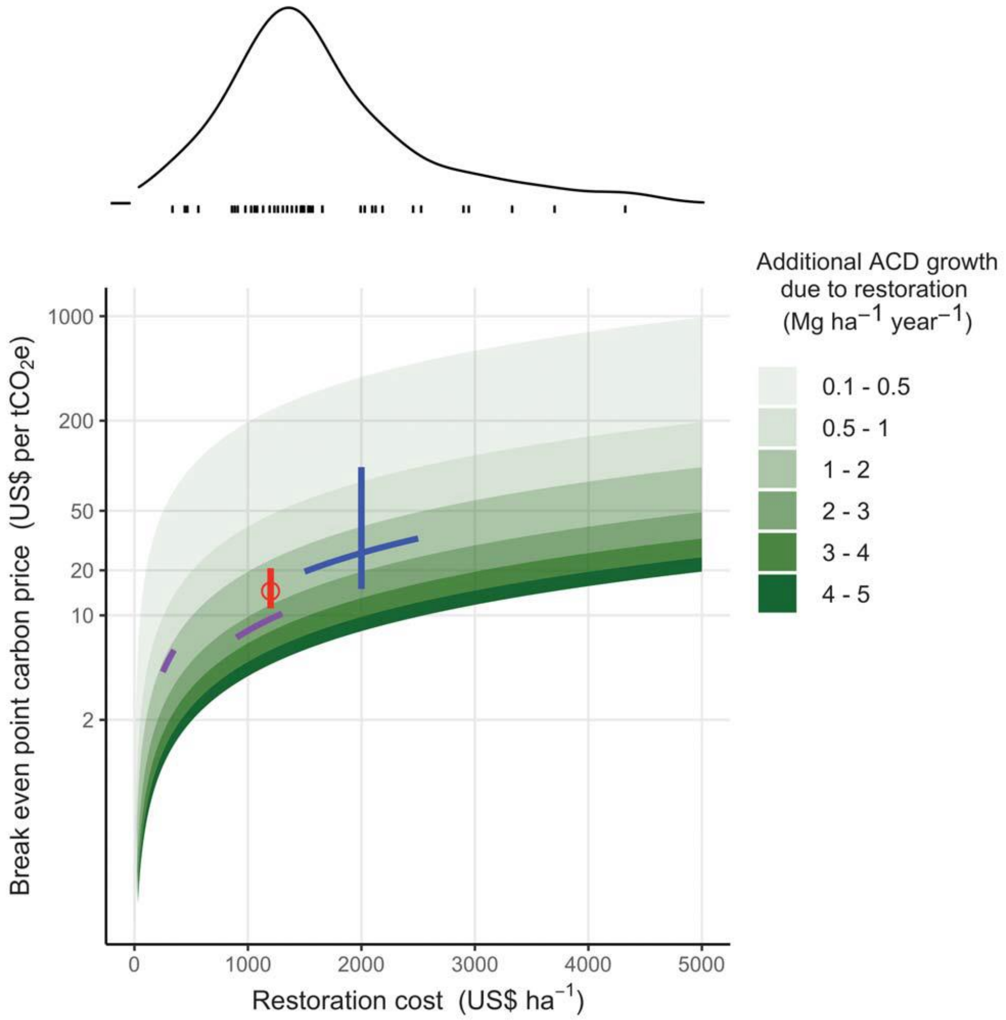

Fig. 4. Carbon price breakeven point estimated for multiple scenarios. (Bottom) Estimates of carbon price breakeven point are calculated over a 30-year period with revenues accrued every 5 years, with a 5% nominal discount rate. Shading represents bins in which the additional ACD accumulation attributable to restoration is 0.1 to 0.5 (lightest green), 0.5 to 1.0, 1.0 to 2.0, 2.0 to 3.0, 3.0 to 4.0, and 4.0 to 5.0 Mg ha^{-1} year^{-1} (dark green). Data from two case studies are superimposed relating to fire protection and native seedling planting in Uganda (red circle) (30), two approaches to restoration of planting tree islands (at a lower cost) and larger-scale restoration in Costa Rica (purple lines) (32), and this study (blue line). The vertical red and blue lines represent 95% CIs for predicted breakeven carbon price based on variation in ACD

accumulation rates in response to restoration. (Top) Density plot of published restoration costs based on values indicated by the tick marks on the horizontal axis (see table S1 for data and details).

List of Supplementary Materials:

Materials and Methods
Figs. S1 to S3
Table S1
References (*39*-*72*)

Supplementary Materials for

Active Restoration accelerates the carbon recovery of human-modified tropical forests

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This PDF file includes:

Materials and Methods
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References (*39*-*72*)

Materials and Methods

Study Area

The study area comprised a matrix of logged and unlogged tropical lowland dipterocarp forest in the Ulu Segama Forest Reserve (USFR) and Danum Valley Conservation Area (DVCA) in southern Sabah, Malaysia (Fig. 3) (*41*). At the Danum Valley Field Centre, which is embedded within the study area, mean annual temperature is 26.7° and annual average rainfall is 2638 mm (*42*, *43*). Northern Borneo experiences limited seasonal climatic variation, although droughts do occur infrequently, usually in association with El Niño-Southern Oscillation (ENSO) events (*42*, *44*). The geology of the area is complex, but mostly comprises rocks of the Kuamut Formation, which includes young sedimentary and volcanic rocks with interbedded sandstone and mudstone (*45-47*). The resulting soils in the area are dominated by ultisols and are easily eroded (*46*, *48*). The study area has an undulating hilly topography lying between 75 and 901 m above mean sea level. The primary vegetation of the study area is representative of the lowland mixed dipterocarp forests that formerly covered much of Borneo and continental Southeast Asia (*49-51*). It is characterised by a high density of species in the family Dipterocarpaceae, which dominates the above-ground biomass and provides a valuable source of timber (*41*). The DVCA contains 438 km^2 of primary unlogged forest that is here assumed to represent the forests of the neighbouring USFR prior to logging in terms of structure, species composition, biomass and above-ground carbon density. The USFR comprises 1268 km^2 of forested land divided into coupes that were each logged once, between 1972 and 1993, using techniques described in (*41*). Between 1999 and 2010 the majority of the surrounding USFR was then logged again except for the area of forest that includes our study plots (the INFRAPRO Forest Rehabilitation Project area, and the coupes that were logged in 1992 and 1993). Across the whole of the USFR the amount of timber extracted from each logging coupe varied but averaged 117 m^3 ha^{-1} during the first logging phase, and residual unlogged forest still survives in patches such as steep slopes and riparian zones (*41*, *44*, *52*).

Between 1993 and 2004, forest restoration treatments in the form of climber cutting and tree planting were implemented on patches of 83 to 1745 ha annually across the logging coupes within the USFR (Fig. S1). The restoration took place an average of nine years after logging when project funding for restoration was available. In principle, starting restoration treatments as early as possible after logging would be desirable in order to maximize site capture by young planted trees before lianas and pioneer trees become dominant. The greater accessibility of remote areas due to the residual infrastructure from logging operations (roads, bridges and field camps) would also enhance the financial feasibility of restoration interventions. At each location chosen for restoration, the following sequence of treatments was implemented: (1) six months prior to planting all climbers and lianas were cut across the entire area, (2) prior to planting, all vegetation was cleared to ground level within 2 m wide parallel lines cut through the logged forest with a spacing of 10 m between lines, (3) seedlings of native tree species (approximately 50 cm height, with 10 leaves) were planted, where possible, every 3 m within the cleared lines, (4) open conditions were maintained within the lines by manual clearance up to four times per year for the three years after planting. The majority of the seedlings planted were Dipterocarpaceae (52 dipterocarp species and five other canopy species), although an additional 16 species of native fruit trees were also included to enhance biodiversity. In very open sites pioneer trees (of three species) and fruit trees were planted. The seedlings had been grown for 4-8 months from seeds collected locally and retained in nurseries where they were maintained under shade in pots of forest soil. Rock phosphate fertiliser was applied in each planting hole (100 g per plant). Up to 2016, 35% of the logged forest within our study area (Fig. 3) had been subjected to these restoration treatments, which included 196 of the 251 plots (Fig. S1) that had been installed to monitor forest recovery from the logging that took place in the period 1981 to 1993 (see below). The remaining 65% of the logged forest within our study area did not receive restoration treatments and was sampled by the other 55 plots.

The entire study area is surrounded by forest. In the north and east this is represented by logged forest in the Ulu Segama Malua Forest Reserve, and in the west and southwest the study area borders a reduced impact logging experiment and primary forest in the Danum Valley Conservation Area (DVCA). The mean distance to the closest boundary with the primary forest in the DVCA was 5.41 km (CI: 5.40 – 5.43) for plots in naturally regenerating forest and 4.0 km (CI: 3.99 – 4.01) for plots in the actively restored forest. This difference is not sufficient to confound the contrast in ACD recovery rate (e.g. due to proximity to seed sources) because dipterocarp fruits are dispersal limited and have maximum dispersal distances of a few tens of meters (Smith *et al.* 2015). The study area is permanently protected as 'Class I Forest Reserve' and this status prohibits any timber harvesting or conversion to agriculture, and following Verified Carbon Standard guidelines (*53*) this would be the case for new forest based carbon offset projects in Malaysia. Full details of the forest restoration treatments can be found in the Verified Carbon Standard (VCS) documents by Face the Future (*54*).

Forest inventory datasets and tree measurements

To determine the recovery of aboveground carbon density from logging, tree census data were obtained from a total of 257 plots representing 51803 individual tree measurements on 45.56 ha of forest (Fig S1). The data-set was compiled from three independent plot networks as follows:

1. In 1996/7 the Developing Ground and Remotely Sensed Indicators of the Sustainability of Tropical Forest Exploitation Systems (INDFORSUS) project established 0.1 ha plots in areas logged between 1981 and 1993 and unlogged primary forest (*55-57*). In 2016, 20 of these plots were relocated and re-censused including six plots in primary forest. The plots have a radius of 17.84 m and include all free-standing woody plants above 20 cm at 1.3 m height above-ground (DBH) measured for DBH, height and identity to the lowest possible taxonomic rank. Trees ≥10 cm DBH and woody plants that reach 1.3 m height were also measured (as above) in nested concentric circles with radii of 12.61 m and 2 m respectively.

2. Thirty-two square 0.08 ha plots were established in 1992, prior to logging, in forest that was logged the following year using conventional logging techniques (*58*). These plots were re-censused in 1996 and 2005, i.e. up to 12 years after logging took place (*59*). Measurements of DBH and identity to the lowest possible taxonomic rank were recorded on all free-standing woody plants ≥ 20 cm DBH across the entire plot, and on trees 10-19 cm DBH, 5-9 cm DBH and 1-5 cm DBH on nested plots of 400 m^2, 100 m^2 and 25 m^2, respectively (*58*). The project is described further by Pinard & Putz (*58*) and Lincoln (*59*).

3. Two hundred and five 0.2 ha plots were established in 2007 (15 years after the start of restoration) across the entire area of logged forest that is managed by the INnoprise FAce PROject INFAPRO project. These plots were re-censused in 2010, and seven were re-censused in 2015. In this case a plot is defined as the pooled sample of trees on four circles of 0.05 ha (radius 12.62 m) located at the points of a cross with their centers separated by 28 m. The DBH and identity to the lowest possible taxonomic rank of all free-standing woody plants ≥ 20 cm DBH was measured in all four circles, while trees 10-20 cm DBH were measured in one circle. Trees 5-10 cm DBH and >0.2 m height and <5 cm DBH were measured in circular plots of 5 m

and 2 m radius, respectively, nested within the circles used to record trees 10-20 cm DBH. A full description of the project can be found in the Verified Carbon Standard (VCS) documents by Face the Future (*54*).

Estimating tree carbon content

The carbon content of trees on all plots was calculated assuming that carbon represented 47% of above-ground biomass (AGB) (*60*). AGB was estimated from allometric equations based on diameter at 1.3m height (DBH), tree height and wood density following (*61*):

$$AGB_{est} = 0.0673 \cdot (\rho DBH^2 H)^{0.976} \tag{1}$$

where DBH is in cm, H is in m, and ρ is in g cm^{-3}. Diameter was measured at 1.3 m height for all trees except when the point of measurement for diameter (DBH_{POM}) had to be raised to avoid buttress roots, in which case a taper model (*62*) was applied to estimate an equivalent stem diameter at 1.3 m aboveground (*DBH*):

$$DBH_{1.3m} = \frac{DBH_{POM}}{\exp\left(-0.029 \cdot (POM - 1.3)\right)} \tag{2}$$

where DBH_{POM} is the stem diameter measurement taken at *POM* (in m aboveground). Tree height was either measured directly (5214 trees) or estimated (50646 tree measurements) using a data-set of diameter and height measurements of 14307 trees located either inside or within 50 km of our study area (CDP, unpublished data) fitted to a three-parameter equation following the Weibull functional form:

$$H = 89.53 \cdot (1 - \exp(-0.0225\, DBH^{0.7383})) \tag{3}$$

Trees within this data-set represented a wide diversity of species and families, and the full range of sizes observed on the census plots (1-200 cm DBH). The three-parameter Weibull model was selected from the 12 models tested by Ledo *et al.* (*63*) because because it displayed the lowest root mean square error (RMSE) and bias for large trees, supporting previous work (*63*). Wood density was obtained from the global wood density database (*64*, *65*). Stems identified to species were assigned the species average, otherwise, the average value on the database for the nearest taxonomic unit was assigned. For the 20% of cases where no botanical information was available for the stem, the average wood density for the plot was assigned. The carbon contents of individual trees were then summed across all trees to estimate above-ground carbon density (ACD in Mg ha^{-1}) per plot. The ACD values of small trees on nested plots were scaled and added to the main plot totals.

Carbon recovery analysis

For each plot, we compiled information on (1) years since logging, (2) logging method (tractor or high-lead) for each setup around the plot (a setup is an area logged by a small team of contractors with a mean size of 31 ha), and (3) whether the area was restored or not. Logging data (1 and 2) were compiled by Moura Costa & Karolus (*52*) from the original records of the logging contractors Pacific Hardwoods (Silam Forest Products) and Kennedy Bay Forest Products (see Fig. S1). For plots in the logged forest, we fit data on ACD to general linear mixed-effects models (LMMs) with fixed effects of years since logging, and a categorical term reflecting the presence or absence of restoration treatments, as well the interactions between these two main effects. It was only possible to test for a linear effect of time since logging as each plot was only measured twice or three times post logging. The intercepts were allowed to vary between inventory plots and the logging method (tractor or high-lead logging) within each coupe as normally distributed random effects (random intercept model). To estimate the mean ACD of the unlogged forest we fitted data on ACD from unlogged plots to a LMM with only an intercept and a random effect for each census.

Independent estimation of above-ground carbon density from airborne LiDAR

Above-ground carbon density was extracted for the study area at a spatial resolution of 30 m from Asner et al. (*10*), which presents a 2016 ACD map for the entire state of Sabah generated using a combination of airborne LiDAR, Landsat 8 apparent surface reflectance, topographic data from NASA's Shuttle Radar Topography Mission, and VH and VV SAR response from Sentinel-1 (for further details see Asner et al. (*10*)). None of the forest plots used to calibrate ACD from LiDAR-derived forest structural metrics were included in the analyses of ACD recovery reported in this paper. Details of the data collection and processing methods used to derive the carbon map are given by Jucker *et al.* (*21*) and Asner *et al*. (*10*). We fit values of ACD from the carbon map to a LMM, with a categorical term reflecting the land use (either primary forest, natural regeneration, or active restoration). The average time since logging was 29.67 years [95% CI: 29.65 – 29.68] for naturally regenerating areas, and 26.79 years [26.78 – 26.81] for actively restored areas (since the map covers areas that have been logged between 24 and 36 years previously). The intercepts were allowed to vary between each logging coupe as normally distributed random effects.

All analyses were carried out using R v. 3.3.3 (*66*). The LMMs were fitted using the lmer() function in version 1.1-13 of the lme4 package (*67*). The LMMs assume homogeneous variance and a normal error distribution, which was confirmed by plotting residuals against the fitted values and using Q-Q plots respectively. The 95% confidence intervals (CIs) of the parameter estimates were computed using a parametric bootstrap with 1000 iterations, implemented using the function bootMer() from the lme4 package.

Calculation of break-even carbon price

To estimate the economic feasibility of implementing tropical forest restoration treatments at other sites around the globe we calculated the price of carbon that would be required to exactly offset restoration costs ("break-even carbon price, C_P") where revenues from selling carbon credits are calculated as the lifetime Net Present Value, assuming a nominal discount rate, r, and that the restoration costs are assumed to be incurred as a single investment at the start of the project. We assume C_P is a static value used in future years without forward inflation, meaning the carbon price in 2025 will be C_P in 2025 dollars and the carbon price in 2030 will be C_P in 2030 dollars. Thus, discounted revenues accrue at five yearly intervals as the carbon credits are accounted. Under these assumptions the break-even carbon price C_P is calculated as:

$$Cp = \frac{R}{\sum_{1}^{n} CC\,(1+r)^{-n}} \tag{4}$$

where R (in US\$ ha^{-1}) is the restoration cost incurred at the initial investment and the denominator represents the total discounted carbon credit (CC) revenue from credits released at five year intervals, computed as follows:

$$\sum_{1}^{n} CC\ (1+r)^{-n} = \frac{3.67ACD_5}{(1+r)^5} + \frac{3.67ACD_{10}}{(1+r)^{10}} + \cdots + \frac{3.67ACD_{30}}{(1+r)^{30}} \tag{5}$$

where ACD_n (in Mg ha^{-1}) is the measured additional ACD accumulated in response to restoration treatments during the five year interval up to year n (7.5 Mg ha^{-1}, bounded by a 95% confidence interval of 2.0 – 13.0 Mg ha^{-1}). The constant 3.67 is required to convert ACD in Mg ha^{-1} to per tCO$_2$ e. Breakeven carbon prices were calculated for assumed restoration costs across the range 0 to 4000 US$ ha^{-1}.

The carbon price on the voluntary market is highly variable, depending on project location and type, and 2016 prices varied in the range US$0.60 to US$11 per tCO$_2$ e (*13*). The average price across all transactions was US$3.0 per tCO$_2$ e (*13*) and we therefore highlight the range US$2 - US$10 per tCO$_2$ e in Fig. 3. The costs of restoration treatments vary depending on the intensity of the intervention required. Planting tree seedlings into logged forests in Southeast Asia requires heavy investment in the infrastructure to collect and propagate seeds and tend seedlings in nurseries, maintain access to planting sites, and labour costs for initial clearance and subsequent maintenance of planting sites(*68*). The current cost of these operations, including climber cutting, vary in the range 1500 to 2500 US$ ha^{-1} in Sabah depending on whether the cutting is conducted once, twice or three times. We therefore calculate the breakeven carbon price (US$ per tCO$_2$ e) for a range of possible restoration costs that encompass these values.

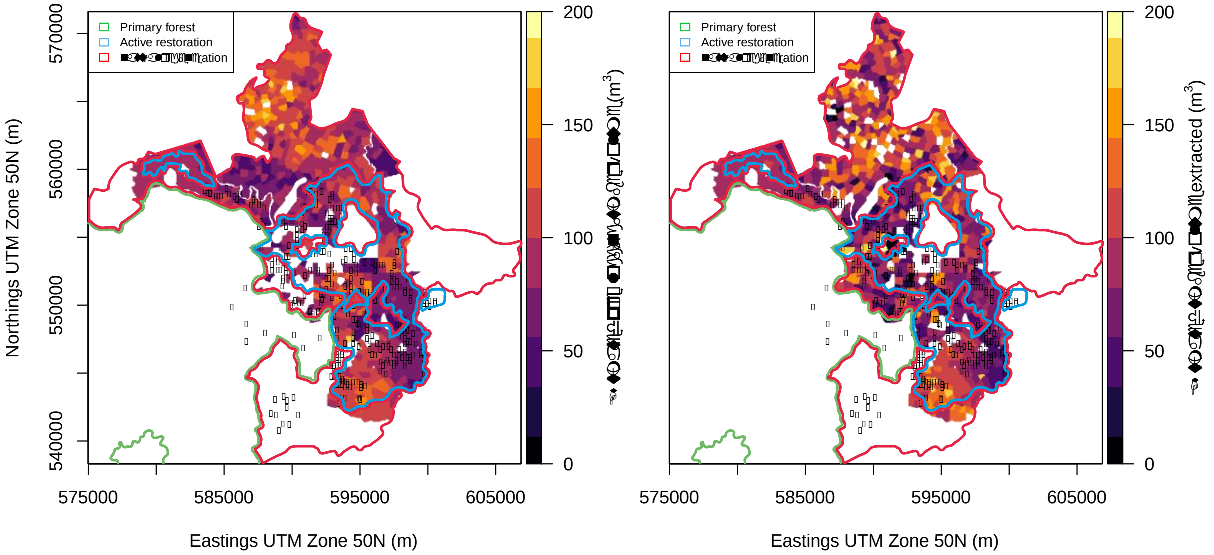

Fig. S1. Estimated pre-logging timber volume in m^3 (left panel) and estimated timber volume extracted in m^3 (right panel). Left panel, timber volume estimated prior to logging for each setup in m^3. Right panel, estimated timber volume extracted in m^3. Where spatially-explicit data were not available, the average value for the logging-coupe was used. Black points indicate inventory plots.

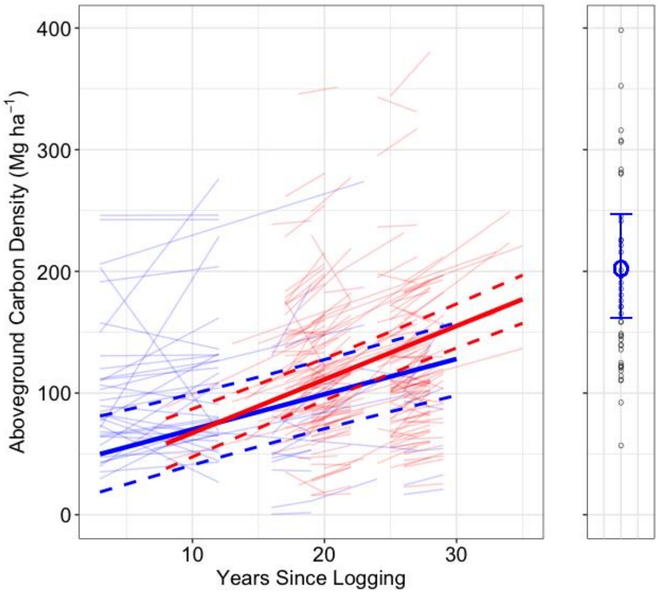

Fig. S2. Aboveground Carbon Density as a function of time since logging. The recovery of ACD in naturally regenerating logged forest (in blue) and, forest with active restoration (in red) using climber-cutting and enrichment planting. Bold solid lines represent the mean recovery rate and dashed lines the 95 % CI. Each transparent line represents the recovery for an individual plot between measurement intervals. The panel on the far right displays the mean (±95 % CI) ACD of unlogged forest and therefore highlights the potential for ACD recovery.

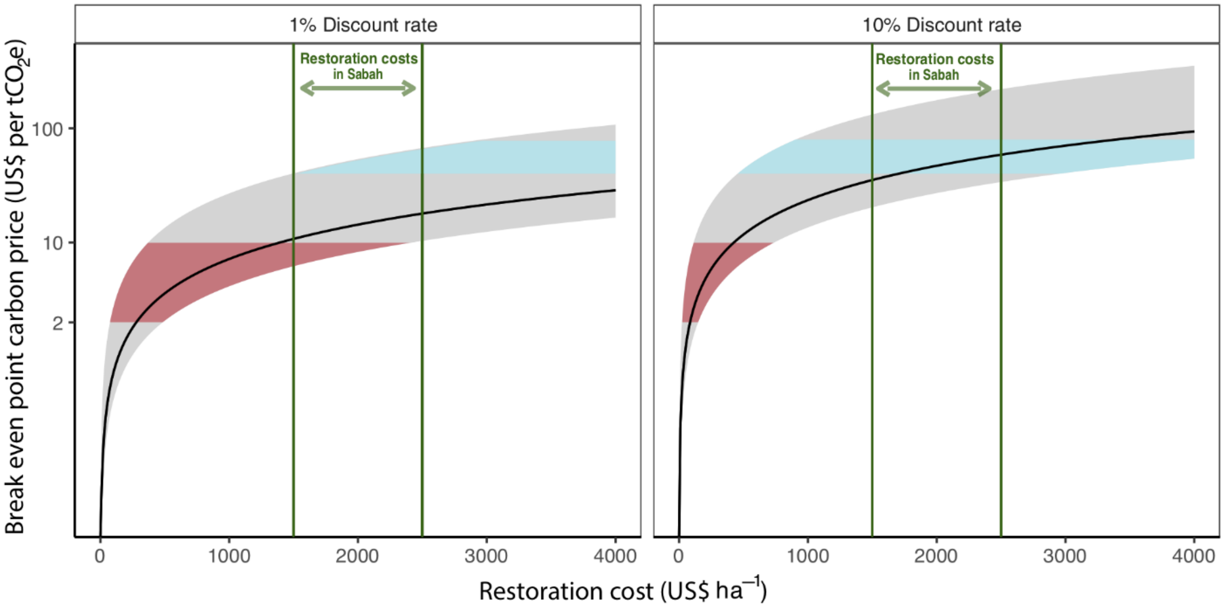

Fig. S3. Carbon price break-even point as a function of restoration costs for Ulu Segama Forest Reserve, Sabah, Malaysia

Estimates of break-even carbon price assuming 1% (left) and 10% (right) nominal discount rates for the increase of 1.5 Mg ha^{-1} yr^{-1} (CI:0.4 – 2.6) in ACD recovery attributed to restoration over a 30-year period with discounted revenues accrued at every five years. The envelope represents the possible range assuming the confidence intervals from the ACD recovery model. The break-even carbon price represents the threshold price required to offset restoration costs. Dark green lines highlight the typical range of enrichment planting costs in Malaysia at the present time. The red region within the confidence envelope highlights the current (2017-2019) range in the voluntary carbon market prices (US$2 – US$10 per tCO_2 e), whereas the blue region highlights the estimated range in carbon price required to fulfil the Paris Agreement and limit global temperature increases to less than 2°C by 2020 (US$40 – US$80 per tCO_2 e).

Table S1. Details of data from published restoration costs. Data from a variety of forest types and locations. Restoration costs are in US$. These values were used for the density plot of restoration costs reported in the upper panel of Fig. 4 (*30-32*, *38*, *69-74*).

(*30-32*, *38*, *69-74*)

Region	Country	Location	Forest type	Restoration Cost [Range in costs]	Restoration activity / aim	ACD growth post-restoration (if reported)	Reference
S. America	Brazil	Tombetas mine, Saracá-Taquera, Pará State	tropical rainforest	$2500	restoration of Tropical Forests on Bauxite-Mined Lands	–	Parrotta & Knowles (1999)
S. America	Argentina	Nahuel Huapi, Rio Negro, Neuquen	dry forest	$9695	establishing native forest as alternative to livstock grazing	–	Birch *et al.* (2010)
S. America	Chile	Quilpue, Valparaiíso region	dry forest	$2067		–	
C. America	Mexico	Central Veracruz, Veracruz	dry forest	$2158		–	
C. America	Mexico	El Tablon, Chiapas	dry forest	$994		–	
C. America	Costa Rica	Agua Buena & Las Cruces, Coto Brus County	premontane rainforest	$1100 [$900 – $1300]	full area planting	2.48 Mg ha $^{-1}$ yr $^{-1}$	Holl *et al.* (2011);
				$297 [$243 – $351]	planting tree islands	1.17 Mg ha $^{-1}$ yr $^{-1}$	Holl & Zahawi (2014)
Australia	Australia	Queensland, multiple sites	tropical rainforest	$6370	enhancing existing forest	–	Catterall & Harrison (2006)
				$17920	reinstating rainforest	–	
Africa	Uganda	Kibale National Park, SW Uganda	moist evergreen forest	$1200	protection from fire & native seedling planting	1.62 Mg ha $^{-1}$ yr $^{-1}$ (CI:1.14-2.11)	Wheeler *et al.* (2016)
SE Asia	Indonesia	E. Kalimantan, Borneo	dipterocarp rainforest	$943 – $1395	enrichment planting (higher costs for more degraded areas)	–	Budiharta *et al.* (2014)
			montane rainforest	$1024 – $1450		–	
			heath rainforest	$1231 – $1964		–	
			peat swamp rainforest	$1047 – $1518		–	
			freshwater swamp rainforest	$1025 – $1463		–	
SE Asia	Indonesia	Sari Bumi Kusuma, C. Kalimantan	dipterocarp rainforest	$429	enrichment planting	–	Ruslandi *et al.* (2017)
SE Asia	Malaysia	INnoprise FAce PROject, Danum Valley, Sabah	dipterocarp rainforest	$2000 [$1500 – $2500]	enrichment planting & climber cutting in logged forest	1.5 Mg ha $^{-1}$ yr $^{-1}$ (CI:0.4 – 2.6)	This study
SE Asia	Indonesia	Indonesia, *circa* 17 sites	multiple forest types: government	$3682 [$43 – $7320]	various, mostly replanting of degraded forest	–	Nawir *et al.* (2003)
		Indonesia, *circa* 7 sites	donors	$7794 [$366 – 15221]		–	
		Indonesia, *circa* 10 sites	private	$4308 [$115 – $8500]		–	