

Prospects for Sustainable Logging in Tropical Forests

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A convincing body of evidence shows that as it is presently codified, sustainable forest-management (SFM) logging implemented at an industrial scale guarantees commercial and biological depletion of high-value timber species within three harvests in all three major tropical forest regions. The minimum technical standards necessary for approaching ecological sustainability directly contravene the prospects for financial profitability. Therefore, industrial-scale SFM is likely to lead to the degradation and devaluation of primary tropical forests as surely as widespread conventional unmanaged logging does today. Recent studies also show that logging in the tropics, even using SFM techniques, releases significant carbon dioxide and that carbon stocks once stored in logged timber and slash takes decades to rebuild. These results beg for a reevaluation of the United Nations Framework Convention on Climate Change proposals to apply a Reducing Emissions from Deforestation and Forest Degradation subsidy for the widespread implementation of SFM logging in tropical forests. However, encouraging models of the successful sustainable management of tropical forests for timber and nontimber products exist at local-community scales.

Keywords: sustainable forest management, high-value timber, primary tropical forest, logging, REDD+

Industrial-scale sustainable forest management (SFM) in the tropics (i.e., managed selective harvesting of timber) has been widely promoted by the international community as a key mechanism to combat tropical deforestation. SFM is integrated into most United Nations (UN) instruments in which sustainable development or biodiversity conservation is addressed, and SFM was recently endorsed by the UN General Assembly in the *Non-legally Binding Instrument on All Types of Forests* (NLBI; UNFF 2007). The UN, World Bank, and other multilateral organizations strongly promote SFM and forest-management certification schemes, such as the Forest Stewardship Council, that seek to create market incentives for SFM.

UN Framework Convention on Climate Change (UNFCCC) negotiations are now poised to create new incentives for SFM in tropical forests by including SFM as an activity under its Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism (UNFCCC 2008). REDD+ could provide major new funding for implementing SFM. The annual funding needs of REDD+ have been estimated at \$28 billion to \$31 billion (Busch et al. 2011).

However, there have long been questions as to whether industrial logging of tropical forests can truly sustain natural ecosystems while permitting repeated harvests of high-value timber (Nasi and Frost 2009). Most tropical trees of undisturbed primary forest, including virtually all currently

high-value timber species, are exceptionally long lived and slow growing, occur at low adult density, undergo high rates of seed and seedling mortality, sustain very sparse regeneration at the stand level, and rely on animal diversity for reproduction, all of which point to the conclusion that tropical trees probably need very large continuous areas of ecologically intact forest if they are to maintain viable population sizes (Pitman et al. 1999). As Schulze (2008) observed, this set of ecological characteristics forms a perfect storm of challenges for managing timber stocks for industrial profit. The storm intensifies when one considers that little or nothing is known about specific autecological characteristics of the timber species to be managed (e.g., species-specific growth rate, germination and growth requirements, animal pollinator and disperser species, edaphic preferences, maximum spacing for pollination, minimum out-crossing requirements; de Freitas and Pinard 2008, Grogan et al. 2008, Schulze et al. 2008a).

In contrast to the life histories of timber species, about which little is known, the drivers and impacts of logging in the tropics are well known and operate virtually identically across the globe. Logging in the tropics follows the same economic model as is evident in most of the world's ocean fisheries: The most-valuable species are selectively harvested first, and when they are depleted, the next-most-valuable set is taken, until the forests are mined completely of their

timber and the land becomes worth more for agriculture or ranching than for forestry (Asner et al. 2006, Karsenty and Gourlet-Fleury 2006, Laporte et al. 2007, Hall 2008, Schulze et al. 2008b). The pursuit of high-value species for export markets drives the expansion into previously unlogged and remote areas of the Amazon, Central Africa, and Borneo (Kammesheidt et al. 2001, Laporte et al. 2007, Hall 2008, Schulze et al. 2008b, Asner et al. 2009, Bryan et al. 2010). With an abundant timber supply from usually illegal and conventionally unmanaged logging, there is no incentive for management or conservation (Nawir and Rumboko 2007). Conventional logging has left much of Southeast Asian and huge swaths of Latin American primary forestlands in degraded secondary forest or, more often, cleared for agriculture. This relentless process that begins with timber high grading is also well under way in the last wilderness forests of Central Africa (Karsenty and Gourlet-Fleury 2006, Zhang et al. 2006, Laporte et al. 2007, Hall 2008). One third of the remaining tropical forest has been degraded by selective logging, which is spreading rampantly through the remainder (Asner et al. 2006, Zhang et al. 2006, Nawir and Rumboko 2007, Bryan et al. 2010, Matricardi et al. 2010). Proponents of SFM propose that widespread implementation of SFM techniques using REDD+ subsidies could slow or stop this process of degradation and deforestation by maintaining the monetary value of tropical forests for timber production.

In the present article, we review the definition of SFM and, in light of scientific understanding of ecological processes that characterize and sustain the regeneration of primary tropical forests and the impacts of logging, evaluate the evidence for the ability of currently defined SFM protocols to sustain timber yields in the world's last large blocks of natural tropical forest. Presently, SFM procedures rely on government-mandated cutting cycles, minimum felling diameters, per-unit-area harvest intensities and seed-tree retention rates applied in combination with proven techniques for reducing damage to the residual stand during logging operations (*reduced-impact logging*, RIL). We ask whether there is evidence that implementation of the current SFM procedures could produce harvests of high-value timber from tropical forests over several cycles while maintaining minimum viable population sizes of these timber species and carbon stocks. In light of this evidence, we discuss possible outcomes for tropical forest ecosystems and climate mitigation if SFM were to receive REDD+ funding.

The definition of SFM

The objectives of SFM have been defined differently by various organizations. The UNFCCC does not define SFM and creates some confusion by using the term *sustainable management of forests* (SMF) rather than the more common SFM (UNFCCC 2008). The UN's Food and Agriculture Organization (FAO) and UN Forum on Forests (UNFF) have each offered interpretations of the term SMF. The FAO has suggested that SMF refers to the "application of forest-management practices for the primary purpose of sustaining

constant levels of carbon stocks over time" (FAO 2009), noting that SMF would not require that other forest values also be sustained. This narrow, carbon-focused approach reflects the FAO and International Tropical Timber Organization (ITTO) definitions of SFM (ITTO 2005, FAO 2010), which give forest managers the discretion to decide which forest values to sustain.

In contrast, the UNFF (2009) cites the NLBI as the relevant authority. The NLBI uses SFM and SMF interchangeably and defines SFM holistically, requiring SFM operations to maintain the full complement of a forest's ecological integrity. The NLBI was developed by the UNFF, the international body tasked with achieving consensus on international forest policy, and was endorsed by the UN General Assembly. Absent a global treaty on forests, the NLBI currently represents the strongest international consensus on SFM.

The discretionary approach proposed by the ITTO and FAO also appears inconsistent with the ITTO's own criteria and indicators for SFM (developed with the FAO), which state that all of its SFM criteria are "essential elements" and are not prioritized (ITTO 2005). The Forest Stewardship Council (FSC), the leading SFM certifier in the tropics, also adopts a holistic approach (FSC 2002), as does most of the literature. The consensus definition of SFM, therefore, encompasses sustaining timber yields while maintaining a forest's full complement of ecosystem services and societal values, which we refer to as *ecological integrity*. However, the SFM objectives listed by different organizations do not yet explicitly require that a forest's structure and composition be maintained. Here, we review scientific findings from forests that are in the tropics and receive more than 1000 millimeters of rainfall annually.

Regeneration of natural tropical forest

The challenge for SFM is to reconcile harvesting protocols with natural regeneration processes of tropical forests, major elements of which are understood. From the gene level to the habitat level, tropical forests have the most terrestrial biodiversity on the planet. More than 50% of known plant species grow in tropical forests. A single hectare (ha) of tropical forest typically contains well over 100 species of trees. A corollary to high species diversity is that a majority of tree species occur locally at low densities (i.e., less than one individual that is more than 10 centimeters [cm] in diameter per ha) but often span broad geographical ranges and may have large absolute population sizes at large spatial scales (Primack and Hall 1992, Poorter et al. 1996, Pitman et al. 1999). For decades, scientists have wondered about the mechanisms that allow so many tree species to coexist in sympatry. How is it that some species in an area do not outcompete the many other rare species, as it happens in less diverse ecosystems?

Part of the explanation can be found with regeneration processes that, in essence, incorporate a substantial element of randomness into any individual tree's chances of reproducing. First, a high percentage of tropical tree species rely

on specialized sets of animal vectors for pollination and seed dispersal—especially insects, birds, bats, and various other mammals—which are both processes that are necessary for successful reproduction by tropical trees (Howe and Miriti 2000, Sist et al. 2003, Anitha et al. 2010). Dispersal is crucial for increasing a seed's chances of escaping predation and shade under the mother tree and reaching microsites favorable for growth, such as tree-fall gaps or better soil (Howe and Miriti 2000, Babweteera and Brown 2010). Because of the diversity of seed types and the behavioral ecology of seed-dispersing animals, the postdispersal patterns of seeds vary widely. Therefore, it is likely that frugivore animal diversity in tropical forests strongly influences tree recruitment and spatial distribution.

Furthermore, with the exception of a few hurricane-prone coastal areas, the regeneration of tropical forests is known to be driven by the small-scale disturbance dynamics of randomly occurring canopy gaps (Denslow 1987). Trees, or parts of trees, fall and open a small gap in the canopy, which allows light through to seedlings and juvenile trees waiting below for their brief moment in the sun. Typically, gaps constitute about 1%–2% of the forest area and most mid- to upper-canopy tree species depend on the light provided in gaps for some stage of their regeneration (Denslow 1987, Kuusipalo 1997, Struhsaker 1997). Tree species are classified along a gradient of the dependence of their regeneration on the existence of gaps: from the fast-growing, light-wooded, shade-intolerant pioneers that require full sun their entire lives to the slow-growing, shade-tolerant primary forest hardwoods that may survive many years in full shade under the canopy (Sist et al. 2003, Vieira et al. 2005, Herault et al. 2010). Gap size and the ephemeral presence of seedlings or seeds that have been dispersed into the gap determine the species composition of the forest patch after a disturbance (Denslow 1987, Howe and Miriti 2000). All currently high-value timber species are adapted for some degree of shade tolerance, from tolerating shade throughout most of their lives—notably, many dipterocarps of Southeast Asia (Kuusipalo et al. 1997, Sist et al. 2003)—to those shade-intolerant species such as the high-value African and Neotropical mahoganies with seedlings that require sunlight within their first few years but that can tolerate shade after establishing (Sist et al. 2003, Hall 2008). No currently high-value timber species is a full-sun-loving pioneer.

Associated with gap-driven regeneration and adaptation for shade tolerance during much of their lives are the long life spans and slow growth rates of primary tropical forest hardwoods, including most currently high-value timber species (Vieira et al. 2005). Nonpioneer tropical trees often live for hundreds of years, and the life spans of some species with very dense wood exceed 1000 years (Kurokawa et al. 2003). Diameter growth rates vary significantly between and within tree species and also in relation to age, season, climatic, and other conditions, such as vine load. Most timber species have low inherent growth rates in the tropics (Dauber et al. 2005, Vieira et al. 2005, Valle et al. 2007, Herault et al. 2010), but

the life-history trade-off is that they can respond quickly to light provided in sporadically and unpredictably occurring canopy gaps by increasing their growth rate (Herault et al. 2010).

A high percentage of tropical tree species are further characterized by population structures skewed toward larger individuals with very low densities of seedlings, saplings, and poles. In the Brazilian Amazon, for example, 26 of 70 commercial species examined had low overall adult densities, populations composed mostly of large trees (more than 50 cm diameter at breast height [DBH]), and sparse seedling regeneration, including the group of premier timber species—namely, mahogany (*Swietenia macrophylla*), Spanish cedar (*Cedrela odorata*), ipê (*Tabebuia* spp.), and jatoba (*Hymenaea courbaril*) (Schulze et al. 2008a). A lack of stand-level regeneration by canopy trees, including the most important timber species, is the norm across the Amazon and Africa and for many species in Southeast Asian forests (Primack and Hall 1992, Poorter et al. 1996, Kammesheidt et al. 2001, Sist et al. 2003, Park et al. 2005, de Freitas and Pinard 2008, Hall 2008, Schulze et al. 2008a, Doucet et al. 2009, Anitha et al. 2010, Babweteera and Brown 2010). The flip side of this size-class-distribution pattern is high seed and seedling mortality rates in natural forests, especially for the nonpioneer light-demanding species whose seedlings cannot tolerate shade (Hall 2008). Many high-value timber species of the tropics belong to this group. This pattern of juvenile scarcity reflects the complex and chancy nature of reproduction by trees in high-biodiversity environments: scanty regeneration, which when summed over landscapes, maintains viable populations.

The direct impacts of selective logging on forest regeneration

The severity of the direct impacts of logging on tropical forests is linked to harvest intensity, which is measured by the number of stems or cubic meters extracted per ha. The higher the harvest intensity is, the greater is the damage to the forest canopy and to residual trees, including young recruits, until a point is passed at which nonpioneer trees of primary forest may no longer grow (Struhsaker 1997, Sist and Nguyen-Thé 2002, Van Gardingen et al. 2006, Anitha et al. 2010). The mechanisms leading to suppression of advance regeneration by primary forest tree species after high-intensity logging (generally considered more than five stems extracted per ha in a tropical forest) are known: (a) A high percentage of future crop and seed trees are killed; (b) 20%–50% of the forest canopy is transformed into open gap, which strongly favors rapid growth by light-loving vines and pioneer vegetation that easily outcompete the slower-growing, slower-establishing nonpioneer tree species; and (c) a reduction in canopy cover and tree density renders residual stands in drier tropical forests fire prone, since they are left full of dried-out dead woody debris, or *slash* (Kuusipalo et al. 1997, Struhsaker 1997, Sist and Nguyen-Thé 2002, Cochrane 2003, Sist et al. 2003, Park et al. 2005,

Karsenty and Gourlet-Fleury 2006, Valle et al. 2007, Forshed et al. 2008, Schulze 2008, Anitha et al. 2010, Huang and Asner 2010, Matricardi et al. 2010). It may be that there is also an adverse impact on populations of animal pollinators and seed dispersers (Struhsaker 1997, Babweteera and Brown 2010), but this potentially dramatic impact on tree regeneration is less well studied.

Forests logged at low intensities—generally considered to be fewer than five trees per ha in tropical forests—may eventually recover much of their prelogging basal area, structure, and species composition, minus usually only the targeted timber species (Struhsaker 1997, Sist and Nguyen-Thé 2002, ter Steege et al. 2002, Hall et al. 2003, Sist and Ferreira 2007). Limited opening of the canopy and soil disturbance enhances the growth of nonpioneer, shade-tolerant and shade-intolerant tree recruits, such as all principal timber species (Kuusipalo et al. 1997, Hall 2008, Herault et al. 2010). However, to restrain the smothering growth of pioneer vegetation, to avoid creating fire risk, and to promote non-pioneer tree recruitment, the rule of thumb appears to be that single gaps should measure less than 500 square meters, the gap's area should not exceed 10% of the canopy's area, and 85% of a stand's basal area should be preserved (Struhsaker 1997, Sist et al. 2003). Therefore, the key to a forest's ability to recover most of its original attributes after selective logging is low harvest intensity.

Unsurprisingly, the world's natural tropical forests are being logged at two to three times higher intensity than what they have shown themselves able to recover from. In Southeast Asia, a single tree family with over 450 species that share commercial wood properties, the Dipterocarpaceae, dominates the species composition of the forests. Therefore, timber stocking is particularly high in Southeast Asia, and so is logging intensity. The virgin forests of Southeast Asia are typically logged at intensities in excess of 10 trees per ha, which leaves 50% of the canopy in gaps and otherwise inflicts severe damage on the residual stand (Sist and Nguyen-Thé 2002, Sist et al. 2003, Forshed et al. 2008). Overall timber stocking is comparable in the forests of Africa and in the Neotropics, but the high-value species are distributed much less densely than are those in Southeast Asia. Therefore, logging in Africa and the Amazon occurs in waves, following a predictable and well-documented cycle: (a) One or two very high-value timber species destined for export pay for building roads into previously inaccessible forests, where these species are selectively logged; (b) the colonization frontier follows these roads, and within a few years, sawmills are built and infrastructure is consolidated; (c) transportation costs fall to allow loggers to reenter stands and harvest the next-most-valuable set of species (Kammesheidt et al. 2001, Blundell and Gullison 2003, Asner et al. 2006, Karsenty and Fleury 2006, Zhang et al. 2006, Hall 2008, Schulze et al. 2008b, Matricardi et al. 2010). So although the first harvest in African and Amazonian forests is often of low intensity and targets only one or two species, ultimately, subsequent harvests of less-valuable species ensure that these forests

undergo heavy logging. The hope is that widespread implementation of SFM with REDD+ subsidies can slow or stop this process of degradation and deforestation.

Clearly, in addition to disturbing forest canopy structure, conventional logging depletes populations of timber trees and most often removes the majority of the reproductive adults, especially of high-value timber species that lack adequate recruitment (Kammesheidt et al. 2001, Hall et al. 2003, Sist et al. 2003, de Freitas and Pinard 2008, Grogan et al. 2008, Schulze et al. 2008a, Doucet et al. 2009). The limited literature on tropical tree pollination, genetic exchange, and reproductive success at varying adult densities suggests that there must be a density below which every tree species faces local extinction (Degen et al. 2006). What that density is remains a universal mystery (Sist et al. 2003, Schulze et al. 2008a).

Sustainable forest management

Full SFM procedure relies on government-mandated cutting cycles, minimum felling diameters, per-unit-area harvest intensities and seed-tree retention rates applied in combination with RIL guidelines. Silvicultural techniques that can enhance the abundance and diameter increment of juvenile timber tree recruits are not yet included in SFM. Is there evidence that implementation of SFM procedures could produce harvests of valuable timber over several cycles while maintaining the minimum viable population sizes of timber species?

Reduced-impact logging. Early in the 1990s, the alarm bell began sounding on the tidal wave of threats facing tropical forests globally. Tropical foresters began experimenting with techniques for reducing the mortality rates suffered by residual trees from logging. The biological objective of this research was to preserve as much ecological integrity as possible of the logged stand, including, most importantly, protecting already-established seedlings, saplings, and subadults of commercial species that, in theory, would form the next crop of trees. The methods developed are known collectively as RIL and, in tests, have proven effective the world over in reducing collateral damage to the residual stand by 20%–50% (reviewed by Putz et al. 2008).

Over the past decade, the encouraging results of RIL have been tempered by data from timber-yield monitoring and modeling studies, which have increasingly revealed that (a) advance regeneration of high-value timber species is often not present in residual stands to begin with and (b) whether RIL was implemented and whether advance regeneration was present, high logging intensities and low minimum cutting diameters usually left such a high percentage of the canopy in open gap (20%–50%) that the residual stand became colonized by fast-growing, light-loving vines and pioneer species. These colonizers are often of no to low commercial value and, for decades, suppress the regeneration of slower-growing, shade-tolerant and shade-intolerant primary forest trees. These studies' authors all conclude that RIL alone does not guarantee sustainable yield, and at higher

harvest intensities (more than five trees per ha), employing diameter-limit cutting, RIL is unlikely to affect future harvests much at all (Kammesheidt et al. 2001, Sist et al. 2003, Van Gardingen et al. 2003, 2006, Sist and Ferreira 2007, Valle et al. 2007, Forshed et al. 2008, Peña-Claros et al. 2008, Kukkonen and Hohnwald 2009).

Government forestry regulations: Minimum cutting cycle, minimum-diameter felling limit, harvest intensity, seed-tree retention rate. Recognizing the imminent threat to survival of their natural forests posed by unmanaged conventional logging, national governments in the tropics have responded in part by designing forestry legislation that, when it is implemented in combination with RIL, might transform today's logging industry from predatory to sustainable. The performance of government forestry regulations has been analyzed in several long-term plot, timber-yield, and modeling studies that were undertaken principally in Southeast Asia and Amazonia. These studies unanimously conclude that even with RIL, virtually all of today's national forestry codes guarantee commercial depletion, if not extirpation, of most timber species within three cutting cycles (Alder and Silva 2000, Huth and Ditzer 2001, Kammesheidt et al. 2001, Hall et al. 2003, Sist et al. 2003, Van Gardingen et al. 2003, 2006, Dauber et al. 2005, Gourlet-Fleury et al. 2005, Degen et al. 2006, Karsenty and Gourlet-Fluery 2006, Sist and Ferreira 2007, Valle et al. 2007, de Freitas and Pinard 2008, Forshed et al. 2008, Grogan et al. 2008, Peña-Claros et al. 2008, Sebben et al. 2008, Schulze et al. 2008a, 2008b, Guitet et al. 2009, Kukkonen and Hohnwald 2009).

Furthermore, these studies have clarified that under prevailing tropical SFM protocols, (a) minimum rotation cycles, typically 25–35 years, are too short by a factor of at least two; (b) minimum felling diameters, most often 50 cm DBH, are too small to preserve adequate populations of reproductive adults and to control harvest intensity, assuming that diameter-limit cutting is the only option; (c) per-unit-area harvest intensities (around eight trees per ha) are too high and leave residual stands most often lacking future tree crop regeneration, overgrown by pioneer vegetation, and fire prone, especially in regions that experience dry seasons; and (d) seed-tree retention rates—that for Brazil is 10% retention of trees greater than 45 cm DBH—are inadequate. In addition, research has clarified that static minimum felling diameter and commercial retention rules cannot be reconciled with marked differences in timber species life histories and the need for management that is adaptive to species-specific local-population structure, growth rates, and relative densities (Poorter et al. 1996, Sist et al. 2003, Dauber et al. 2005, de Freitas and Pinard 2008, Schulze et al. 2008a, Sebben et al. 2008, Herault et al. 2010). Unfortunately, very few data exist for any forest on species-specific life history and the local-population structures of timber species.

Silviculture. The historical objective of silviculture in natural tropical forest has been to enhance the growth increment

and abundances of timber species (Kuusipalo et al. 1997, Yasman 1998, Sist et al. 2003, Peña-Claros et al. 2008, Guitet et al. 2009). Silviculture in the tropics was intended to maximize access to light and nutrients for high-value timber trees, seedlings, and saplings and, therefore, relied on removing competing trees and vines. Primary forest tree species respond to competitive release and will, for a time, increase their growth rate, although treatments must usually be reapplied at intervals to maintain a growth advantage (de Graaf et al. 1999, Peña-Claros et al. 2008, Herault et al. 2010). However, silviculture models developed for tropical forests have yet to result anywhere in a sustainable timber yield at an operational scale. Where attempts have been made to apply postlogging silviculture treatments broadly, such as in Indonesia and Malaysia, they have failed to achieve the objective of sustainable timber production or forest conservation (Kuusipalo et al. 1997, Yasman 1998, Hall et al. 2003, Sist et al. 2003, Nawir and Rumboko 2007).

Many studies have demonstrated the unlikelihood of hardwood timber tree species' regenerating adequately on their own after SFM logging. Large logging gaps tend to become overwhelmed by pioneer vegetation, and although the saplings of many tree species are capable of surviving long periods of suppression until the canopy opens again through the senescence of pioneers, suppressed stems do not grow at rates that will result in commercial-size trees in 50–70 years (the projected third harvest). We now know that under the present SFM guidelines, tropical forests left to regenerate naturally will be composed largely of light-wooded tree species of no to low commercial value, whereas dense-wood, high-value timber species will experience severe population declines (Kuusipalo et al. 1997, Hall et al. 2003, Park et al. 2005, Valle et al. 2007, Schulze 2008). The additional silvicultural treatments or alternative cutting prescriptions needed to help increase the growth rates and abundances of nonpioneer shade-tolerant and -intolerant tree species after selective logging are not presently components of RIL or SFM, nor are they included as criteria for forest certification under FSC.

Recent research has indicated a potential for the recovery of commercial tree populations after SFM logging through the enrichment planting of pregrown seedlings and their subsequent tending in small logging gaps (Kuusipalo et al. 1997, Park et al. 2005, Grogan et al. 2008, Hall 2008, Schulze 2008, Doucet et al. 2009). In Southeast Asia, advance dipterocarp regeneration is sometimes abundant enough to allow for the skipping of the enrichment-planting step, but the requirement for tending established seedlings in small gaps is the same as in Africa and Amazonia (Kuusipalo et al. 1997, Sist et al. 2003). Single-tree-size logging gaps mimic the natural conditions for primary forest tree regeneration and offer the potential for the regrowth of timber trees (Kuusipalo et al. 1997, Sist et al. 2003, Schulze 2008, Herault et al. 2010). Seedlings grow well in logging gaps if competitive and suppressive pioneer vegetation is thinned regularly during at least the first few years (Park et al. 2005,

Hall 2008, Peña-Claros et al. 2008, Schulze 2008). The production of commercial-size timber in logging gaps by the third harvest is the silvicultural goal now recommended by most tropical forestry researchers (Park et al. 2005, Hall 2008, Peña-Claros et al. 2008, Schulze 2008, Doucet et al. 2009).

Impacts on biodiversity

The direct impacts of logging on animal biodiversity in the tropics vary widely, depending on different combinations of many factors, including phylogeny, ecological niche, logging intensity, proximity, and the extent of undisturbed forest, the degree of fragmentation, and so on. However, the direct impacts of logging on biodiversity pale in comparison to its secondary impacts. Secondary impacts follow a well-documented course that ends in the destruction of natural forest biodiversity. These impacts come from road building, colonization, hunting, depletion of timber stocks, clearing for agriculture, or fire in adjacent degraded forests (Cochrane 2003, Asner et al. 2006, Karsenty and Gourlet-Fleury 2006, Zhang et al. 2006, Laporte et al. 2007, Nawir and Romboko 2007, Hall 2008, Schulze et al. 2008b, Matricardi et al. 2010).

Climate change mitigation

Industrial logging in the tropics contributes a significant proportion of the gross annual anthropogenic flux of carbon dioxide (CO₂) and continues to expand rapidly into virgin forests of all regions (Laporte et al. 2007, Asner et al. 2009, Bryan et al. 2010, Huang and Asner 2010, Matricardi et al. 2010). Recent remote-sensing studies have made the monitoring of selective logging from space possible (Laporte et al. 2007, Huang and Asner 2010, Matricardi et al. 2010). New data have revealed, for example, that (a) in the Brazilian Amazon, between 1999 and 2002, logging ranged from 12,075 to 19,823 square kilometers (km²) per year (Huang and Asner 2010) and is spreading rapidly (Asner et al. 2006, Matricardi et al. 2010); (b) in one 30,000-km² area of the Brazilian Amazon, in 2004, selective logging alone disturbed 31% of the natural forest area, whereas 29% was deforested outright (Matricardi et al. 2010); (c) an estimated 41% of Papua New Guinea's emissions in 2001 resulted from logging (Bryan et al. 2010); (d) logging roads account for 38% of all roads in Central Africa, and the rates of logging-road construction are increasing throughout the region (Laporte et al. 2007); (e) the average biomass of unlogged forest in Papua New Guinea was estimated at 358 tons per ha, whereas it was 161 tons per ha in conventionally logged forests (Bryan et al. 2010); and (f) logging increases the gross annual carbon emissions from Amazon forests by up to 25% over carbon losses from deforestation alone (Asner et al. 2006). The most recent high-resolution remote-sensing analysis of a 2,664,960-km² region of the Brazilian Amazon indicates that selective logging was responsible for 15%–19% higher carbon emissions than that reported from deforestation (clearcutting) alone (Huang and Asner 2010).

Implementation of RIL techniques across the tropics might reduce carbon emissions by an average of about 30% relative to conventional logging (Putz et al. 2008). However, logging intensity and cycle are the major determinants of the extent to which forest carbon stocks are depleted, with the result that even under widespread implementation of RIL, industrial logging will provoke the emission of gigatons of CO₂, carbon that it will take decades for the forest to resequenter (Blanc et al. 2009, Koltunov et al. 2009, Huang and Asner 2010). Mazzei and colleagues (2010) recorded a 23% reduction in aboveground biomass (AGB) after RIL logging at an Amazonian site with an additional 10% AGB reduction within the first year from the high mortality rates of damaged trees. Regrowing this AGB volume would be impossible within a 30-year cutting cycle without reducing logging intensities by at least 40%–50%, including leaving more large trees unharvested (Mazzei et al. 2010). A long-term plot study in French Guiana showed that conventional logging led to emissions equivalent to more than one third of AGB, and these logged plots were predicted to recover their aboveground carbon within 45 years (Blanc et al. 2009). Therefore, Putz and colleagues' (2008) estimate of a roughly 30% reduction in CO₂ emissions with RIL bears out. RIL logging would still generate enormous volumes of CO₂ emissions annually (Huang and Asner 2010) compared with virtually none if, instead, these steady-state or near-steady-state primary forests were protected from logging (Vieira et al. 2005, Huang and Asner 2010).

Logging-induced changes in forests architecture and composition result in a cascading set of impacts on the carbon cycling of rainforest ecosystems (Huang and Asner 2010, Matricardi et al. 2010). Logging removes large trees, which are the principal carbon stores of a tropical forest (Vieira et al. 2005). Furthermore, all logging, even at usual SFM-mandated harvest intensities, leaves behind large amounts of slash. Decomposing slash, combined with an increased mortality of residual trees, increases ecosystem heterotrophic respiration and CO₂ emissions for years following harvest (Blanc et al. 2009, Huang and Asner 2010). Increased levels of radiation beating down through logging gaps also dry out the slash. Consequently, logged forests, especially in regions that experience dry seasons, become fire prone. Just 5%–10% canopy damage, which falls within the lower range of SFM and RIL impacts, has a significant and long-lasting effect on forest phenology and the associated reduction of moisture content (Koltunov et al. 2009). Quantitative estimates of forest area burned are sporadic or nonexistent for most tropical countries, but what has been well documented is disturbing. In Southeast Asia and Latin America, more than 20 million ha of logged-over forest burned in the 1997–1998 El Niño drought year (Cochrane 2003). The emissions from tree fires alone from that year in Brazil, Indonesia, and Mexico may have equaled 41% of those from world fossil-fuel emissions (Cochrane 2003). The first major forest fires experienced by Indonesia coincided with the presence of vast areas of logged-over forest and burned about 3.2 million ha

in the previous severe El Niño year of 1982–1983 (Nawir and Rumboko 2007). Indonesia now has a serious problem with forest fire (Nawir and Rumboko 2007) because of illegal logging, and the process is also under way in the drier frontier forests of the southeastern Amazon (Matricardi et al. 2010). Selective logging catalyzes colonization and the associated use of fire. It is the synergy between the two land uses that promulgates fire in tropical forests degraded by logging (Cochrane 2003, Nawir and Rumboko 2007, Matricardi et al. 2010).

Conclusions

A large and growing body of research illuminates ever more clearly that industrial logging regimes are several hundred years out of sync with the life cycles of high-value timber trees in the tropics. It appears that we have not been able to reconcile these opposing biological and economic forces. So far, we cannot produce valuable timber from primary tropical forests in great enough quantity or with enough speed to generate financial profit over the long term.

As it is presently conceived, industrial-scale SFM guarantees the commercial and biological depletion of high-value timber species within three harvest rotations in all three major tropical forest regions. The scientific evidence in support of this conclusion is substantial and all points in one direction. Research is pointing to key components that, if they are incorporated into an SFM would increase the potential for sustainable yields of high-value tropical timber. These minimum standards combine: RIL; cutting cycles of 60 years or more; harvest intensities of less than five trees per ha and basal area removal approximately of 15% or less; logging gaps that measure no more than 500 square meters; a minimum felling diameter of 60 cm; retention of seeds trees on the basis of consideration of the specific life history (autecology) of the species under management; postlogging silviculture treatment in logging gaps that includes the enrichment planting of seedlings where future crop trees are absent, followed by intensive tending of seedlings until they reach pole size. Such a revised protocol for SFM would substantially diminish harvestable timber volume while further increasing management and training costs.

Logging leads to far worse consequences for tropical forest ecosystems than the depletion of timber species: road building, colonization, land clearing for agriculture, and large-scale forest fire threaten their destruction. This process, triggered by even low-intensity logging of high-value species, continues to engulf tropical forests around the world, and no government has yet shown much capacity to control it. Weak governance in the forest sector remains a major obstacle to implementing any form of forest management in the tropics. Law enforcement is lacking, corruption is rampant, land tenure is often not well established, and forestry codes need clarification and updating (Blaser and Sarre 2010). Although illegal logging has declined from peak levels in some countries, it continues nonetheless to be common across the tropics, generating about 100 million cubic

meters of timber per year and leading to the degradation or loss of about 5 million ha of forest annually (Lawson and MacFaul 2010). In the Brazilian Amazon, for example, where monitoring and technical capacity is particularly good and in a region already receiving significant outside support for controlling illegal deforestation and degradation, widespread illegal logging for high-value timber continues to plague forests (Blundell and Gullison 2003, Asner et al. 2006, Schulze 2008). After all, forests nationally designated for timber production require the same level of protection from deforestation and illegal activity as do other forms of protected areas in the tropics. Governance is the foundation on which any form of forest management must be built, and this foundation is lacking at the national level in the forest sector of many tropical countries. In light of the evidence that current SFM protocol is unlikely to lead to the sustainable production of high-value timber, the question arises as to whether it is reasonable to expect REDD+ investment for implementing SFM to impede the processes of tropical deforestation in regions of weak governance.

In contrast to industrial logging, many small-scale community and private landowner timber and nontimber forest-management options, often in combination with other small-scale economic alternatives, have proven to lead to the protection of reasonably intact tropical forest ecosystems while promoting sustainable livelihoods (e.g., Bray et al. 2003). The common thread of these models of successful common-pool resource management in the tropical forestry sector is governance—if only at the local or community level—but only when it is fostered by national legislation, especially the ratification of community land tenure. Correlates of the successful sustainable management of common-pool resources, such as forests, are known (Ostrom et al. 1999). The most important reason that these successful local-scale SFM models have not been scaled up to secure the world's remaining tropical forests is a lack of funding—a situation that REDD+ investment might correct. That SFM remains undefined within the UNFCCC and is biologically unsustainable under current protocols begs a reevaluation of proposals for REDD+ to subsidize widespread implementation of industrial SFM in the world's last frontier tropical forests.

Acknowledgments

We thank the reviewers of this article and the following colleagues, whose comments on earlier drafts also led to improvements in the final version of the manuscript: Andrew Howard, Celia Harvey, John Musinsky, Tim Killeen, Brendan Mackey, and Virginia Young. CFK thanks Conservation International for contributing support during the research and development of this article.

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