

Sustaining conservation values in selectively logged tropical forests: the attained and the attainable

Francis E. Putz^{1,2}, Pieter A. Zuidema^{2,3}, Timothy Synnott⁴, Marielos Peña-Claros^{3,5}, Michelle A. Pinard⁶, Douglas Sheil⁷, Jerome K. Vanclay⁸, Plinio Sist⁹, Sylvie Gourlet-Fleury⁹, Bronson Griscom¹⁰, John Palmer¹¹, & Roderick Zagt¹²

¹ Department of Biology, P.O. 118526, 209 Carr Hall, University of Florida, Gainesville, FL 32611–8526, USA

² Prince Bernhard Chair for International Nature Conservation, Utrecht University, Padualaan 8, 3584 TC Utrecht, the Netherlands

³ Forest Ecology and Forest Management Group, Centre for Ecosystem Studies, Wageningen University, PO Box 47, 6700 AA Wageningen, the Netherlands

⁴ Paseo de las Cumbres 1050, Lomas de Lourdes, 25090 Saltillo, Coahuila, México

⁵ Instituto Boliviano de Investigación Forestal (IBIF), PO Box 6204, Santa Cruz de la Sierra, Bolivia

⁶ Institute of Biological and Environmental Sciences (IBES), University of Aberdeen, St Machar Drive, Cruickshank Building, Aberdeen AB24 3UU, UK

⁷ Institute of Tropical Forest Conservation, PO Box 44, Kabale, Uganda and Center for International Forestry Research, P.O. Box 0113 BOCBD, Bogor 16000, Indonesia

⁸ School of Environmental Science and Management, Southern Cross University, PO Box 157, Lismore, NSW, Australia

⁹ CIRAD, Campus International de Baillarguet, TA C-36/D, 34398 Montpellier cedex 5, France

¹⁰ The Nature Conservancy, 320 Franklin St., Harrisonburg, VA 22801, USA

¹¹ Forest Management Trust, 2724 West Cortez St., Chicago, IL 60622–3419, USA

¹² Tropenbos International, PO Box 232, 6700 AE Wageningen, the Netherlands

Keywords

Biodiversity conservation; FLEGT; forest carbon; REDD; sustainable forest management; tropical forestry; tropical silviculture.

Correspondence

Francis E. Putz, Department of Biology, P.O. 118526, 209 Carr Hall, University of Florida, Gainesville, FL 32611–8526, USA.

Tel.: 1–352-392-1486; fax: 1–352-392-3701.

e-mail: fep@ufl.edu

Received

16 August 2011

Accepted

23 March 2012

Editor

Dr. Belinda Reyers

doi: 10.1111/j.1755-263X.2012.00242.x

Abstract

Most tropical forests outside protected areas have been or will be selectively logged so it is essential to maximize the conservation values of partially harvested areas. Here we examine the extent to which these forests sustain timber production, retain species, and conserve carbon stocks. We then describe some improvements in tropical forestry and how their implementation can be promoted.

A simple meta-analysis based on >100 publications revealed substantial variability but that: timber yields decline by about 46% after the first harvest but are subsequently sustained at that level; 76% of carbon is retained in once-logged forests; and, 85–100% of species of mammals, birds, invertebrates, and plants remain after logging. Timber stocks will not regain primary-forest levels within current harvest cycles, but yields increase if collateral damage is reduced and silvicultural treatments are applied.

Given that selectively logged forests retain substantial biodiversity, carbon, and timber stocks, this “middle way” between deforestation and total protection deserves more attention from researchers, conservation organizations, and policy-makers. Improvements in forest management are now likely if synergies are enhanced among initiatives to retain forest carbon stocks (REDD+), assure the legality of forest products, certify responsible management, and devolve control over forests to empowered local communities.

Introduction

Strict protection of purportedly pristine forests will likely remain a conservation priority in the tropics (e.g., Sodhi *et al.* 2009; Gibson *et al.* 2011), but the values of other

sorts of forests are increasingly being recognized (e.g., Ghazoul & Sheil 2010). Increased recognition that the posited dichotomy between primary and modified habitats is artificial and often obstructive (Miller *et al.* 2010; Sheil & Meijaard 2010) has led to increased attention

to the environmental values of secondary and selectively logged forest (e.g., Chazdon *et al.* 2009; Berry *et al.* 2010; Edwards *et al.* 2011; Gibson *et al.* 2011). Here we evaluate timber production and the conservation values of selectively logged tropical forests and discuss how these values can be enhanced. This focus seems justified given that tropical forests are logged at about 20 times the rate at which they are cleared (Asner *et al.* 2009) and that 403 million hectares of tropical forest are officially designated for timber production (Blaser *et al.* 2011). Furthermore, because selectively logged forests are classified as “degraded,” they are very susceptible to conversion to nonforest land uses (e.g., Xingli *et al.* 2011).

We performed a simple meta-analysis to assess the extent to which selectively logged tropical forests retain their productive potential for timber, carbon stocks, and species richness. Based on this meta-analysis we argue for the distinction between exploitative timber extraction and responsible forest management. With this distinction recognized, attention can focus on improving forest management practices through enhancing synergies between initiatives to improve national and international forest governance (e.g., demand-side legality assurance legislation), market-based initiatives (e.g., forest product certification and crediting for reduced greenhouse gas emissions), and devolution of control over forests to empowered local communities.

The attained: conservation values and timber productive potentials of selectively logged tropical forests

In our unweighted meta-analysis we used 59 studies from lowland tropical forests in 10 countries on three continents that reported on timber production from selectively harvested forests (Tables S1 and S2). These studies used a variety of simulation models calibrated with measured rates of tree growth, mortality, and recruitment to predict commercial timber volume increments over government-mandated minimum harvest cycles of 20–40 years starting with old-growth (= primary) forest. Logging intensities in the studied forests varied by more than two orders-of-magnitude (1–220 m³/ha) and the periods of post-logging monitoring of stand dynamics were always less than a single harvest cycle. Landscape-level and long-term impacts of repeated logging were not addressed in the studies reviewed, and few provide the information needed to compare harvesting practices. Nevertheless, given the allowed presence of researchers, we suspect that there was a bias toward better-run logging operations.

Critical assessments of the sustainability of timber production require clarity about what is to be sustained. Here we accept that the number of harvested species increases over time with enhanced marketability but do not accept reductions in minimum harvest diameters. With these assumptions, our meta-analysis revealed that, on average, just over 54% of the timber volume extracted during the first harvest from primary forest will be available for the second and third cuts (Table S2; Figure 1). In contrast, if only the same species continue to be harvested, only 35% of the original timber stock will be available for the second cut and yields will likely decline thereafter (Table S1). It is important to emphasize that the among-study variation in volume recovery rates is huge (range = 0–220%; Tables S1 and S2), presumably because of differences in logging intensities and techniques, as well as ecological differences among the commercial species. Despite this variation, average volume recovery was significantly below 100% (one-sample *t*-tests, Table S5). To our surprise, we did not find any published studies on timber recovery from the same tree species from tropical Asia, the region harboring the most important timber-yielding tree species. Studies on African timber species were also scarce. In view of the importance of international sales of tropical timber (Kastner *et al.* 2011) and the attention given to sustainable forest management over the past 20 years, it is remarkable that information on timber recovery has been published for only 27 tree species.

Considering the impacts of selective timber extraction on carbon stocks, the 22 studies we found suggested that, soon after logging, once-harvested stands retain about 76% of their above-ground live carbon (Figure 1). The high variation in carbon retention (47–97%) reflects the range in harvest intensities and undoubtedly also the care with which harvests were performed (Table S3). In the five cases in which logging was carried out by trained and supervised crews working with the aid of detailed harvest plans, substantially more biomass was retained through the first harvest than in matched areas that were conventionally logged (Pinard & Putz 1996; Bryan *et al.* 2010; Medjibe *et al.* 2011; Miller *et al.* 2011; Medjibe 2012;). After logging in at least some forests, carbon recovery rates can be extremely rapid if harvests are performed with care (Pinard 2009).

Assessments of the impacts of logging on biodiversity are more complicated than those on timber yields or carbon stocks. Published studies vary in whether they focus on changes in species richness, species composition, or of particular taxa. Variation in temporal and spatial scales further complicates comparisons. For example, biodiversity impacts on obligate forest understory species soon after intensive logging are likely to be more severe than

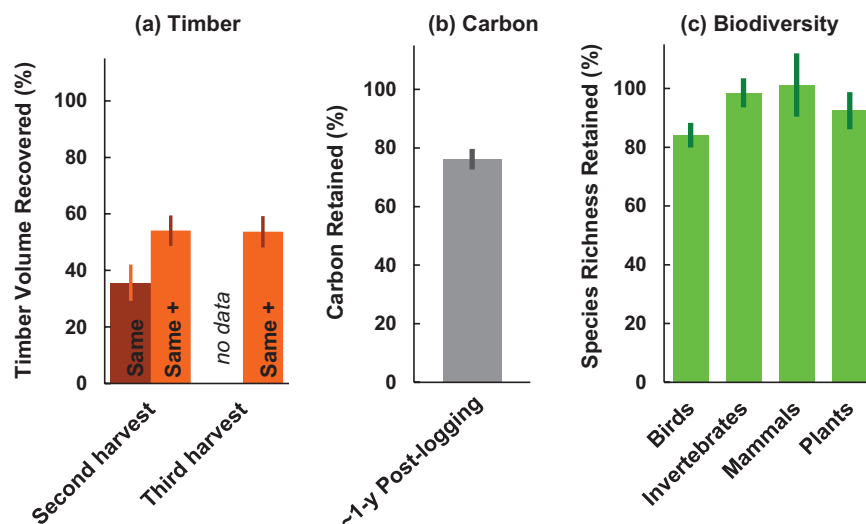


Figure 1 What is sustained in logged tropical forests? Three elements of sustainability based on simple meta-analyses of studies that reported: (a) merchantable timber volumes after one or two government-specified cutting cycles of 20–40 years each if the same tree species is harvested (“Same”) or additional species are harvested (“Same+”); (b) carbon in living

tree biomass approximately one year after selective logging; (c) species richness of birds, invertebrates, mammals, and plants in selectively logged forests compared to undisturbed old-growth forests. Means and standard errors in a, b and c are based on 59, 22, and 109 studies, respectively (see Supplemental Tables in Supporting Information for data and sources).

the longer term impacts of low-intensity logging on a wide variety of taxa averaged over large spatial scales that include enclaves of un-harvested forest. Also, disturbance often allows generalist species to enter closed forests where they were previously absent, thus increasing local diversity (Bongers *et al.* 2009). These limitations notwithstanding, a meta-analysis based on 109 studies of selective logging of primary tropical forest carried out 1–100 years after a single harvest (Table S4) revealed modest impacts on species richness of birds, mammals, invertebrates, and plants (Figure 1). Birds represented the most severely affected of the groups studied; selectively logged forests supported, on average, only 84% of the species richness of unlogged forest ($P < 0.001$; Table S5). For plants, mammals, and invertebrates, average species richness of harvested and not-yet harvested forests did not differ significantly. These results are in agreement with those of Gibson *et al.* (2011), who reported only slightly reduced biodiversity in selectively logged forests. Remarkably, reports from Borneo suggest substantial biodiversity retention after extremely intensive exploitative logging (Cannon *et al.* 1998; Edwards *et al.* 2011) as well as after heavy logging followed by strip planting with native timber species (Ansell *et al.* 2011). These overall favorable results are especially impressive given that few studies were conducted in forests with third-party certification for good management (van Kuijk *et al.* 2009),

which suggests that further improvements are possible (Meijaard *et al.* 2005).

In addition to noting the substantial variability in the results of the studies we reviewed, we recognize that species richness data cannot reveal changes in species composition. Furthermore, the mostly near-term effect studies we reviewed cannot account for the possibility of longer-term species losses (i.e., extinction debts). In regard to changes in species composition in response to logging, we note that because of differences in harvest intensities and techniques as well as changes in the harvested tree species, the reported impacts on disturbance-sensitive, rare, or otherwise noteworthy species are mixed (Putz *et al.* 2001; Meijaard *et al.* 2005; Fisher *et al.* 2011a; Nasi *et al.* 2012). We also note that populations of old-growth species are more likely to rebound than to decline with time after a selective harvest as long as hunting and fire are excluded (Poulsen & Clark 2010) and premature reentry logging is prohibited. We base this hopeful prediction on the observation that biodiversity research is typically carried out soon after logging in the areas most heavily affected and not in the substantial areas that are regenerating after previous harvests. Also disregarded are forest patches within designated cutting blocks that remain unscathed because of lack of harvestable timber or restrictions on harvesting near rivers, on steep slopes, or in designated high conservation value areas.

The attainable: improving conservation values and timber yields in managed tropical forests

Decreases in timber yields after the first harvest from old-growth forests seem inevitable. For selectively logged forests to regain during 20–40 years harvest cycles the volumes of timber accumulated over the preceding centuries, forest management practices would need substantial modification. In particular, harvest intensities would need to be reduced, which would reduce profits, and post-logging silvicultural treatments would need to be applied, which carries some financial as well as environmental costs. In the interest of retaining the many other values of managed forests, we recommend acceptance of a “primary forest premium,” with subsequent yields sustained at an agreed upon lower level.

Although seldom recognized outside of forestry circles, the notion of a primary forest premium is not new; 100 years ago Gifford Pinchot (1910) accepted a downward adjustment of yield expectations after enjoyment of what he termed “nature’s bounty.” The allowable magnitude of the primary forest premium should reflect both biophysical capacities of forests and land-use objectives, but could be substantially higher than the 46% observed with current management practices. Alternatively, sustained yields in the sense of fixed annual or periodic yields of the same quantities, qualities, sizes, or species might not be required. Instead, the focus could be on the use of production systems and harvesting practices that are compatible with the stated, long-term, multiple objectives of management, and do not adversely affect the productive capacity of the site or impair species survival.

Including more species in estimates of future timber stocking may seem like unwarranted lowering of expectations, but over time and with dwindling supplies, mills typically accept smaller and lower quality logs of a wider variety of species (Aplet *et al.* 1993). Nevertheless, sequential depletion of species remains a concern that can be mitigated through application of silvicultural treatments designed to augment the regeneration and growth of the most valuable species. On the other hand, some changes in species composition are an inevitable consequence of even gentle management of tropical production forests.

One straightforward way to sustain timber yields is to lower the frequency of timber harvests (Sist *et al.* 2003). At least if no silvicultural treatments are applied to increase tree growth rates, cutting cycles would generally need to be lengthened to 50–100 years for full recovery of timber stocks (Kammesheidt *et al.* 2001; Brienens & Zuidema 2007). Both the carbon and biodiversity benefits of reduced frequencies of disturbance would likely

be substantial, but with any positive discount rate, the financial costs of such delays can be large. Unfortunately, although often not noticed or reported, the trend is more often in the opposite direction toward premature reentry logging, which makes financial sense but is detrimental to future timber yields, carbon stocks, and biodiversity.

Reduced harvest intensities would help sustain timber harvests, retain carbon, and maintain preintervention forest structure and composition, but not without financial and other costs. Intensities can be lowered by capping harvest volumes, increasing the minimum allowable diameters, or increasing the minimum distances between harvested trees. Of course reducing harvest intensities will impede regeneration of the light-demanding trees species that dominate the tropical timber trade (Fredericksen & Putz 2003). Alternatively, low landscape-level logging intensities can be secured by allowing high logging intensities in some stands to promote regeneration of light-demanding species, but with corresponding increases in areas set aside from logging. In any case, we support the protection of very large trees because of their disproportionately large contributions of food, seeds, and habitat (Sist *et al.* 2003). Though at first sight this appears to sacrifice major timber revenues, many huge trees are hollow or harbor heartrots, and can be difficult to fell and process.

Future timber yields, carbon stocks and recovery rates, and biodiversity retention all increase if collateral damage during harvesting is reduced. Guidelines for reduced-impact logging (RIL) have been available for several decades and such measures are included in the criteria used by most forest certification schemes (Putz *et al.* 2008a). When these practices are properly implemented, damage to remaining trees and soils are substantially reduced (Putz *et al.* 2008b). Use of RIL practices also reduces carbon emissions, but supporting data are scarce and difficult to interpret because of differences in logging intensities (Table S3). In regard to the likely biodiversity benefits of RIL, the sole publication we found (Davis 2000) supports this expectation.

After timber extraction, future timber yields and carbon stock recovery can be enhanced by silvicultural treatments. As has been long known (e.g., Wyatt-Smith *et al.* 1964) and confirmed recently (Villegas *et al.* 2009), freeing future crop trees from vines and other competitors can increase their growth rates substantially. Given that most of the carbon in tropical forests is in the boles of large trees, these timber volume benefits translate directly into carbon benefits. In regard to biodiversity, even intensive restoration interventions applied in forests severely degraded by very intensive uncontrolled logging reportedly result in few deleterious impacts (Edwards *et al.* 2009; Ansell *et al.* 2011). Overall, we need to be aware

of the tradeoffs involved in trying to maximize timber yields, carbon storage, and biodiversity retention.

Improved prospects for sustainable forest management

Although tropical forest management practices have improved (Blaser *et al.* 2011), past efforts at reforming tropical forestry fell short of their objectives basically because management for long-term timber production is seldom the most lucrative land-use option (Rice *et al.* 1997). Instead, the most financially profitable option is to extract all the profit-generating timber as rapidly as possible and then either abandon the area or convert it to soybean fields, oil palm or pulpwood plantations, or cattle ranches (Pearce *et al.* 2002; Fisher *et al.* 2011b; Ruslandi *et al.* 2011; Persson 2012). Even in production forests, requirements to leave marketable trees standing or to delay their harvest incur major opportunity costs and are unlikely to be accepted without sufficient incentives coupled with adequate enforcement (Palmer & Bulkan 2010).

With their high biodiversity, carbon, and other environmental values, well-managed tropical forests represent a “middle way” between deforestation and total forest protection. Once environmentalists, civil society, governments, and markets recognize the many benefits of responsible tropical forest management and it is more widely incorporated into diverse portfolios of conservation strategies, the four complementary political, economic, environmental, and social initiatives mentioned below should be marshaled to promote improvements. These initiatives have natural synergies that need to be explored to enhance biodiversity protection, climate mitigation, timber supplies, and rural livelihoods.

- (1) Assurance of the legality of forests products through initiatives such as the European Union’s due Diligence Regulation and its linked Forest Law Enforcement, Governance and Trade Voluntary Partnership Agreements (www.euflegt.efu.int), as well as the 2008 Amendment of the Lacey Act in the USA (www.forestlegality.org), will serve to increase market prices and access for legally produced timber while promoting more responsible forest management. Given that these regulations apply to the entire market chain from forest to consumer, even wood products processed in countries less scrupulous about their sources will need to carry assurances of legality if they are to be traded in markets in Europe and the USA. Such assurances are critical because, despite increasing scarcity of tropical forests, tropical timber prices have increased little in real terms over the past decades (<http://www.itto.int/mis>). This
- global market failure is greatly exacerbated by competition from illegally harvested wood (Seneca Creek Associates 2004; Lawson & MacFaul 2010).
- (2) Voluntary third-party certification promotes responsible management by securing or even increasing market access and prices for forest products (Auld *et al.* 2008). The financial benefits of certification should be enhanced to render this mechanism more effective at stimulating improvements in tropical forest management. Benefits can be increased by reducing certification costs through market and regulatory mechanisms. For example, certification might substitute for costly governmental regulation (e.g., Nittler & Nash 1999) or certified firms might be given preference in the allocation of new concessions (Blundell *et al.* 2011). Independent and critical evaluations of the biodiversity and carbon benefits of certification are now needed so that synergies with initiatives designed to enhance the retention of these values can be realized in cost-effective manners (van Kuijk *et al.* 2009).
- (3) The substantial carbon benefits from improvements in tropical forest management should be recognized and paid for by climate change mitigation programs designed to reduce emissions from deforestation and forest degradation and to enhance forest carbon stocks (REDD+; Angelsen *et al.* 2009). Improved forest management, as one land use included in systematic conservation planning (e.g., Wilson *et al.* 2010), figures prominently in REDD+ plans, both in voluntary schemes and as part of the new climate treaty being negotiated (Diaz *et al.* 2011). Where REDD+ payments are used to improve rather than halt timber harvesting, the costs of maintaining forest cover are reduced relative to strict protection and there is less risk of activity-shifting leakage due to loggers going elsewhere to harvest timber. Further advantages of using performance-based REDD+ payments to improve management derive from the fact that the forests must remain standing for the carbon contract’s duration. These managed forests provide streams of social, economic, and environmental benefits while being more resistant to fire and resilient to climate change than conventionally logged forest.
- (4) Devolution of control over forests to indigenous and other rural communities together with other efforts to clarify forest tenure can serve the goals of improved tropical forest management as it reduces the likelihood of deforestation and contributes to human welfare (e.g., Chhatre & Agrawal 2008). But given the many challenges involved in running a forest industry, communities with decision-making authority should be provided long-term support on

the full spectrum of activities from business practices and marketing to road engineering and tree felling. Often it is best to employ any of a variety of company–community partnerships, with which experience is accumulating (Vermeulen *et al.* 2008). But whatever form community participation takes, it should be with free, prior, and informed consent.

The “conservation through use” issue is politically charged and sustainability—a key point of reference—remains poorly defined. Financial losses and other trade-offs among the goods and services to be sustained in managed tropical forests need to be understood and minimized. Rather than expecting timber yields from managed tropical forests to be sustained without any changes in species or log size and quality, emphasis should be on assuring that production forests remain standing in the best condition possible. To the extent that growing volumes of merchantable timber increase the value of forests and thereby decrease the likelihood of conversion, maintaining timber stocks should remain a priority. But even where sustaining timber yield is not the principal goal of management, it can serve as one indicator of the continued provision of other forest goods and services including carbon and biodiversity. And while it is possible to restore the capacities of forests to store carbon, produce timber, and support biodiversity after unnecessarily destructive logging, it is better to avoid degradation in the first place through responsible forest management.

Substantial and extensive improvements in tropical forest management are now more likely than ever if synergies can be secured between the naturally complementary efforts to control illegal logging, certify well-managed forests, maintain and enhance carbon stocks, and devolve rights and management responsibilities to local communities. One straightforward example that is already operational to some degree involves forest assessment teams that simultaneously audit for management certification, legality assurance, biodiversity impacts, and carbon emissions. The collaboration of rural communities in these assessments (e.g., Skutsch 2010) will strengthen the fourth pillar of responsible forest management. But even with these synergies fully developed, great care is warranted to avoid the pitfalls encountered by other interventions designed to reform tropical forestry such as the Tropical Forestry Action Plan (Pfaff *et al.* 2010).

Supporting Information

Additional Supporting Information may be found in the online version of this article, including Supplementary Methods and References.

Table S1: Results of a meta-analysis of studies predicting timber volume recuperation after selective logging of tropical forests for cases in which the same species is harvested

Table S2: Results of a meta-analysis of studies predicting timber volume recuperation after selective logging of tropical forests for cases in which a changing set of species is harvested

Table S3: Results of a meta-analysis of studies reporting retention of carbon stocks in aboveground biomass after selective logging of tropical forests

Table S4: Results of a meta-analysis of studies reporting retention of species richness (i.e., species density) of birds, invertebrates, mammals, and plants in selectively logged tropical forests or after selective logging

Table S5: Results of statistical tests for retention of timber, carbon and species richness in selectively logged forests. Variables as in Tables S1–S4

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

References

- Angelsen, A., editor. (2009) *Realising REDD+: national strategy and policy options*. Center for International Forestry Research, Bogor, Indonesia.
- Ansell, F.A., Edwards, D.P & Hamer, K.C. (2011). Rehabilitation of logged rainforests: avifaunal composition, habitat structure, and implications for biodiversity-friendly REDD+. *Biotropica*, **43**, 504–511.
- Aplet, G.H., Johnson, N., Olson, J.T. *et al.* (1993) *Defining sustainable forestry*. Island Press, Washington, D.C.
- Asner, G.P., Rudel, T.K., Aide, T.M., Defries, R. & Emerson, R.E. (2009) A contemporary assessment of change in humid tropical forests. *Conserv. Biol.*, **23**, 1386–1395.
- Auld, G.L., Gulbrandsen, L.H., & McDermott, C.L. (2008) Certification schemes and the impacts on forests and forestry. *Ann. Rev. Environ. Res.*, **33**, 187–211.
- Berry, N.J., Phillips, O.L., Lewis, S.L. *et al.* (2010) The high value of logged tropical forests: lessons from northern Borneo. *Biodivers. Conserv.*, **19**, 985–997.
- Blaser, J., Sarre, A., Poore, D. *et al.* (2011) Status of tropical forest management 2011. ITTO Technical Series **38**, International Tropical Timber Organization, Yokohama, Japan.
- Blundell, A.G., Thirathon, A., Flaming, B. *et al.* (2011) The Responsible Asia Forestry and Trade (RAFT) Alliance: final program evaluation. U.S. Agency for International Development, Washington, D.C. Available from:

- http://pdf.usaid.gov/pdf/pdf_docs/PDACS537.pdf. Accessed 20 April 2012
- Bongers, F., Poorter, L., Hawthorne, D. *et al.* (2009) The intermediate disturbance hypothesis applies to tropical forests, but disturbance contributes little to tree diversity. *Ecol. Lett.*, **12**, 798–805.
- Brienen, R.J.W. & Zuidema, P.A. (2007) Incorporating persistent tree growth differences increases estimates of tropical timber yield. *Front Ecol. Environ.*, **5**, 302–306.
- Bryan, J., Shearman, P., Ash, J. *et al.* (2010) Impact of logging on aboveground biomass stocks in lowland rain forest, Papua New Guinea. *Ecol. Appl.*, **20**, 2096–2103.
- Cannon, C.H., Peart, D.R. & Leighton, M. (1998) Tree species diversity in commercially logged Bornean rainforest. *Science*, **281**, 1366–1368.
- Chazdon, R.L., Peres, C.A., Dent, D. *et al.* (2009) The potential for species conservation in tropical secondary forests. *Conserv. Biol.*, **23**, 1406–1417.
- Chhatre, A. & Agrawal, A. (2008) Forest commons and local enforcement. *Proc. Nat. Acad. Sci. USA*, **105**, 13286–13291.
- Davis, A.J. (2000) Does reduced-impact logging help preserve biodiversity in tropical rainforests? A case study from Borneo using dung beetles (Coleoptera: Scarabaeoidea) as indicators. *Environ. Entomol.*, **29**, 467–475.
- Diaz, D., Hamilton, K. & Johnson, E. (2011) *State of the forest carbon markets 2011*. Forest Trends/Ecosystem Marketplace, 70 pp.
- Edwards, D.P., Ansell, F.A., Ahmad, A.H. *et al.* (2009) The value of rehabilitating logged rainforest for birds. *Conserv. Biol.*, **23**, 1628–1633.
- Edwards, D.P., Larsen, T.H., Docherty, T.D.S. *et al.* (2011) Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proc. Biol. Sci.*, **278**, 82–90.
- Fisher, B., Edwards, D.P., Giam, X. *et al.* (2011a) The high costs of conserving Southeast Asia's lowland rainforests. *Front. Ecol. Environ.*, **9**, 329–334.
- Fisher, B., Edwards, D.P., Larsen, T.H. *et al.* (2011b) Cost-effective conservation: calculating biodiversity and logging trade-offs in Southeast Asia. *Conserv. Lett.*, **4**, 443–450.
- Fredericksen, T.S. & Putz, F.E. (2003) Silvicultural intensification for tropical forest conservation. *Biodivers. Conserv.*, **12**, 1445–1453.
- Ghazoul, J. & Sheil, D. (2010) *Tropical rain forest ecology, diversity, and conservation*. Oxford University Press, Oxford, UK.
- Gibson, L., Tien, M.L., Lian, P.K. *et al.* (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, **478**, 378–381.
- Kammesheidt, L., Kohler, P. & Huth, A. (2001) Sustainable timber harvesting in Venezuela: a modelling approach. *J. Appl. Ecol.*, **38**, 756–770.
- Kastner, T., Erb, K.-H. & Nonhebel, S. (2011) International wood trade and forest change: a global analysis. *Global Environ. Change*, **21**, 947–956.
- Lawson, S. & MacFaul, L. (2010) *Illegal logging and related trade*. Chatham House, London.
- Medjibe, V.P. (2012) *Carbon dynamics in Central African forests management for timber*. Ph.D. Dissertation. University of Florida, Gainesville, FL.
- Medjibe, V.P., Starkey, M., Ndouna, A.A. *et al.* (2011) Impacts of timber extraction on above-ground forest biomass on Monts de Cristal in Gabon. *For. Ecol. Manage.*, **262**, 1799–1806.
- Meijaard, E., Sheil, D., Nasi, R. *et al.* (2005) *Life after logging*. Center for International Forestry Research, Bogor, Indonesia.
- Miller, K.A., Meijaard, E., Drummond, S. *et al.* (2010) Conserving biodiversity in production landscapes. *Ecol. Appl.*, **20**, 1721–1732.
- Miller, S.D., Goulden, M.L., Hutrya, L.R. *et al.* (2011) Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. *Proc. Natl. Acad. Sci. USA*, **108**, 19431–19435.
- Nasi, R., Billand, A. & Vanvliet, N. (2012) Managing for timber and biodiversity in the Amazon Basin. *For. Ecol. Manage.*, **268**, 103–111.
- Nittler, J.B. & Nash, D.W. (1999) The certification model for forestry in Bolivia. *J. For.*, **97**, 32–36.
- Palmer, J. & Bulkan, J. (2010) Legitimacy of public domain forest taxation, and combating corruption in forestry. *Int. For. Rev.*, **12**, 150–164.
- Pearce, D., Putz, F.E. & Vanclay, J. (2002) Sustainable forestry: panacea or pipedream? *For. Ecol. Manage.*, **172**, 229–247.
- Persson, U.M. (2012) Conserve or convert? Pan-tropical modeling of REDD-bioenergy competition. *Biol. Conserv.*, **146**, 81–88.
- Pfaff, A., Sills, E.O. & Amacher, G.S. (2010) *Policy impacts on deforestation: lessons learned from past experience to inform new initiatives*. Nicholas Institute, Duke University, Durham, North Carolina.
- Pinard, M. (2009) Carbon-neutral logging in a Malaysian rainforest: reduced collateral damage fosters rapid recovery. Pages 256 in A. Angelsen, editor. *Realising REDD+: national strategy and policy options*. Center for International Forestry Research, Bogor, Indonesia.
- Pinard, M.A. & Putz, F.E. (1996) Retaining forest biomass by reducing logging damage. *Biotropica*, **28**, 278–295.
- Pinchot, G. (1910) *The fight for conservation*. Harcourt Brace, New York.
- Poulsen, J.R. & Clark, C.J. (2010) Congo Basin timber certification and biodiversity conservation. *Eur. Trop. For. Res. Network*, **51**, 55–60.
- Putz, F.E., Blate, G.M., Redford, K.H. *et al.* (2001) Biodiversity conservation in the context of tropical forest management. *Conserv. Biol.*, **15**, 357–385.

- Putz, F.E., Sist, P., Fredericksen, T.S. *et al.* (2008a) Reduced-impact logging: challenges and opportunities. *For. Ecol. Manage.*, **256**, 1427–1433.
- Putz, F.E., Zuidema, P.A., Pinard, M.A. *et al.* (2008b) Tropical forest management for carbon retention. *PLoS Biol.*, **6**, 1368–1369.
- Rice, R., Gullison, R.E. & Reid, J.W. (1997) Can sustainable management save tropical forests? *Sci. Am.*, **276**, 44–49.
- Ruslandi, Venter, O. & Putz, F.E. (2011) Over-estimating the costs of conservation in Southeast Asia. *Front Ecol. Environ.*, **9**, 542–544.
- Seneca Creek Associates and Wood Resources International (2004) Illegal logging and global wood markets: the competitive impacts on the US wood products market. Available from: <http://www.illegal-logging.info/uploads/afandpa.pdf>. Accessed 18 January 2012.
- Sheil, D. & Meijaard, E. (2010) Purity and prejudice: deluding ourselves about biodiversity conservation. *Biotropica*, **42**, 566–568.
- Sist, P., Sheil, D., Kartawinata, K. *et al.* (2003) Reduced-impact logging and high extraction rates in mixed dipterocarp forests of Borneo: the need for new silvicultural prescriptions. *For. Ecol. Manage.*, **179**, 415–427.
- Skutsch, M., editor. 2010 *Community forest monitoring for the carbon market: opportunities under REDD*. Earthscan, London, UK.
- Sodhi, N.S., Tien, M.L., Lian, P.K. *et al.* (2009) A meta-analysis of the impact of anthropogenic forest disturbance on Southeast Asia's biotas. *Biotropica*, **41**, 103–109.
- van Kuijk, M., Putz, F.E. & Zagt, R.J. (2009) *Effects of forest certification on biodiversity*. Tropenbos International, Wageningen, the Netherlands.
- Vermeulen, S., Nawir, A.A. & Mayers, J. (2008) Rural poverty reduction through business partnerships? Examples of experience from the forestry sector. *Environ. Dev. Sustain.*, **10**, 1–18.
- Villegas, Z., Peña-Claros, M., Mostacedo, B. *et al.* (2009) Silviculture treatments enhance growth rates of future crop trees in a tropical dry forest. *For. Ecol. Manage.*, **258**, 971–977.
- Wyatt-Smith, J., Panton, W.P. & Mitchell, B.A. (1964) Manual of Malayan silviculture for inland forest. *Malayan Forest Record*, **23**, Kuala Lumpur, Malaysia.
- Xingli, G., Clements, G.R., Aziz, S.A. *et al.* (2011) Rethinking the 'back to wilderness' concept for Sundaland's forests. *Biol. Conserv.*, **144**, 3149–3152.