Actively restoring resilience in selectively logged tropical forests

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Abstract

1. Huge tracts of tropical forest are selectively logged. Meanwhile, emerging global agendas are providing unprecedented incentives for large-scale restoration within human-impacted tropical forest landscapes. Whilst logged forests have high conservation value, their adoption within these agendas remains controversial.

2. We review the value of restoring logged tropical forests for boosting economic and environmental resilience. Targeted interventions can recover depleted timber stocks, increase saleable carbon stores, and deliver employment and non-timber forest products (NTFPs) to local communities. Restoration has mixed outcomes for biodiversity but if it improves relogging practices and protects forests from conversion to agricultural plantations may have major positive impacts.

3. We also examine socio-economic and political pathways for upscaling logged forest restoration and their incorporation into sustainable forestry, given political and commercial malaise on post-logging interventions. Spurring these transitions will require strong institutions, executed by policies that enable long-term concession licences and community land tenure, that leverage commercial involvement and payments for ecosystem services, and that optimise existing interventions.

4. Research frontiers include: (a) validating the economic and technical feasibility of different interventions; (b) understanding how these interventions impact on synergies and trade-offs between ecosystem services, NTFPs, and biodiversity; and (c) identifying when to restore a logged forest. This requires establishing long-term experimental trials that jointly track environmental and socioeconomic outcomes.

5. Synthesis and applications. Post-logging interventions can deliver various timber, carbon, socioeconomic and potentially biodiversity benefits but are underemployed and undervalued pantropically. Opportunities exist to optimise interventions by tailoring incentives, policies, and management to ecological and social circumstances. Governments, conservation bodies and the private sector must underscore restoration of production forests as a major future objective, including via greater adoption in global initiatives, including forest and landscape restoration under the Bonn Challenge and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) agenda.
1 | INTRODUCTION

Human activities have overtaken natural forces, like hurricanes and wildfires, as dominant drivers of tropical forest disturbance (Lewis, Edwards, & Galbraith, 2015). Selective logging is the most prevalent of these disturbances. Over a fifth of tropical forests were selectively logged between 2000 and 2005 (Asner, Rudel, Aide, Defries, & Emerson, 2009) and an area approximately twice the size of Greenland (400 million hectares) is currently designated as production forest globally (Blaser, Sarre, Poore, & Johnson, 2011).

Logging is environmentally harmful, driving declines in interior forest wildlife and carbon stocks, and bisecting forests with road networks that facilitate incursion by poachers and illegal loggers (Edwards, Tobias, Sheil, Meijaard, & Laurance, 2014). Yet regenerating logged forests retain high conservation value, preserving most biodiversity and ecological processes, and continuing to store and sequester carbon, regulate climate and maintain large-scale hydrological processes (Edwards, Tobias, et al., 2014), particularly in comparison with the agricultural lands often replacing them (Gaveau et al., 2016).

A global restoration agenda is emerging as a key way of enhancing the recovery of ecosystem services and biodiversity in human-impacted tropical forest landscapes (Brancalion et al., 2017). International initiatives, like the Bonn Challenge and New York Declaration, have garnered astonishing political traction with over 40 countries and institutions committed to recovering 150 million hectares of degraded ecosystems by 2020 and 350 million hectares by 2030 (Bonn Challenge, 2018). Bolstered by a suite of additional programs and the potential emergence of billion-dollar carbon markets, there is now unprecedented impetus for large-scale restoration of human-impacted tropical forests (Aronson & Alexander, 2013).

Here, we explore the role of post-logging interventions in recovering timber stocks and biodiversity, providing climate change mitigation, non-timber forest products (NTFPs) and social benefits. We find theory suggesting that these added values can hinder the conversion of logged forest. Unfortunately, the benefits of post-logging interventions are often underappreciated and are rarely employed at scale. We thus explore ways for operationalising and incorporating restoration activities within logged-over forest and identify crucial avenues for future inquiry.

2 | INTERVENTION GOALS WITHIN SELECTIVELY LOGGED FORESTS

Different reasons for logged forest interventions exist, warranting different activities (Table 1). Importantly, the type of intervention employed will track closely the form of management that logged forests falls under (Table 1). Thus, “ecosystem restoration” will be most suitable in exhausted timber concessions or within protected area frameworks, “timber enhancement” best within actively managed permanent timber estate, and “ecosystem service enhancement”

### TABLE 1 A summary of the diverse objectives that might drive post-logging interventions

<table>
<thead>
<tr>
<th>Intervention type</th>
<th>Main objective</th>
<th>Potential activities</th>
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<tbody>
<tr>
<td>Ecosystem restoration</td>
<td>Recover the structural complexity, biodiversity, and ecosystem functions and services present in old-growth forest</td>
<td>Protect forests from further logging and allow natural regeneration&lt;br&gt;Restore logging-damaged habitat features like streams and rare microhabitats&lt;br&gt;Assist natural succession by liberating seedlings from outcompeting pioneers or lianas&lt;br&gt;Plant a wide range of species, including those of wildlife importance (e.g. fruit trees, habitat-providing and rare species) or resilient to shifts under projected climate regimes</td>
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<tr>
<td>Timber enhancement</td>
<td>Recover timber stocks between logging rotations to ensure a sustainable yield of merchantable timber</td>
<td>Liberating understory timber seedlings from competing pioneer trees or lianas&lt;br&gt;Plant and tend a small number of merchantable timber species, including those valuable species found at low-density</td>
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<tr>
<td>Carbon enhancement</td>
<td>Recover carbon stocks</td>
<td>Liberating trees with the highest carbon sequestration potential.</td>
</tr>
<tr>
<td>Ecosystem service</td>
<td>Maintain or recover a range of ecosystem services important for communities and enhance the flow of forest products of livelihood importance</td>
<td>Enrichment planting&lt;br&gt;Planting or tending of species providing timber and non-timber forest products. Restoration to mitigate for poor logging practices: e.g. planting on over-logged steep slopes to improve hydrological processes</td>
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KEYWORDS
biodiversity, climber cutting, enrichment planting, logged tropical forest, REDD+, restoration, selective logging, silviculture
optimal wherever production forests are managed or depended upon by rural communities. Additionally, "carbon enhancement" is appropriate wherever interventions increase emissions-capture versus business-as-usual management, meaning activities could target forests either historically or actively managed for timber.

Another goal of post-logging interventions may be averting conversion to other land-uses. Across 40 years in Malaysian Borneo, 57%–60% of old-growth and selectively logged forest loss was linked with conversion to industrial oil-palm and pulpwood plantation (Gaveau et al., 2016), whilst ~33 million hectares of Indonesian production forest was recently omitted from a major Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiative with Norway, rendering them vulnerable to conversion (Sloan, Edwards, & Laurance, 2012). If interventions occur within well-managed forests, this may lower risk of conversion. Between 2000 and 2010, permanent timber concessions in Indonesia that avoided government reclassification to plantations suffered indistinguishable deforestation rates from protected areas (Gaveau et al., 2013). According to the objective, economic or environmental benefits of post-logging interventions can accrue to a variety of factors, including logging companies and governments (via timber enhancement) or global communities (via carbon enhancement, limiting global warming to 2°C increase).

3 | IMPACTS OF POST-LOGGING INTERVENTIONS

3.1 | Timber recovery

Repeated logging cuts the economic value of standing forest by depleting timber reserves. On average, 54% of timber volume extracted during the first cutting cycle is available at the second, with this varying enormously according to logging intensity, technique and commercial species ecology (Putz et al., 2012). Reduced-impact logging (RIL) reduces collateral tree damage during timber extraction, whereas increasing the recovery period between logging events and reducing overall timber extraction can further sustain yields (Sist, Picard, & Gourlet-Fleury, 2003). These activities, however, are often insufficient to maintain timber yields under economically attractive cutting cycles, so tropical foresters have long examined methods of speeding merchantable timber species recovery through post-logging interventions. Theoretically, post-logging interventions that boost the financial value of logged forests can reduce the economic imperative for conversion to alternative land-uses. Potential interventions depend mainly on forest condition. Where the understory contains existing stocks of commercial seedlings then vines or over-topping non-commercial trees, which compete for with them light, can be cut or poisoned (Sasaki et al., 2011). This accelerates average tree growth by 9%-27%, more than doubling the natural growth of commercial species (Peña-Claros et al., 2008). However, excessive thinning creates light conditions that may favour proliferation of low-valued pioneer species, such that an optimal thinning intensity exists (Swinfield, Afrianda, Antoni, & Harrison, 2016).

Where logged forests lack sufficient commercial seedlings, enrichment planting may be warranted (Sasaki et al., 2011). One option is planting seedlings within logging gaps; commercial-scale planting of the native fast-growing tree Schizolobium parahyba in the Amazon is an innovative example. Within 13 years, this species can be grown and processed into plywood, generating revenue whilst slow-growing timber species replenish (Schwartz, Pereira, Siviero, & Yared, 2017). Another option is planting species along cleared lines. Legislation in Indonesia calling for silvicultural intensification within ~65 million hectares of natural forest could see this method widely applied, generating high timber yields (Ruslandi, Cropper, & Putz, 2017). Line planting of dipterocarps within twice-logged forest recovers merchantable timber stocks equivalent to primary forest within 40 years; comparable naturally regenerating forests recover below half of this volume after 60 years (Figure 1a). Moreover, within twice-logged forest, timber enhancement is projected to yield a net present value three times greater than natural regeneration alone (at <6% annual discount rate, Ruslandi, Romero, & Putz, 2017).

3.2 | Climate change mitigation

Annually, around 1 billion tons of CO₂ is released from tropical timber harvesting (Pearson, Brown, Murray, & Sidman, 2017). Yet despite the large carbon footprint of timber extraction, ceasing logging operations is not necessarily optimal for reducing greenhouse emissions, as market forces could drive the substitution of low-energy building wood with high-energy construction alternatives, like steel (Oliver, Nassar, Lippke, & McCarter, 2013). Instead, strategic interventions can enhance carbon profiles in production forest.

Lianas reduce large tree carbon stocks by up to 50% (Durán & Ernasto, 2013). Correspondingly, since large trees disproportionately store carbon in tropical forests, their increased growth following liana and pioneer removal directly increases carbon sequestration (Villegas et al., 2009). Over 24 years in the Central African Republic, post-logging thinning of pioneer species fostered a near-doubling of aboveground biomass compared to naturally regenerating logged forests (Figure 1b). Such activities can provide cost-effective carbon sequestration, since the expenses of raising and planting seedlings are avoided. In Bolivia, girdling competing trees costs as little as $5.08 per hectare (Sasaki et al., 2011). Enrichment planting also increases carbon sequestration albeit at greater expense. After 60 years in Indonesia, neither once- nor twice-logged forests recover primary forest levels of above-ground biomass, yet with enrichment planting and liana cutting, complete carbon recovery occurs within 35–40 years (Ruslandi, Cropper, et al., 2017).

By reducing collateral tree damage during timber extraction, RIL can fast-track above-ground biomass recovery (West, Vidal, & Putz, 2014), although typically lower harvesting intensities under RIL are rarely controlled for. Indeed, when 50% of biomass is extracted under RIL in the Amazon, natural carbon recovery can still take up to 75 years (Rutishauser et al., 2015), leading many to promote RIL+, whereby careful extraction is supplemented by post-logging...
silvicultural procedures (Peña-Claros et al., 2008; Ruslandi, Cropper, et al., 2017; Sasaki et al., 2011).

Such carbon stock enhancements above the background rates of carbon sequestration from natural recovery may become saleable as carbon credits under REDD+ initiatives (Edwards, Fisher, & Boyd, 2010), although the economic viability of active carbon sequestration within logged forests partly depends on the ability to offset lost revenues from alternative land-use activities. Payment for sequestered carbon from line enrichment planting within logged Bornean forest is significantly less profitable than conversion to oil palm
(Ruslandi, Romero, et al., 2017), suggesting a need for funding mechanisms that also capture the non-carbon benefits of well-managed timber estates.

Ecosystem restoration may also better maintain the important local and regional climate regulating functions provided by logged-over forests. Insights from biodiversity ecosystem functioning theory, and experimentation in other biomes, suggest that planting trait-diverse and species-rich seedling mixes could render logged forests more resistant and better able to recover from unpredictable threats set to intensify under climate change, like parasitism and extreme weather (Mori, Lertzman, & Gustafsson, 2016; O’Brien, Reynolds, Ong, & Hector, 2017). The true value of ecosystem restoration of logged forest could thus only become apparent retrospectively, when compared to otherwise unrestored logged forests, which may be more prone to future breakdowns in carbon storage and other ecosystem services.

3.3 | Non-timber forest products

Many people rely on NTFPs for their livelihoods. However, a review found that logging deleteriously impacts NTFP availability in 82% of cases, via direct harvesting or damage of NTFP-providing species, or by creating a forest environment hostile to NTFP regeneration or availability (Rist et al., 2012). Increasing or recovering NTFP stocks may thus require active interventions—although some NTFPs recover unaided after logging (e.g. non-vascular epiphytes) or benefit from enhanced post-logging light conditions (e.g. rattan) (Ashton, Gunatileke, Gunatileke, Tennakoon, & Ashton, 2014).

Where NTFPs are globally or nationally in-demand, post-logging interventions can prove profitable. For instance, Brazil nuts are the most valuable NTFP harvested in the Amazon, but logging operations may reduce nut production by damaging trees (Rockwell et al., 2015). Applying liberation cutting of lianas choking Brazil nut trees can triple nut production (Figure 1c), boosting harvester’s gross annual incomes by US$500 (Kainer, Wadt, & Staudhammer, 2014).

Under certain conditions, NTFP enhancement could protect against agricultural conversion by increasing the standing value of logged forest and providing a near-term cash flow between timber harvests. Managing the mixed-dipterocarp forests of Sri Lanka solely for timber fetches approximately a third of the $26,000 ha⁻¹ derivable from conversion to tea plantations (Ashton et al., 2001). However, incorporating enrichment planting of commercially valuable NTFPs, including sugar-producing fishtail palm, wild cardamom and rattan, alongside timber management, generates $23,000 ha⁻¹ (Net Present Value, under 4% discount rates; Ashton et al., 2001), incentivising forest retention.

Enhancing and commercialising NTFPs is an important component of Indonesia’s Ecosystem Restoration Concession (ERC) programme for averting deforestation in unmanaged degraded forests. Indonesian businesses apply for management authority over an ERC for up to 95 years, committing to zero timber extraction and agricultural conversion. In return, managers can generate income from NTFPs (e.g. fruit, rattan and bamboo), by commercialising carbon or hydrological services (e.g. under REDD+), and via ecotourism or conservation funds (Walsh, Hidayanto, & Asmui, 2012). Impediments to expanding ERC networks include high upfront transaction costs and unfavourable taxation structures, although ERCs are galvanising private sector interest (as of 2016, 16 ERC licences have been issued, covering 623,075 ha). Empirical examinations of the efficacy of ERCs in maintaining forest cover are required to ensure such investments are not just green-washing.

Managing NTFPs within degraded forests to bolster against conversion is also complicated by the challenges of tapping into diverse commodity markets and scaling up multiple-use forest management. These often make commercial investment into co-management of timber and NTFPs financially unworkable, particularly in societies entering capitalist development phases that favour commodity (e.g. timber) specialisation (García-Fernández, Ruiz-Pérez, & Wunder, 2008). However, because certain NTFPs provide an important means of direct consumption and income generation in local households and markets, hold cultural value, and provide a safety net for the forest poor during hardship, enhancing flows of locally important NTFPs post-logging might be considered a social investment even when wider marketisation is unviable (Shakleton & Pandey, 2014). In particular, the emerging forest and landscape restoration (FLR) programme under the Bonn Challenge, with its high-level political buy-in and its broad objectives of enhancing human wellbeing and ecosystem provisioning across landscapes whilst stocking carbon, might forge partnerships with forestry and non-forestry governmental departments, enabling better integration of livelihood-enhancing management of NTFPs within logged forests.

3.4 | Social impacts

Forests support livelihoods of over one billion people in extreme poverty, and restoration activities within logged forests can provide substantial benefits to rural poor (Edwards et al., 2010). Enhancement of commercially valuable NTFPs can boost household incomes (Kainer et al., 2014) and provide an important safety net during hardship. Post-logging interventions also create jobs for local people, particularly where policies strive for local workforce recruitment (Edwards et al., 2010). Within the tropical logging sector, workers are typically hired on a short-term, discontinuous basis, creating boom-and-bust employment and unemployment cycles (FAO et al., 2013). In part, the concentration of labour needs during particular seasons and stages of logging drives this (FAO et al., 2013), suggesting that diversifying forest management to include post-logging interventions could increase employment opportunities.

Livelihood benefits derived from secure employment, or additional incentive systems, are likely to increase necessary long-term community support (Holl, 2017). Additionally, interventions could enhance the provisioning of ecosystem services, including reduced soil erosion, which affects local fisheries—notwithstanding potentially socially undesirable outcomes (e.g. removal of medicinal plants) associated with certain intensive post-logging interventions (Guariguata, García-Fernandez, & Sheil, 2010).
3.5 | Biodiversity

The impacts of post-logging activities on biodiversity hinge on the intervention. Where harvesting has ended, replanting of species targeted by logging—including rare or habitat/food providing species—could reverse biodiversity losses. However, adverse biodiversity impacts may ensue where carbon sequestration or accelerated timber recovery are core aims (Putz & Redford, 2009). First, planting of a few fast-growing tree species could reduce tree diversity, produce an even-aged timber stand vulnerable to ecologically damaging timber extraction en masse (Putz & Romero, 2015), and create a forest lacking resilience to increasingly severe droughts under climate change (O’Brien et al., 2017). Second, the removal of vines, climbing bamboos and understory plants could negatively affect biodiversity, because many lianas and understory species produce fruit, provide dense tangles used as foraging substrate, nesting and protection, or are themselves rare (Edwards, Ansell, Ahmad, & Hamer, 2009).

The limited evidence base suggests mixed impacts of post-logging interventions on biodiversity. In Panama, liana removal increases community-level canopy tree reproduction (León, Izquierdo, Mello, Powers, & Schnitzer, 2018) and tree species diversity in logging gaps by 65% (Schnitzer & Carson, 2010), whereas non-timber tree thinning in the Congo Basin has little effect on tree diversity (Gourlet-Fleury, Beina, et al., 2013), though it accelerates post-logging recovery of floristic composition (Ouedraogo et al., 2011). In Borneo, intensive enrichment planting and liberation cutting has little or no impact on the abundance of invertebrates (Edwards, Backhouse, Wheeler, Khen, & Hamer, 2011) or logging sensitive and IUCN Red-listed birds (Ansell, Edwards, & Hamer, 2011).

There are negative impacts of liberation cutting for fruit-eating birds in Borneo, probably because vines are an important fruit source, but positive impacts for insect-eating birds, which presumably benefit from the more open understory (Edwards et al., 2009). Moreover, bird communities inhabiting restored forest in Borneo have fewer species with specialised traits and a more truncated evolutionary history than communities in naturally regenerating logged forest (Figure 1d), with potential ramifications for ecosystem service provisioning within these forests (Cosset & Edwards, 2017). This suggests that when the objective is carbon or timber enhancement, interventions should seek to minimise potential threats to biodiversity.

4 | USING TIMBER ENHANCEMENT TO DESIGN BIODIVERSITY-FRIENDLY PRODUCTION LANDSCAPES

A key issue is how to manage logging to least harm biodiversity (Edwards, Gilroy, et al., 2014). “Land sparing” logging (Figure 2ai) couples the protection of large contiguous blocks of old-growth forest with intensive logging elsewhere, whereas “land sharing” logging (Figure 2bi) applies less-intensive logging over larger scales (Edwards, Gilroy, et al., 2014). Timber enhancement could influence the long-term viability of land-sparing or land-sharing logging, acting as an important component in designing biodiversity-friendly concessions. Despite potentially harmful effects at the stand level, intensive timber enhancement could have substantial net biodiversity benefits if it prevents illegal logging via the continued presence of forest managers, or more generally, if it discourages the political or economic imperative to reclassify logged forest for conversion to low biodiversity plantation (Gaveau et al., 2013), to log spared old-growth patches, or to prematurely re-log forests.

Edwards, Gilroy, et al. (2014) found that land sparing benefits more Bornean bird, leaf-litter ant and dung beetle species than land-sharing logging, whilst also limiting the development of damaging roads (Kleinschroth, Healey, & Gourlet-Fleury, 2016, Figure 2a vs b). However, the benefits of sparing are presumably undone if future logging operations foray into spared forest (Figure 2a). Since the successful maintenance of uncut forest portions will likely depend on intensively logged areas maintaining timber yields over time, timber enhancement within intensively logged areas could protect against future incursions into old-growth (Figure 2a).

Alternatively, Griscom, Goodman, Burivalova, and Putz (2017) demonstrated that when land tenure is secure and Forest Stewardship Council-certified RIL is employed, low-intensity land-sharing logging might best prevent species loss. A drawback of land-sharing logging is that stakeholders may intensify logging practices following the first low-intensity rotation, thereby subjecting the forest to further degradation and biodiversity loss (Figure 2a). Timber enhancement could prevent this by satiating enough of the timber demand that the remaining forest can continue under low intensity treatment (Figure 2a).

5 | ALTERNATIVE TARGETS FOR RESTORATIVE INTERVENTIONS

Limited resources for enhancing biodiversity, ecosystem services or livelihoods mean that treatments must be cost effective. Key restoration targets beyond logged forest exist. The FLR agenda seeks to recover landscape-wide ecosystem services and functions in degraded areas via recovering secondary forest or establishing agroforestry, silvopasture, or single- or multi-species plantations (Brancalion et al., 2017). Early evidence suggests that market or performance-based climate change mechanisms, like REDD+, are likewise targeting projects in socially and environmentally beneficial ways. But how much should post-logging interventions be promoted relative to these alternatives?

Natural regrowth of secondary forests on unproductive or abandoned agricultural lands is a scalable restoration strategy, with yearly carbon sequestration 2.3 times that of selectively logged forests in the Neotropics (Poorter et al., 2016). Moreover, such forests eventually recover biodiverse communities (Gilroy et al., 2014), although land-zoning mechanisms are required to ensure that any regrowth is not undermined by future conversion (Phalan et al., 2016). However,
a recent meta-analysis found highly variable forest recovery for both actively and passively restored former agricultural lands (Meli et al., 2017) and large-scale regrowth on viable cropland could trigger conversion of intact forest. Thus, although greater ecological gains might occur when restoration is targeted towards re-growing forest, this may switchback towards post-logging interventions whenever this averts deforestation, because of the disproportionate erosion of biodiversity that follows conversion of intact and relatively unfragmented forest (Betts et al., 2017).

Forest and landscape restoration activities and funds could energise ecosystem restoration, or carbon and ecosystem service enhancement (see Table 1) within ex-production forest, especially near well-populated areas. Urgent exploration of the comparative social, environmental and economic costs and benefits of different interventions within heterogeneous landscapes are needed. For example, Budiharta et al. (2014) integrate data on the habitat sensitivity of threatened mammal species, with model-derived estimates of the future carbon sequestration potential and specific cost of various restoration techniques, to systematically prioritise activities within forests of varying condition in East Kalimantan. Ultimately, such strategic planning should factor-in opportunities for natural or assisted regeneration on deforested lands, as well as the substantial benefits arising if logged forest interventions simultaneously avert agricultural conversion.

Planning might also include the various opportunity costs under different logged forest management regimes. For instance, carbon- or other ecosystem service-enhancements within once-logged forest where future logging is prevented will have large opportunity costs from forgone timber revenues, and as such these activities are likely more cost-effective and permanent when targeted towards timber depleted forests (e.g. Fisher et al., 2011). Alternatively, where silviculture is conducted between logging rotations to maintain timber yields within permanent timber estate, opportunity costs will likely be lower.

6 OPERATIONALISING POST-LOGGING INTERVENTIONS

Timber logging in the tropics is geared towards short-term profit maximisation over long-term sustainability, rarely spawning management plans beyond initial timber harvesting. High discount rates and upfront costs of seedling planting or liberation cutting generally make timber enhancement for future harvests commercially risky and
uneconomic (Schulze, 2008; Schwartz, Bais-Moleman, Peña-Claros, & Arts, 2016), although certain interventions are profitable for long-term investors (Ruslandi, Romero, et al., 2017). For ecosystem restoration or ecosystem service enhancement, the resources, expertise and governance needed are typically lacking, whilst the permanence of interventions is questionable, because logged forests are usually degradation and deforestation prone areas. Together, these factors explain why post-logging interventions largely remain confined to experimental plots and small-scale projects subsidised by conservation charities and external agencies (Putz & Romero, 2015).

Depleting stocks coupled with increasing demand for tropical timber may cement timber enhancement as a new trajectory in production forests (Putz & Romero, 2015). Spurring transitions towards well-managed timber landscapes that sustain yields of commercially important species in socially and environmentally acceptable ways requires institutions that generate the funding and enabling policies needed for post-logging interventions, influence business norms, build capacity and optimise existing practices.

6.1 | Influencing business norms

Much tropical logging is conducted by large (trans-)national corporations, known to “cut-and-run” (Laurance, 2000). However, such corporations could also drive transformative change in production forestry because they control significant areas, are connected across the tropics by a network of subsidiaries, engage directly in high-level governance processes and some are vertically integrated (operating throughout supply chains from logging to retail) (Österblom, Jouffray, Folke, & Rockström, 2017). Scientists and donors have understandably hesitated to engage such corporations, because of their reputation for forest degradation (Griscom et al., 2017).

Whilst we condemn malpractice, industrial logging will continue within tropical forests and short-term attempts to reduce logging levels within legal concessions might be counteracted by upsurges in illegal logging or climate change-driving substitution of wood with high-energy building materials. Ensuring logging in legal concessions is sustainable thus requires important actors to adopt “cut-and-stay” mentalities, beyond simply reducing the impacts of harvesting. Institutions must find leverage points for catalysing such system-wide shifts in business norms. Forging new science-business initiatives that engage keystone actors in solution-focused sustainability initiatives (e.g. Österblom et al., 2017) is a largely unexplored avenue that holds potential in driving transformative change. Encouraging certification standards to steer more aggressively towards sustaining timber yields could forge further improvements (Peña-Claros et al., 2008), notwithstanding the presumably lower uptake of stronger labels, costly certification, and at-times relatively poor enhanced market access relative to uncertified timber.

6.2 | Securing funding

Stimulating greater commercial investment could make post-logging interventions self-financing, releasing them from competition with alternative restoration investments. Governments can forge economic environments favourable to corporate investment by reducing the costs (or increasing profits) of interventions, via subsidies, loans, direct payment or tax breaks (Brancalion et al., 2017). For instance, governments should redirect reforestation funds paid by concessionaires back into timber enhancing activities in their own concessions or provide discount rates for carbon enhancement in line with those for climate-change projects (Ruslandi, Cropper, et al., 2017).

Payment for ecosystem services schemes, including REDD+, could levy funds for interventions that increase carbon storage above business-as-usual rates (Edwards, Tobias, et al., 2014; Ruslandi, Romero, et al., 2017). Thus far, the materialisation of carbon markets has been underwhelming, with funds from both voluntary and regulated markets (only US$220 million in 2012) dwarfed by government support for REDD+ (over US$7 billion in 2014) (Brancalion et al., 2017), and rarely invested in better management of production forests (Putz & Romero, 2015). However, with the likely growth of nonmarket-funded REDD+ financed by performance-based payments from the Green Climate Fund (Angelsen et al., 2017), new opportunities for logging companies employing climate-smart practices may emerge.

Because even intensively treated logged forests presumably maintain key soil and watershed processes, as well as biodiversity (Ansell et al., 2011), a fruitful avenue for funding post-logging interventions is complementing carbon payments with other payments for ecosystem services (Brancalion et al., 2017) and targeting such bundles towards well-managed timber estates. Moreover, since the FLR agenda includes climate change mitigation and improved human well-being, some forthcoming funds might be directed towards increasing carbon sequestration and hardwood recovery between rotations in active logging concessions, whenever this demonstrably provides climatic benefits and silvicultural employment for local people.

6.3 | Enabling policies

Commercial reluctance to invest in post-logging interventions often arises because political volatility and granting of short-term timber exploitation licences means concessionaries risk not cashing-in on future benefits accrued by present day management (FAO and van Hensbergen, 2016). By issuing long-lasting licences and awarding new concessions based on a track record of high-quality management, governments could promote commercial investment in long-term yield-sustaining activities (FAO and van Hensbergen, 2016). If well managed, such concessions would further supplement conservation efforts outside of protected areas (Gaveau et al., 2013). Additionally, governments should introduce legal and enforcement mechanisms similar to the mining sector, which dictate post-exploitation interventions.

Since logged forests have important restoration potential within heterogeneous, degraded landscapes, policies should strive to extend the socio-economic role of post-logging interventions within wider landscapes, via mechanisms such as community forest management (Asare, Keyei, & Mason, 2013) and public-private...
partnerships. A critical barrier is clarifying and securing land tenure and improving sectorial land planning, since forest management licences are usually expensive, large in area, and relatively short term. Breaking down such barriers to award smaller licences that enable integrated community management of heterogeneous landscapes (e.g. Asare et al., 2013) is critical if post-logging interventions are to take a central role in the FLR agenda.

6.4 Optimising post-logging interventions

Expensive restocking through enrichment planting should be confined to forests with low natural regeneration of timber species, with liberation of existing seedlings employed within well-stocked forest (Ruslandi, Cropper, et al., 2017). Where enrichment planting is required, key is ensuring seed or seedling stocks have ample genetic diversity (Kettle, 2010; Thomas et al., 2014), by knowledge-sharing of seed selection and supply options, and exchanging seeds across landscapes (Jalonen, Valette, Boshier, Duminil, & Thomas, 2017). Furthermore, enrichment planting should be designed to minimise ecological impacts, including of future timber extraction (Putz & Romero, 2015). Inter-planting timber species that mature at different speeds, rather than enriching stands with species that reach harvestable sizes near-simultaneously, could protect against impacts tantamount to clear-cutting logging. Concentrating intensive treatments to small areas (“land-sparing” timber enhancement) could spatially constrain any deleterious biodiversity impacts.

Innovative silvicultural practices worthy of immediate exploration exist. One promising example is exploiting the suitability of logging road verges to support valuable fast-growing timber species in the Amazon and Congo Basin. Roadside seedling enrichment or liberation could be financially remunerative, buffer forest interiors from edge effects, and spare forest from new road construction during subsequent rotations by promoting reopening of old roads to harvest roadside timber (Kleinschroth et al., 2016).

6.5 Building capacity and scalability

Optimally implementing post-logging interventions largely depends on: (a) availability of foresters trained in silviculture (Putz & Romero, 2015); (b) often-lacking taxonomic expertise to identify naturally regenerating merchantable seedlings for liberation and monitor the impacts of post-logging silviculture on wider biodiversity; and (c) finding ways of making interventions technically and financially scalable. Whilst these constraints are symptomatic of the presently low commercial and political emphasis on post-logging management, they are not insurmountable.

Training programmes like those used for RIL could enhance silvicultural capacity (Sasaki et al., 2011) and para-botanical expertise, easy to identify and monitor indicator taxa could facilitate monitoring of wider biodiversity, whilst company-community models, including timber out-grower training schemes, can engage local communities. Investing in social capital via bottom-up approaches would help ensure the permanence of restoration efforts (Holl, 2017), particularly when coupled with top-down land-zoning that renders treated forests off-limits from conversion. Piloting innovative post-logging interventions at various scales and under different incentive/disincentive structures could reveal low-cost options for large-scale roll-out and iterative adjustment according to local political or socioecological dynamics.

7 OUTSTANDING QUESTIONS AND FUTURE DIRECTIONS

7.1 The economics and feasibility of post-logging interventions

The long-term profitability of liberation cutting, thinning of merchantable species (particularly with mechanisation) and enrichment planting are unknown for most of the tropics. Although line-planting of dipterocarps at large scales in Borneo generates substantial timber volume increments (Dawkins & Philips, 1998; Ruslandi, Cropper, et al., 2017), the technical and financial feasibility of planting regimes elsewhere are less well established and hard to extrapolate to industrial scales. Most studies calculate future yields based on short-term measurements of seedling survival and growth rates within a few small experimental plots (e.g. Schulze, 2008), thus generating high uncertainty and leaving significant scope for longer-term and large-scale assessments.

Other crucial questions include: (a) what is the cost-effectiveness of sequestered carbon in production forest; (b) what combinations of penalties, rewards and forest concession licensing or tenure arrangements can incentivise adoption of appropriate silvicultural practices by logging industries or communities; and (c) which business models and scenarios make managed logged forests for restoration viable and scalable over land-use alternatives? Developing and evaluating post-logging interventions that recover the economic potential of exhausted timber concessions and thus constrain their risk of conversion is crucial (Harrison & Swinfield, 2015).

7.2 Impact on ecosystem services and NTFPs

Long-term effects of forest interventions on soil fertility, water retention, carbon storage and resilience against stressors including drought and parasitism are unknown. Optimal management even for internationally traded NTFPs is little understood, leaving scope for empirical exploration of NTFP-maximising strategies in production forest. In some cases, planting lianas may aid restoration by sealing forest edges from edge effects and supporting important ecological and geochemical processes (e.g. nutrient turnover), but this requires validation (Campbell, Edwards, Odell, Mohandass, & Laurence, 2015).

7.3 Impact on biodiversity

The impact of post-logging interventions on most taxonomic groups and potential benefits of wildlife-friendly practices, including supplementing enrichment planting of commercial species with fruit
trees and applying breaks or reduced-intensity in liberation cutting to allow retention of microhabitats (Ansell et al., 2011) are untested. Long-term experiments that measure carbon, timber and biodiversity outcomes along manipulated gradients of post-logging silvicultural intensities would be invaluable for assessing synergies and trade-offs. Such joint assessments of timber production, economic productivity and biodiversity outcomes of various interventions could also inform best practices for designing biodiversity-friendly concessions (Figure 2). Ultimately, this could instruct least-harmful application of ecologically damaging activities—for example, by demonstrating whether for a given volume of recovered timber, it is better for biodiversity to concentrate intensive liberation cutting in a small forest area or employ lower-intensity liberation cutting (e.g., incorporating cutting breaks) at wider scales.

7.4 | When to restore a logged forest

Vital management decisions include when to actively intervene and when to allow unassisted recovery of logged forests. This depends on the degradation level (Rutishauser et al., 2015) and cost-benefit ratio of interventions relative to other land-use targets, including restoration alternatives (Budharta et al., 2014). Whether enhancement of future timber stocks favours early re-logging or increases a forest’s standing value, reducing conversion risk (Edwards, Tobias, et al., 2014), and whether passive regeneration and the associated lack of forest operators increases the risk of illegal encroachment or reclassification to industrial plantations (Gaveau et al., 2013; Zahawi, Reid, & Holl, 2014) are research frontiers. Given various post-logging objectives (Table 1), developing multi-stakeholder platforms would help determine the type and spatial configuration of interventions to deliver mutual conservation, timber or social benefits (Ruslandi, Cropper, et al., 2017).

8 | CONCLUSIONS

Retaining unlogged, old-growth forest within networks of protected areas remains a global priority (Gibson, Lee, Koh, & Sudhi, 2011; Lewis et al., 2015). However, this alone cannot retain tropical species into the future, reinforcing the importance of human-impacted forests in on-going conservation agendas. Logged tropical forests are second only to old-growth forest in their biological value and capacity to provision an array of ecosystem services valued by human-kind. However, they are vulnerable to a suite of threats, including agricultural conversion (Edwards, Tobias, et al., 2014). In this review, we provide evidence that the growing dominance of production forest landscapes and the failures of past efforts to reduce logging means that alongside working to improve existing logging practices, post-logging interventions are important for improving logged forest management and breathing new life into already degraded forests. The research gaps and opportunities for optimising these interventions that we have identified require further study to ensure that logged forests unlock their full potential in emerging global restoration agendas.

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