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ELIASCH REVIEW: FOREST MANAGEMENT IMPACTS ON ECOSYSTEM SERVICES

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EXECUTIVE SUMMARY

General description

This report provides an overview of the direct impacts of different forest management models on carbon and non-carbon environmental ecosystem services, with a primary focus of tropical forest types.

Assumptions, challenges and limitations

There are considerable challenges when comparing the impacts of different forest management practices on ecosystem services. These include the availability of primary research, the diversity of research goals, and the development of sensible and objective means of comparison. Some aspects of ecosystem services are well covered in the published literature, while others receive little or no treatment. For example, the impact of logging on biodiversity is a topic of much research, while the influence of logging on hydrological processes is typically sparse. Once the evidence base had been assembled, comparisons were then hindered by the diversity of variables, including geography/topography, biota, and regional climate. The number of side-by-side comparisons of forest management practices was exceedingly small. Because of these constraints, the best means of comparing impacts across geographies and time scales was to develop relative rankings of impacts.

Main findings

Carbon: Primary forests in tropical regions represent one of the greatest stores of carbon in the world. All of the forest management practices reviewed are likely to cause significant releases of carbon to the atmosphere, as biomass, soil and decomposing litter are disturbed. As the forest regenerates, carbon is sequestered at a steady rate as biomass. However, carbon in biomass may represent only 30-40 percent of the total carbon in a tropical forest system. Soil carbon can represent 40-50 percent of the total carbon stored in an undisturbed tropical forest system and is located in the top 5-10 centimetres of the soil. The initial loss of soil organic carbon can be as high as 3-5 percent of the total ecosystem carbon store, and the rate of loss can sometimes remain elevated for 5-30 years, depending on the amount of human intervention. Even after 30 years, soil carbon sequestration rates might only just replace soil carbon losses from erosion. It must be noted that soils from the various tropical forest regions will respond differently to similar stresses, consequently direct comparison between studies and forest management practices remain problematic.

Biodiversity: Primary forests in tropical regions represent some of the greatest concentrations of species diversity in the world. The complex structure of primary forest vegetation produces a wide array of temporal and spatial habitat niches. The forest management practices that simplify this complex structure will typically reduce species diversity and population densities. Immediately following their application, it is common to see an initial increase in diversity and abundance of exotic species in an area. The presence of these invaders is often short-lived in small-scale applications. Forest management practices applied at larger scales enable exotic species to persist for longer and can cause changes in species assemblages. Some groups of species, such as bats, insects and some birds, are positively affected or unaffected by forest management, while other groups are negatively affected in the short-term and can return to pre-disturbance levels of diversity and population density. Still other groups, such as forest-obligate species, may dramatically decline or become locally extinct.

Hydrology: Some of the longest lasting impacts of forest management practices are on the hydrological functioning of tropical forests. Alterations to the forest canopy will impact microclimates and increase ambient temperatures and water infiltrability. Timber harvesting has clearly demonstrable negative impacts on soil compaction and erosion, at least in the short-term, and longer lasting impacts on soil moisture and surface runoff. It is not known, however, how long these impacts will persist or their relationship with logging intensity.

Conclusions

The most severely negative forest management practices tend to be those that have the most dramatic impacts on vegetation structure, such as clear-cutting and plantations. They exhibit negative to very negative impacts on carbon storage (particularly soil carbon), biodiversity, hydrology and other ecosystem services. Less detrimental forest management practices are those that reduce the areal extent or intensity of alterations to vegetation structure, including shifting agriculture and selection cutting whose impacts range from neutral to negative.

The practices that minimally disturb, replace or maintain the original structure of tropical forests tend to be those that are most likely to be sustainable in the long-term. Examples include agro forestry, reduced impact logging, conservation and regeneration/rehabilitation; these range in their impacts from negative to positive. However, the long-term sustainability of these activities will depend heavily on forest planning, monitoring and adaptive management strategies to ensure the successful maintenance of the ecosystem services that human cultures depend on.

1 INTRODUCTION

1.1 Background

Forests provide many ecosystem services ranging from biological refugia to water regulation. They also have an important role in the carbon cycle and hence climate change. The Eliasch Review is reporting on this role of global forests in tackling climate change and requires an assessment of the mitigation potential of different management models and their impact on other environmental ecosystems services.

1.2 Objective

This report provides an overview of the direct impacts of different forest management models on carbon and non-carbon environmental ecosystem services, with a primary focus of tropical forest types.

1.3 Occurrence of tropical forests

The FAO's ecological zones contain several categories of tropical forest, including tropical rain forests, tropical moist deciduous forests, tropical dry forests and tropical mountain systems. Their global distribution includes equatorial and sub-equatorial regions of Central and South America, Africa, and Asia. The availability of data on forest management practices across all four tropical forest categories is insufficient to permit meaningful comparisons to be made. Therefore, the review focuses on tropical rain forests and tropical moist deciduous forests, for which good data are available.

1.4 Ecosystem services provided by tropical forests

The ecosystem services provided by tropical forests are highly varied and exert tremendous influences on climate, landscape, and human populations and cultures. Tropical forests are known to contain 50-90% of the world's species (WRI, 1992) and some of the highest concentrations of biomass in any of the world's ecosystems. The Millennium Ecosystem Assessment (2005) describes four broad categories of services provided by ecosystems: support, provision, regulation and cultural. These are sub-divided into 15 sub-categories that include such diverse elements as nutrient cycling, climate regulation and recreational opportunities. The sub-categories can be split still further into more than 100 specific services. This report focuses on three specific ecosystem services: carbon storage and sequestration, biodiversity, and hydrological functioning. It will further identify other ecosystem services where appropriate.

1.5 Structure of report

There are considerable challenges when comparing the impacts of different forest management practices on ecosystem services. These include the availability of primary research, the diversity of research goals, and the development of sensible and objective means of comparison. Some aspects of ecosystem services are well covered in published literature, while others receive little or no treatment. For example, the impact of logging on biodiversity is a topic of much research, while the influence of logging on hydrological processes is typically sparse. Once the evidence base had been assembled, comparisons were then hindered by the diversity of variables, including geography/topography, biota, and regional climate. The number of side-by-side comparisons of forest management practices was exceedingly small. Because of these constraints, the best means of comparing impacts across geographies and time scales was to develop relative rankings of impacts. The rankings are described later in the report.

The report is organised according to the predominant impacts of forest management practices on ecosystem services. Section 2.0 reviews the main forest management practices occurring in tropical forests, what they entail and where they take place. Section 3.0 reviews evidence of impacts on carbon storage and sequestration rates. Section 4.0 evaluates recent research into the impacts on biodiversity, hydrology and other ecosystem services. Section 5.0 synthesises the findings from sections 2.0-4.0 and characterises the range and magnitude of impacts on ecosystem services. Supporting information is contained in the annexes.

2 FOREST MANAGEMENT MODELS

A variety of forest management systems are utilised throughout the tropics and a general definition for each is given below. Statistics on logging intensities are not available, so it is not possible to quantify the extent of harvesting operations in tropical forests. The amounts of land under other forest management practices are given in Table 1 below.

Conservation: The designation of forest and other wooded areas for the conservation of biodiversity and ecosystems is a key mechanism for mitigating deforestation. Forest conservation management is focussed on, but not restricted to, species and habitats in legally protected areas (FRA, 2000).

Harvesting, selection cutting and reduced impact logging: Harvesting practices are driven by social, economic and environmental objectives in a given area and range from complete removal of all trees (clear-cutting) to the removal of selected trees according to their economic, environmental or ecological effects (selection cutting/reduced impact logging). Selection cutting removes a proportion of trees in a stand to protect forest soils, maintain and improve wildlife habitat, and increase forest productivity and species diversity. It may also include opening up areas to allow tree species that require greater light intensity to grow (Nyland 1998).

Selective logging systems can be subdivided into two categories: mechanised systems and semi-mechanised systems. Tractor-based mechanized systems are most common in lowlands, but are being increasingly used in hilly terrain. Their application typically results in severe damage to residual stands and forest soils. Road construction associated with mechanized logging further contributes to soil erosion attributed to improper construction and maintenance. Aerial logging (helicopter and skyline/cable logging) can significantly reduce damage to residual stands but, due to high costs and personnel and technical requirements, is not often cost-effective. Semi-mechanised systems include manual skidding and animal logging through the use of elephants or other livestock.

Reduced impact logging is a carefully planned and controlled harvesting practice that minimises impacts on forest stands and soils (Schwab *et al.*, 2001). It safeguards biodiversity and maintains forest functions for future generations (Lohuji & Martin, 2001). It also ensures that carbon dioxide emissions from forest management are reduced (Pinard *et al.*, 1995). Reduced impact logging involves ground-based crawler tractor or rubber-tired skidder systems. Ideally, it is characterized by:

- Pre-harvest inventory and planning of harvesting operations, regeneration and terrain conditions.
- Carefully planned low extraction intensity to conserve the forest's productive potential for subsequent cutting cycles, and simultaneously reduce logging damage.
- Logging restrictions, including skidding operations, only during dry weather and excluding protected areas.
- Post-harvest treatment immediately after logging (e.g. erosion prevention on skid trails and log landings, road decommissioning) and damage assessment.

Agroforestry, afforestation and plantations: The establishment of forest and other wooded areas on land not previously classified as forest serves to counter deforestation elsewhere. Afforestation relates to the transformation of non-forest land use to forest and includes agroforestry practices such as growing plantations of native or introduced tree species in areas broadly characterised as agricultural or as agro-ecosystems. Common agroforestry practices include 'complex' agroforestry, boundary plantings, hedgerow intercropping and home gardens. Plantations commonly contain few species grown in straight lines and/or in even-aged stands (FRA, 2000) in areas that were previously cleared of native forest.

Regeneration: Deforested areas may be allowed to regenerate through natural or assisted succession of native species. This may follow human activities such as selective logging, agricultural use and fire, and temporary abandonment of lands once considered as forest. Modified natural forest will result where clearly visible indications of human activities remain (FRA, 2000).

Restoration and rehabilitation: Forest restoration and rehabilitation projects can vary widely in terms of objectives, implementation and scale. The overarching aim, however, is to re-establish through planting, seeding or assisted natural regeneration the structure, productivity and species diversity of the forest originally present at a particular location. Deliberate efforts, such as thinning or fertilizing, may be made to increase/optimise the proportion of desired species. Naturally regenerated trees from other species other than those planted/seeded may also be present. In time, the ecological processes and protective functions of the resulting semi-natural forest should closely match those of the original (UNEP-WCMC FRIS website; GFRA, 2005).

Reclamation and reforestation: Forest reclamation aims to recover the productivity (but little of the original biodiversity) at a degraded site and may include the establishment of plantations of both native and exotic species on abandoned lands once considered as forest. In time, the protective function and many of the original ecological services may be re-established. Forests reclaimed for their protective functions provide essential environmental services such as soil and water conservation, but tend to lack species diversity; they are characterized by straight tree lines and even-aged stands (UNEP-WCMC FRIS website; FRA 2000).

Table 1: Percentage and area estimates of tropical forest under management practices to mitigate deforestation in example nations (based on Global Forest Resources Assessment, 2005).

Forest Management Model	African examples	Asian examples	Central/South American examples
Conservation	DR Congo – Not Available Congo – 4.4% Liberia – 4.1% Ghana – 0.8%	Indonesia – 18.6% Malaysia – 5.4% Myanmar – 15.2% Thailand – 58.3%	Brazil – 8.1% Columbia – 14.1% Peru – 26.9% Bolivia – 20.0%
Plantations	DR Congo – Not Available Congo – 51k ha Liberia – 8k ha Ghana – 160k ha	Indonesia – 3399k ha Malaysia – 1573k ha Myanmar – 696k ha Thailand – 1997k ha	Brazil – 5384k ha Columbia – 312k ha Peru – 754k ha Bolivia – 20k ha
Regeneration	DR Congo – Not Available Congo – 14957k ha Liberia – 3017k ha Ghana – 5004k ha	Indonesia – Not Available Malaysia – Not Available Myanmar – 31373k ha Thailand – 4970k ha	Brazil – 56424k ha Columbia – 7337k ha Peru – 6932k ha Bolivia – 29360k ha
Reclamation-Reforestation	DR Congo – Not Available Congo – Not Available Liberia – Not Available Ghana – Not Available	Indonesia – Not Available Malaysia – Not Available Myanmar – 153k ha Thailand – 1102k ha	Brazil – Not Available Columbia – 16k ha Peru – Not Available Bolivia – Not Available
Restoration - Rehabilitation	DR Congo – Not Available Congo – Not Available Liberia - Not Available Ghana – Not Available	Indonesia – 36394k ha Malaysia – 15497k ha Myanmar – Not Available Thailand – Not Available	Brazil – Not Available Columbia – Not Available Peru - 0 Bolivia – Not Available

3 CARBON IMPACTS

3.1 Overview

There is considerable disagreement among national estimates of total carbon stored in tropical forest ecosystems. This depends on the data sets (forest inventory data, harvest data) and methods used to generate biomass and carbon storage estimates. Annex 2 cites data from Gibbs *et al*. (2007) that provide a starting point for estimating carbon storage. In a large number of the studies reviewed, only the amount of carbon or biomass lost through forest management is reported; the amount of carbon stored in similar areas of primary forest is only rarely given. Ideally, relative measures of carbon or biomass lost per unit area should be calculated, but this would be extremely difficult without consistent measurement at national level.

In this section, an attempt is made to synthesize available data on carbon storage in tropical forest ecosystems and, where possible, disaggregate total carbon stored into above ground carbon, below ground carbon, soil carbon and necromass. Given the caveats outlined above, the relative amount of carbon or biomass lost is reported only where total carbon estimates for primary forests are available; in other instances, only positive or negative trends are given.

3.2 Forest management practices

Shifting cultivation: The amount of biomass or carbon lost through shifting cultivation is largely un-quantified as these small plots are often burned. However, two studies examined carbon sequestration trends in soil organic matter; these were negative, even 5-10 years after the initial disturbance (Woomer *et al.*, 1994; Kotto-Same *et al.,* 1997).

Timber management: Quantification of logging intensity would be extremely useful when comparing the various logging techniques used in tropical regions.

Clear-cutting: A study by Sierra *et al.* (2007) provided the following estimate of carbon storage losses through clear-cutting a stand in the Porce region of Colombia: total carbon reduction 41%; above ground carbon reduction 81%; below ground carbon reduction 71%; soil carbon reduction 16 %; necromass carbon reduction 70%. Healey *et al.* (2000) similarly observed a 50% reduction in total carbon stored. In a study of regenerating secondary forest in Brazil following clear-cutting, Tiepolo *et al.* (2002) observed a 60% reduction in total carbon stored.

The impact of clear-cutting on soil organic carbon sequestration was found to be negative in studies throughout Asia (Andriesse and Schelhaas, 1987). Forest management practices have a neutral impact on rates of carbon sequestration in soils, even under increasing amounts of living biomass (Schedlbauer and Kavanaugh, 2008).

Selection cutting: The literature on selection cutting is not extensive. However, total carbon stored following selection cutting is generally negative and heavily dependant on logging intensity (Asner *et al*., 2005; Kirby and Potvin, 2007).

No data were available for impacts of selection cutting on carbon sequestration rates.

Reduced impact logging: Healey *et al.* (2000) observed that total carbon stored following reduced impact logging was 31% lower than in primary forests.

Significant positive carbon sequestration rates were also noted by Healey *et al.* (2000) for reduced impact logging.

Plantations: Most studies of monoculture plantations in the tropics exhibit drastic reductions in total carbon stored. For example, Wauters *et al.* (in press) observed reductions of 53-77% in Ghana and Brazil. Similarly, van Noordwijk *et al.* (2002) observed 69-80% reductions in Indonesia. For studies that reported biomass (instead of carbon stored), Glenday (2006) observed a 15-25% reduction in above ground biomass, while Stefan-Dewenter *et al.* (2007) reported a strongly negative change in above ground biomass.

No data were available for impacts of plantations on carbon sequestration rates.

Agro forestry: Very little data exists on total carbon storage losses through initial clearance of primary forest.

While total carbon or biomass stored in agro forestry is rarely quantified, carbon sequestration rates for various agro forestry practices are available, with examples provided in Table 2 below. Carbon sequestration rates are positive for complex agro forestry (Beer *et al.,* 1990; Albrecht and Kanji, 2003), boundary planting (Baggio and Heuveldop, 1984; Albrecht and Kanji, 2003), hedgerow intercropping (Evensen *et al*., 2002; Viswanat *et al*., 1998; Alegre and Rao, 1996), and 'home gardens' (Kirby and Potvin, 2007).

Table 2: Carbon sequestration rates for selected agro forestry practices.

Agro forestry Practice	Carbon Sequestration Rate	Region
Complex agro forestry	11 tonnes Ce ha^{-1} $year^{-1}$	Central Africa
Complex agro forestry	8-21 tonnes Ce ha^{-1} $year^{-1}$	Costa Rica
Boundary planting	35-50 tonnes Ce ha^{-1} $year^{-1}$	Central Africa
Hedgerow intercropping	1–37 tonnes Ce ha^{-1} $year^{-1}$	Indonesia and India
Home gardens	145 tonnes Ce ha^{-1} $year^{-1}$	Panama

Regeneration and rehabilitation: No primary literature was found to assess the impacts of regeneration and rehabilitation activities on carbon storage and sequestration.

3.3 Temporal changes

Short-term changes: Immediate changes under all forest management practices include the reduction of stored carbon through removal of above ground biomass, followed by reductions in soil carbon and necromass.

Long-term changes: After 20 to 30 years, total carbon storage under all forest management practices can be as little as 60% of the amount stored under primary forests (Tiepolo *et al*., 2002).

Soil carbon sequestration rates may be neutral (Schedlbauer and Kavanaugh, 2008) and soil carbon as much as 70% below that of primary forest (Sierra *et al*., 2007).

3.4 Conclusions

- The total amount of carbon removed will be directly related to above ground biomass and logging intensity. Since logging intensity is not commonly reported, it is difficult to make direct comparison between studies and forest management practices. Carbon sequestration rates are typically steady until stand maturity is reached.
- Following maturity, carbon sequestration in biomass declines. However, soil carbon sequestration rates are variable and depend on climate, region and specific soil type. It is not always certain that soils will begin to sequester carbon immediately following

disturbance. If vegetation is continuously removed, carbon sequestration from biomass production might be offset by losses of soil carbon from erosion.

4 ECOSYSTEM IMPACTS

4.1 Biodiversity Impacts

4.1.1 Overview

Plants are heavily impacted by all of forest management practices. Of seven studies reviewed, six indicated deleterious impacts on plant diversity and richness, vegetation structure and proportions of endemic species. Only a single study showed a neutral effect.

Mammals are also heavily impacted by forest management practices Five out of six studies reviewed showed negative impacts on species populations and species diversity; only one study indicated positive effects.

Insects are impacted in a number of ways by forest management practices. Of six studies reviewed, two indicated negative impacts on butterfly diversity and species richness; two indicated neutral impacts on species diversity and abundance of bees, ants and terrestrial isopods; and two indicated positive impacts on moth diversity and general insect abundance.

Birds also show mixed impacts from forest management practices. Negative impacts include reduced numbers of bird species (1 study), declining population trends in selected ecological guilds (1 study), and reduced levels of species diversity (2 studies). Positive impacts include increased species richness (I study) and population increases in certain ecological bird guilds (1 study). Neutral impacts include no significant change to forest bird diversity (1 study) and changes to species composition that do not impact species abundance or richness (1 study).

Amphibians again show mixed impacts from forest management practices. For example, in South America amphibian species diversity declined following forest management, while in West Africa no effects were observed in species abundance or richness.

4.1.2 Forest management practices

Shifting cultivation results in a reduction in the number of endemic plant species, but not in the proportion of rare species between control and treatment plots (van Gemerden *et al.*, 2003). Naidoo (2004) observed no differences in bird diversity, but did note changes in bird community composition between areas previously under shifting cultivation and primary forest.

Timber harvesting has highly variable impacts. Comparisons between the various practices are difficult to make because of regional variability in species diversity and the intensity of logging associated with each technique. In principal, reduced impact logging has the lowest logging intensity and clear-cutting the greatest impact.

Clear-cutting: Plant and butterfly diversity were found to decrease under clear-cutting (Chapman and Fimbel, 2001; Farius, 2000). Greater densities of logging roads increased access to primary forest for local hunters, resulting in significantly increased pressure on terrestrial vertebrates (Wilkie *et al.*, 1992). Other studies showed a range of impacts. For example, lightly logged sites were found to have greater moth diversity than primary forest, while heavily logged sites had fewer species but more individuals (Chey, 2002). Hasall *et al.* (2006) saw no significant difference in species richness or equitability of terrestrial isopods.

Selection cutting: A number of studies indicate negative impacts on bird species diversity and population densities (Lambert, 1992; Thiollay, 1992; Wong, 1986); depending on the intensity of logging, this can lead to local extinctions (Thiollay, 1992). The impacts on mammalian species diversity and population density were seen to be neutral to negative (Wilson and Johns, 1982). Those on amphibian species richness and population density are cited as neutral (Fredericksen and Fredericksen, 2004; Ernst *et al.*, 2006) or negative (Ernst *et al.*, 2006), depending on the tropical forest region.

Reduced impact logging: Bat diversity increased and species abundance declined in stands subjected to reduced impact logging (Castro-Arellano *et al.*, 2007). In one study, bird and invertebrate species richness increased (Azevedo-Ramos et al., 2006), while the species diversity of mammals (Azevedo-Ramos *et al.*, 2006) and bees and ants (Eltz and Bruhl, 2001) did not differ significantly from primary forest. Vegetation stand structure exhibited significant negative impacts (Sist and Ferreria, 2007).

Plantations: The initial impacts of plantations are strongly negative. Plant diversity under oil palm plantations in Indonesia declined by 80% (Casson, 2003), while the number of exotic weedy plant species sharply increased. Similarly, animal diversity and the density of animal populations exhibited a strongly negative trend (Wilson and Johns, 1982). Plantations can, however, increase connectivity between habitat patches; Bali *et al.* (2007) observed that coffee plantations form an important buffer around wildlife sanctuaries.

Agroforestry: While the biodiversity impacts of many agro forestry practices are poorly understood, a few have received more detailed study. Although agro forestry does negatively impact biodiversity, Gordon *et al.* (2007) noted that enrichment planting increased species richness and abundance of forest-affiliated birds when compared to monocultures such as coffee plantations. They also noted that mammal capture rates were extremely low in agro forestry areas when compared to primary forest. 'Home gardens' (gardens cultivated under forest canopy) are commonly allowed to recover *via* natural succession pathways and have greater basal area and plant species richness than forest plantations (Garcia-Fernandez and Casado, 2005).

Regeneration and rehabilitation: Following the negative impacts of certain forest management practices, regeneration and rehabilitation activities tend to improve conditions for biodiversity. The magnitude of benefits observed commonly depends often depends on the proximity of the impact to native forest. For example, plant diversity in regenerating plots was found to be lower as distance from primary forest increased (Mesquita *et al.*, 2001). However, pre-harvest planning to maintain some original forest vegetation can be extremely important in regeneration efforts. Retaining large original forest trees as perching sites can attract frugivorous birds and has been observed to increased the number of late successional forests tree saplings in study areas (Guevara *et al.*, 1986). Use of remnant vegetation to attract seed-dispersing animals has been successful in other tropical regions as well (Puyravaud *et al.*, 2003).

4.1.3 Temporal changes

Short-term changes: The majority of studies reviewed in this report examined changes in species diversity, population density and habitat structure in the short-term, which occurred fewer than 10 years from the forest manipulation. All of the major species groups identified exhibited some degree of negative impacts due to forest management.

Intermediate-term changes: Only six studies documented changes in the intermediate-term (10-20 years). These studies noted neutral or negative impacts on amphibians, bees and ants and forest birds; one study indicated positive impacts to moth diversity (Chey, 2002), three studies indicated neutral impacts on bees, ants and amphibians, and two studies indicated lingering negative impacts on birds and amphibians.

Long-term changes: Long-term effects of forest management were observed in both plants and animals. Bird species diversity levels were still significantly below those of primary forests 30 years after a selection cutting regime (Wong, 1986). Plant species diversity recovery rates after 30-50 years were either slow or rapid, depending on the tropical forest region (van Gemerden *et al.*, 2003). Vegetation structure (Sist and Ferreria, 2007) and floristic recovery (Kurpick *et al.*, 1997) still bore the negative impacts of selection cutting and reduced impact logging 30-200 years after the initial impact.

4.1.4 Conclusions

- In the short-term, the common trend following forest manipulation is an initial increase in diversity and abundance of species as exotic species colonise an area. As time goes by, the forest regenerates while exotic species decline. It is likely that recovery rates of forest-obligate species depend largely on proximity of intact primary forest. However, species diversity levels may remain significantly below those of 'pristine' habitat.
- Retaining much of the original vegetation structure is beneficial to biodiversity. Reduced impact logging and 'home gardens' are most likely to maintain higher levels of biodiversity, though statistics could not be found to support this statement. Sites of low impact forestry can also provide habitat buffers and connectivity between primary forest patches.
- Many forest bird and amphibian species can act as indicators of overall ecosystem 'health'.

4.2 Hydrological Impacts

4.2.1 Overview

The body of research available for comparisons of hydrological impacts from forest management techniques is limited. Six studies were identified in total: four relate to timber harvesting, one to shifting agriculture, and one to forest plantations; no research was identified for agro forestry. The six studies covered Africa, Asia and Central and South America. Each study controlled for regional variations in climate, precipitation, edaphic conditions and vegetation structure. Consequently, direct quantitative comparison of hydrological impacts across the diverse tropical forest regions of the world is problematic. Additional variations stem from time lags between field studies being carried out and subsequent forest manipulations (logging, shifting agriculture, etc). Despite the regional and temporal variation of these studies, general trends can be identified.

4.2.2 Forest management practices

Shifting cultivation: Van Gemerden *et al.* (2003) observed that artificial gaps in the over story tree canopy were significantly larger than gaps created by natural disturbances. These large gaps resulted in the penetration of solar radiation increasing ambient temperature and reducing soil moisture.

Timber harvesting: Timber-harvesting contributes to increased soil compaction, surface runoff and soil erosion. It is also linked with a general drying effect that increases the risk of forest fires (Cochrane *et al.*, 2002). Both clear-cutting and selection cutting practices were examined in the studies, but variations in the hydrological parameters measured prohibit direct comparison of results. Stream sedimentation was found to be unaffected in one study of selection cutting. None of the studies quantified logging intensity. It would be highly instructive to policy analysts to understand the relationship between logging intensity and variables such as soil compaction and surface runoff.

Agro-forestry: Zimmermann *et al.* (2006) observed increased surface runoff from banana, capoeira and teak plantations when compared to primary forest. Land cleared for grazing pasture exhibited higher levels of surface runoff than forestry plantations or primary forest.

Regeneration and rehabilitation: No primary literature was identified to assess the hydrological impacts of rehabilitation and regeneration methods.

4.2.3 Temporal change in hydrologic impacts

The hydrological impacts of forest management remain evident in the landscape for many years. In central Africa, van Gemerden *et al*. (2003) observed increased soil compaction and erosion 2-5 years after selection cutting, and elevated solar radiation and lower soil moisture 30-40 years after shifting agriculture. Zimmermann *et al*. (2006) observed increased surface water runoff from tropical forest plantations 25-30 years after the plantations had been established.

4.2.4 Conclusions

- Artificial alterations of the forest canopy can have lasting impacts on the hydrological functioning of tropical forests.
- Timber harvesting has demonstrable negative impacts on soil compaction and erosion, at least in the short term, and longer lasting impacts on soil moisture and surface runoff. It is not known, however, how long these impacts will persist or their relationship with logging intensity.
- Comparisons between surface runoff from agro forestry plantations and timber harvesting are desirable, but the current paucity of literature makes objective assessments impossible.

4.3 Other ecosystem services impacts

This report has assessed the available evidence of the impacts of forest management practices on carbon storage and sequestration, biodiversity and hydrology; these are all topics of considerable scientific research. Other ecosystem services (e.g. pollination, fuel, fibre, food, and medicinal/pharmaceutical plants) have received comparably little or no attention in the academic literature. What little literature does exist fails to consider the impacts on these extremely important and valuable ecosystem services. For example, non-wood forest products are vital in developing tropical nations and provide a substantial component of household income (Odebode, 2003). They include spices, bushmeat, fruits, nuts, etc. Bushmeat and fish contribute 20% of dietary protein in 62 developing countries (Bennet and Robinson, 2000). Ricketts *et al.* 2004 observed greater yields (20%) and quality on coffee plantations located next to primary forest in Costa Rica. Furthermore, wood fuels make up 15 percent of the developing world’s energy needs (WEC, 1999). The total value of all these types of ecosystem services has been estimated by Michie *et al.* (1999) to be in the order of $90-120 billion.

5 SYNTHESIS

5.1 General trends

Carbon: Primary forests in tropical regions represent one of the greatest stores of carbon in the world. All of the forest management practices reviewed are likely to cause significant releases of carbon to the atmosphere, as biomass, soil and decomposing litter are disturbed. As the forest regenerates, carbon is sequestered at a steady rate as biomass. However, carbon in biomass may represent only 30-40 percent of the total carbon in a tropical forest system. Soil carbon can represent 40-50 percent of the total carbon stored in an undisturbed tropical forest system (Sierra *et al*., 2007). This store of carbon is located in the top 5-10 centimetres of the soil. The initial loss of soil organic carbon can be as high as 3-5 percent of the total ecosystem carbon store (Andriesse and Schelhaas, 1987; Kotto-Same *et al*., 1997), and the rate of loss can sometimes remain elevated for 5-30 years, depending on the amount of human intervention. Schedlbauer and Kavanaugh (2008) noted that, even after 30 years, soil carbon sequestration rates might only just replace soil carbon losses from erosion. It must be noted that soils from the various tropical forest regions will respond differently to similar stresses, consequently direct comparison between studies and forest management practices remain problematic.

Biodiversity: Primary forests in tropical regions represent some of the greatest concentrations of species diversity in the world. The complex structure of primary forest vegetation produces a wide array of temporal and spatial habitat niches. The forest management practices that simplify this complex structure will typically reduce species diversity and population densities. Immediately following their application, it is common to see an initial increase in diversity and abundance of exotic species in an area. The presence of these invaders is often short-lived in small-scale applications. Forest management practices applied at larger scales enable exotic species to persist for longer and can cause changes in species assemblages (Naidoo, 2004; Azevedo-Ramos *et al.*, 2006). Some groups of species, such as bats, insects and some birds, are positively affected or unaffected by forest management (Castro-Arellano *et al.*, 2007; Hasall *et al.*, 2006). Other groups are negatively affected in the short-term and can return to pre-disturbance levels of diversity and population density (Thiollay, 1992). Still other groups, such as forest-obligate species, may dramatically decline or become locally extinct (Thiollay, 1992).

Hydrology: Some of the longest lasting impacts of forest management practices are on the hydrological functioning of tropical forests. Alterations to the forest canopy will impact microclimates and increase ambient temperatures and water infiltrability. Timber harvesting has clearly demonstrable negative impacts on soil compaction and erosion, at least in the short-term, and longer lasting impacts on soil moisture and surface runoff. It is not known, however, how long these impacts will persist or their relationship with logging intensity.

Ecological zone	Initial forest cover	Forest Management	Carbon impact	Non-carbon impacts			Timescale
				Biodiversity	Hydrology	Other	
Tropical rainforest	Primary	Conservation	Carbon sequestration - positive	Biodiversity - positive	Water runoff - positive	Pollination - positive	
Tropical rainforest	Secondary	Shifting cultivation	Carbon storage – no data Carbon sequestration - negative	Biodiversity – slightly negative	Soil moisture - negative		> 10 years
Tropical rainforest	Primary	Clear-cutting	Carbon storage – very negative Carbon sequestration - negative	Biodiversity – very negative Exotic species - negative	Water runoff - negative		> 10 years
Tropical rainforest	Secondary	Selection logging	Carbon storage – negative Carbon sequestration – no data	Biodiversity – negative	Soil compaction – negative Forest fire risk - negative		> 10 years
Tropical rainforest	Secondary	Reduced impact logging	Carbon storage – negative Carbon sequestration – positive	Biodiversity - neutral	No data		> 10 years
Tropical rainforest	Secondary	Complex agroforestry	Carbon storage – negative Soil carbon sequestration – slightly positive	Biodiversity – negative	No data		> 10 years
Tropical rainforest	Secondary	Boundary planting agroforestry	Carbon storage – negative	Biodiversity – no data	No data		> 10 years

			Soil carbon sequestration – slightly positive				
Tropical rainforest	Secondary	Hedgerow intercropping	Carbon storage – negative Soil carbon sequestration – slightly positive	Biodiversity – no data	No data		> 10 years
Tropical rainforest	Secondary	Home gardens	Carbon storage – negative Carbon storage – very negative	Biodiversity – negative	No data		> 10 years
Tropical rainforest	Secondary	Plantations	Carbon storage – very negative Carbon sequestration - nodata	Biodiversity – very negative Exotic species – negative	Rainfall interception - negative	Pollination - negative	> 10 years
Tropical rainforest	Secondary	Forestation	No data	Biodiversity - positive	No data		> 10 years
Tropical rainforest	Secondary	Regeneration	No data	Biodiversity – positive	No data		> 10 years
Tropical rainforest	Secondary	Restoration	No data	Biodiversity – positive	No data		> 10 years

Biodiversity: ‘Positive’ indicates increased species richness/abundance; ‘negative’ reduced species richness/abundance when compared to primary/secondary forest.

Carbon sequestration: ‘Positive’ indicates carbon sequestration sinks; ‘negative’ indicates carbon sources. These indicators do not compare sequestration rates against those of primary/secondary forests.

Carbon storage: ‘Positive/negative’ indicates increased/decreased amount of carbon stored in biomass, soil carbon and necromass compared to primary/secondary forest.

Exotic Species: ‘Positive’ indicates reduced exotic species abundance; ‘negative’ indicates elevated levels of exotic species abundance.

Forest fire: ‘Positive’ indicates low relative risk of forest fire; ‘negative’ indicates higher relative risk of forest fire.

Soils moisture: ‘Positive/negative’ indicates increased/decreased levels of soil moisture compared to primary/secondary forest.

5.2 Forest management practices

Shifting cultivation: This use of tropical forests is the least likely to contribute significantly to deforestation, largely due to the small spatial scale at which it is practiced. Its negative impacts include:

- Release of stored biomass and soil carbon.
- Negative impacts to endemic plant species and potentially to animal species assemblages.
- Local increases in ambient temperature and decreased soil moisture.

However, shifting agriculture commonly occurs at very local scales, over short time periods, and within a large primary forest matrix. In theory, this use of forest can be implemented sustainably if population pressures do not dramatically increase the size or duration of this practice.

Clear-cutting: This management practice removes all timber from a stand; it is often carried out at large spatial scales and in conjunction with other forest management practices, such as plantations. Its negative impacts include:

- Large releases of stored carbon from biomass.
- Large and dramatic declines in species diversity, population size and even local extinctions.
- Large increases in the abundance of exotic species.
- Significantly increased surface runoff that contributes to declines in soil carbon.
- Roads associated with logging contribute to increased hunting pressures on larger vertebrates.

Clear-cutting can be sustainably maintained at very small scales within a large forest matrix to encourage regeneration, but economic considerations often increase the scale and frequency of clear-cutting operations.

Plantations: Once timber is removed through clear-cutting, plantations can be developed for tree crop species such as, for example, oil palm, coffee, banana and rubber. Negative impacts include:

- Large losses of above ground biomass, total carbon stored and soil carbon.
- Large losses of plant and animal diversity.
- Large increases of exotic species.

Plantations are often established as monocultures. The inclusion of various crop trees may slightly enhance their role in carbon storage, biodiversity protection and hydrological functioning. While plantations do not produce complex vegetation structures and are continually impacted by human activities, they can serve as buffer habitat to nature reserves and act as wildlife corridors. The effectiveness of such corridors is the subject of debate, but enhancing the complexity of a plantation’s vegetative structure could be beneficial.

Agro forestry: Many of the forest management practices associated with agro forestry have been developed with sustainability in mind. These include complex agro forestry, boundary plantings, hedgerow intercropping, enhancement plantings and ‘home gardens’. All of these practices have been designed to minimally impact the forest landscape. Among the positive impacts of agro forestry are:

- Positive changes in total carbon stored.
- Increases in soil carbon sequestration rates.
- Greater forest bird diversity when compared to monoculture plantations.

Negative impacts include:

- Moderate losses to plant and animal species diversity and population density.
- Moderate increases to surface water runoff.

Reduced impact logging: This approach to logging was also developed with sustainability in mind. Efforts have been made to minimise harvesting intensities, while simultaneously insuring the economic viability of harvesting operations. Reduced impact logging does represent a significant improvement over clear-cutting; however, it remains unclear whether this practice is truly sustainable over decades and centuries. Positive impacts include:

- Increased carbon sequestration rates.
- Moderate increases to bird and invertebrate diversity.
- Neutral impacts on mammals, bees and ants.

While its protective role in ecosystem functioning has been advocated, the application of reduced impact logging has shown that there can be significant drawbacks; these can be countered through careful planning. Negative impacts include:

- Moderate total carbon losses.
- Large negative impacts on vegetation stand structure.

Selection cutting: While reduced impact logging intentionally minimises its negative effects, selection cutting merely reduces the intensity of logging, but retains some of the high impact logistical methods of cutting and transporting timber. It is, however, an improvement over clear-cutting in that stands retain some degree of forest structure. Among the positive impacts are:

- Benefits to some forest bird species.
- No effects on bird species diversity (in some instances).
- No effects on mammal species diversity (in some instances).
- No effects on amphibian species diversity (in some instances).

There are some significant drawbacks; negative impacts include:

- Moderate decreases to total carbon stored.
- Moderate increases to soil compaction and soil erosion.
- Increased risk of forest fire.

Regeneration and rehabilitation: This suite of activities tends to be largely positive for biodiversity and the restoration of vegetation structure that is so important to the functioning of tropical forests. It is assumed that any regeneration activities that proceed along natural or semi-natural successional pathways will increase the amount of carbon stored when compared with human-dominated land use types. While the available literature on this topic is sparse, it will certainly receive increasing public and scientific scrutiny.

5.3 Conclusions

The most severely negative forest management practices tend to be those that have the most dramatic impacts on vegetation structure, such as clear-cutting and plantations. They exhibit negative to very negative impacts on carbon storage, biodiversity, hydrology and other ecosystem services. Less detrimental forest management practices are those that reduce the areal extent or intensity of alterations to vegetation structure, including shifting agriculture and selection cutting whose impacts range from neutral to negative.

The practices that minimally disturb, replace or maintain the original structure of tropical forests tend to be those that are most likely to be sustainable in the long-term. Examples include agro forestry, reduced impact logging, conservation and regeneration/rehabilitation;

these range in their impacts from negative to positive. However, the long-term sustainability of these activities will depend heavily on forest planning, monitoring and adaptive management strategies to ensure the successful maintenance of the ecosystem services that human cultures depend on.

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ANNEX 1: CARBON, BIODIVERSITY AND HYDROLOGICAL TRENDS RELATED TO FOREST MANAGEMENT PRACTICES

Ecological Zone	Initial Forest Cover	Forest Management	Carbon Trend	Time Scale	Citation	Biodiversity Trend	Time Scale	Citation	Hydrology Trend	Time Scale	Citation
Tropical Rain Forest	Secondary	Shifting cultivation	Soil organic carbon: negative	Not available	Woomer *et al.* (1994)	Endemic plant species: negative	10 – 50 years	van Gemerden *et al.* (2003)	Ambient temperature: higher	30-40 years	van Gemerden *et al.* (2003)
Tropical Rain Forest	Secondary	Shifting cultivation	Soil organic carbon: negative	5-10 years	Kotto-Same *et al.* (1997)	Proportion of rare plant species: neutral	10 – 50 years	van Gemerden *et al.* (2003)	Solar radiation: higher	30-40 years	van Gemerden *et al.* (2003)
Tropical Rain Forest	Secondary	Shifting cultivation				Number of bird species: neutral	Not available	Naidoo (2004)	Soil moisture: lower	30-40 years	van Gemerden *et al.* (2003)
Tropical Rain Forest	Secondary	Shifting cultivation				Bird species composition: altered	Not available	Naidoo (2004)			
Tropical Rain Forest	Secondary	Clear-cutting	Soil organic carbon: negative	Not available	Andriesse & Schelhaas (1987)	Species diversity: negative	Not available	Chapman & Fimbel (2001)	Surface water runoff: increased	Not available	Maimer (1992)
Tropical Rain Forest	Secondary	Clear-cutting	Soil carbon sequestration rate: neutral	5-30 years	Schedlbauer & Kavanaugh (2008)	Butterfly diversity: negative	< 10 Years	Fairus (2000)			
Tropical Rain Forest	Secondary	Clear-cutting	Carbon stored: 50% lower	17 years	Healey *et al.* (2000)	Hunting pressure: increased	Not available	Wilkie *et al*. (1992)			
Tropical Rain Forest	Secondary	Clear-cutting	Carbon sequestration rate: positive	17 years	Healey *et al.* (2000)	Moth diversity: positive	< 10 years	Chey (2002)			
Tropical Rain Forest	Secondary	Clear-cutting	Carbon stored: negative	10-15 years	Glenday (2006)	Species richness of terrestrial isopods: neutral	Not available	Hasall *et al.* (2006)			
Tropical Rain Forest	Secondary	Clear-cutting	Carbon stored: 5 % reduction	Not available	Tiepolo *et al.* (2002)						
Tropical Rain Forest	Secondary	Clear-cutting	Carbon stored: 60% reduction	Not available	Tiepolo *et al.* (2002)						
Tropical Rain Forest	Secondary	Clear-cutting	Total carbon: 41% reduction	4-22 years	Sierra *et al.* (2007)						
Tropical Rain Forest	Secondary	Clear-cutting	Above ground carbon: 82% reduction	4-22 years	Sierra *et al.* (2007)						
Tropical Rain Forest	Secondary	Clear-cutting	Below ground carbon: 71% reduction	4-22 years	Sierra *et al.* (2007)						
Tropical Rain Forest	Secondary	Clear-cutting	Soil organic carbon: 16% reduction	4-22 years	Sierra *et al.* (2007)						
Tropical Rain Forest	Secondary	Clear-cutting	Necromass carbon: 70% reduction	4-22 years	Sierra *et al.* (2007)						
Tropical Rain Forest	Secondary	Plantations	15-25% reduction in above ground biomass	10-15 years	Glenday (2006)	Plant species diversity: very negative	Not available	Casson (2003)	Rainfall interception: 30% reduction	2-5 years	Dietz *et al*. (2006)
Tropical Rain Forest	Secondary	Plantations	Above-ground biomass: very negative	25 years	Stefan-Dewenter *et al.* (2007)	Animal diversity: very negative	3-5 years	Wilson & Johns (1982)			
Tropical Rain Forest	Secondary	Plantations	Soil carbon stored: negative to very negative	15-25 years	Aweto (1995)	Exotic plant species: positive	Not available	Casson (2003)			
Tropical Rain Forest	Secondary	Plantations	Total carbon stored: 69-80% reduction	2-30 years	Van Noordwijk *et al.* (2002)	Biomass of terrestrial vertebrates: very negative	Not available	Fa *et al.* (2006)			

Ecological Zone	Initial Forest Cover	Forest Management	Carbon Trend	Time Scale	Citation	Biodiversity Trend	Time Scale	Citation	Hydrology Trend	Time Scale	Citation
Tropical Rain Forest	Secondary	Complex agroforestry	Total carbon: positive	10 years	Beer *et al.* (1990)	Forest bird diversity of enrichment plantings: positive compared to monoculture	2 years	Gordon *et al.* (2007)			
Tropical Rain Forest	Secondary	Complex agroforestry	Soil organic carbon: neutral	Not available	Albrecht and Kandji (2003)	Mammal population density: negative	2 years	Gordon *et al.* (2007)			
Tropical Rain Forest	Secondary	Complex agroforestry	Soil organic carbon: positive	10 years	Beer *et al.* (1990)						
Tropical Rain Forest	Secondary	Boundary planting	Total carbon stored: positive	4 years	Baggio & Heuveldop (1984)						
Tropical Rain Forest	Secondary	Boundary planting	Soil organic carbon: neutral	4 years	Albrecht and Kandji (2003)						
Tropical Rain Forest	Secondary	Hedgerow intercropping	Total carbon stored: positive	Not available	Evensen *et al.* (1994); Viswanath *et al.* (1998)						
Tropical Rain Forest	Secondary	Hedgerow intercropping	Soil organic carbon: 12% increase	5 years	Alegre and Rao (1996)				Surface water runoff: increased	25-30 years	Zimmermann *et al.* (2006)
Tropical Rain Forest	Secondary	Home gardens	Carbon stored: very negative	Not available	Kirby and Potvin (2007)	Plant species richness: negative		Garcia-Fernandez and Casado (2005)			
Tropical Rain Forest	Secondary	Reduced impact logging	Carbon stored: 31% lower	17 years	Healey *et al.* (2000)	Bat diversity: positive	2-4 years	Castro-Arellano *et al.* (2007)			
Tropical Rain Forest	Secondary	Reduced impact logging	Carbon sequestration rate: positive	17 years	Healey *et al.* (2000)	Bat species abundance: negative	2-4 years	Castro-Arellano *et al.* (2007)			
Tropical Rain Forest	Secondary	Reduced impact logging				Bird/invertebrate species richness: positive	6 months	Azevedo-Ramos *et al.* (2006)			
Tropical Rain Forest	Secondary	Reduced impact logging				Mammal species richness/abundance: neutral	6 months	Azevedo-Ramos *et al.* (2006)			
Tropical Rain Forest	Secondary	Reduced impact logging				Bee/ant diversity/abundance: neutral	<10 years	Eltz and Bruhl (2001)			
Tropical Rain Forest	Secondary	Reduced impact logging				Vegetation stand structure: very negative	30 years	Sist and Ferreira (2007)			
Tropical Rain Forest	Secondary	Selection cutting	Carbon stored: negative	5 years	Asner *et al.* (2005)	Plant species diversity recovery: rapid	<30-40 years	van Gemerden *et al.* (2003)	Soil compaction: increased	2-5 years	van Gemerden *et al.* (2003)

Ecological Zone	Initial Forest Cover	Forest Management	Carbon Trend	Time Scale	Citation	Biodiversity Trend	Time Scale	Citation	Hydrology Trend	Time Scale	Citation
Tropical Rain Forest	Secondary	Selection cutting	Carbon stored: negative	Not available	Kirby and Potvin (2007)	Floristic recovery: slow	200 years	Kurpick *et al.* (1997)	Soil erosion: increased	2-5 years	van Gemerden *et al.* (2003)
Tropical Rain Forest	Secondary	Selection cutting				Butterfly species richness: negative	5 years	Hill *et al.* (2005)	Stream sedimentation rates: neutral	Not available	Fletcher and Muda (1999)
Tropical Rain Forest	Secondary	Selection cutting				Forest bird diversity: neutral	8 years	Lambert (1992)	Risk of forest fire: increased	Not available	Cochrane *et al.* (2002)
Tropical Rain Forest	Secondary	Selection cutting				Species composition: negative (Flycatchers, woodpeckers, trogons and wren-babblers)	8 years	Lambert (1992)			
Tropical Rain Forest	Secondary	Selection cutting				Species composition: positive (Nectarivorous and frugivorous species)	8 years	Lambert (1992)			
Tropical Rain Forest	Secondary	Selection cutting				Bird species diversity: negative	30 years	Wong (1986)			
Tropical Rain Forest	Secondary	Selection cutting				Mammal species diversity: neutral	3-5 years	Wilson and Johns (1982)			
Tropical Rain Forest	Secondary	Selection cutting				Mammal population density: reduced	3-5 years	Wilson and Johns (1982)			
Tropical Rain Forest	Secondary	Selection cutting				Species richness and abundance: 27-33% decrease	1 and 10 years	Thiollay (1992)			
Tropical Rain Forest	Secondary	Selection cutting				Population trend: 42% of primary forest species decreased sharply or disappeared	1 and 10 years	Thiollay (1992)			
Tropical Rain Forest	Secondary	Selection cutting				Population trends: 34% increased or remained unchanged.	1 and 10 years	Thiollay (1992)			
Tropical Rain Forest	Secondary	Selection cutting				Amphibian species richness: neutral (west Africa).	15-20 years	Ernst *et al.* (2006)			
Tropical Rain Forest	Secondary	Selection cutting				Amphibian species richness: negative (South America)	15-20 years	Ernst *et al.* (2006)			
Tropical Rain Forest	Secondary	Selection cutting				Species composition: altered	1-10 years	Barlow *et al.* (2006)			
Tropical Rain Forest	Secondary	Selection cutting				Amphibian abundance, species richness: neutral	1 year	Fredericksen & Fredericksen (2004)			
Tropical Mountain System	Secondary	Shifting cultivation				Floristic recovery: highly variable	60-70 years	Kappelle *et al.* (1995)			

ANNEX 2: National-level forest biomass carbon stocks estimates (M t C), Adapted from Gibbs *et al.*, 2007

	Based on compilations of harvest data			**Based on forest inventory**		**Total range**
	Olson *et al.* (1983); Gibbs (2006b)	Houghton (1999); DeFries *et al.*(2002)	IPCC (2006)c	Brown (1997); Achard *et al.* (2002, 2004)	Gibbs and Brown (2007a, 2007b)	Based on all estimates
Bolivia	6,542	9,541	9,189	2,469	—	2,469–9,189
Brazil	54,697	81,187	82,510	82,699	—	54,697–82,699
Cameroon	3,721	3,454	6,138	3,695	3,622	3,454–6,138
Cambodia	1,008	1,800	1,222	1,334	1,914	957–1,914
Colombia	6,737	10,085	11,467	2,529	—	2,529–11,467
Congo	3,458	3,549	5,472	3,740	4,739	3,458–5,472
Costa Rica	471	704	593	493	—	471–704
D.R. Congo	22,986	22,657	36,672	24,020	20,416	20,416–36,672
Eq. Guinea	304	313	474	330	268	268–474
Gabon	3,063	3,150	4,742	3,315	4,114	3,063–4,742
Ghana	880	612	2,172	678	609	609–2,172
Guyana	2,494	3,742	3,354	923	—	923–3,354
India	5,420	8,997	5,085	7,333	8,560	5,085–8,997
Indonesia	13,143	25,547	25,397	16,448	20,504	10,252–25,547
Liberia	506	515	1,302	543	707	506–1,302
Malaysia	2,405	4,625	4,821	2,984	3,994	2,405–4,821
Mexico	4,361	5,924	5,790	4,646	—	4,361–5,924
Myanmar	2,843	5,182	4,867	4,024	4,754	2,377–5,182
PNG	4,154	8,037	7,075	5,160	—	4,154–8,037
Peru	7,694	11,521	13,241	2,782	—	2,782–13,241
Sierra Leone	136	114	683	123	240	114–683
Thailand	1,346	2,489	2,215	1,923	2,104	1,346–2,489
Venezuela	6,141	9,202	7,886	2,326	—	2,326–9,202
Vietnam	774	1,632	1,546	1,169	1,642	774–1,642