LETTER

Over-harvesting driven by consumer demand leads to population decline: big-leaf mahogany in South America

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Abstract

Consumer demand for the premier neotropical luxury timber, big-leaf mahogany (*Swietenia macrophylla*), has driven boom-and-bust logging cycles for centuries, depleting local and regional supplies from Mexico to Bolivia. We revise the standard historic range map for mahogany in South America and estimate the extent to which commercial stocks have been depleted using satellite data, expert surveys, and sawmill processing center data from Brazil. We estimate an historic range of 278 million hectares spanning Venezuela to Bolivia, 57% of this in Brazil. Approximately 58 million hectares (21%) of mahogany's historic range had been lost to forest conversion by 2001. Commercial populations had been logged from at least 125 million more hectares, reducing the commercial range to 94 million hectares (34% of historic). Surviving stocks are extremely low-density populations in remote regions representing a smaller fraction of historic stocks than expected based on estimated current commercial range. Our method could advance international policy debates such as listing proposals for CITES Appendices by clarifying the commercial and conservation status of high-value timber species similar to mahogany about which little information is available. The fate of remaining mahogany stocks in South America will depend on transforming current forest management practices into sustainable production systems.

Introduction

Consumer demand for high-value luxury timbers has been a principal driver of predatory logging in the tropics for several centuries (Lamb 1966). The pursuit of big-leaf mahogany (*Swietenia macrophylla*, Meliaceae) across southern Amazonia since the early 1970s has opened roads hundreds of kilometers into previously inaccessible primary forests, in turn opening those forests to cattle ranching, small-holder agriculture, and agribusiness and provoking conflict with Indigenous Amerindians that has frequently been disruptive and violent (Watson 1996; Fagan & Shoobridge 2005). Commercial mahogany stocks have been eliminated at local and regional scales through overharvesting, forest degradation, and deforestation (White 1978; Veríssimo *et al*. 1995; Gullison *et al*. 1996; Calvo & Rivera 2000; Grogan *et al*. 2002; Kometter *et al*. 2004). This pattern is now being repeated in the Amazon for similar high-value species such as ipê (*Tabebuia* spp., Bignoniaceae), to supply the U.S. residential

decking market (Schulze *et al*. 2008a,b), and Spanish cedar (*Cedrela odorata*, Meliaceae), a mahogany relative.

Since the Spanish began exporting mahogany to Europe during the early 1500s, its exploitation has followed boom-and-bust cycles depleting local and regional supplies from Mexico through Central America (Calvo & Rivera 2000) and then across South America. The international community debated mahogany's commercial and conservation status during the 1990s through repeated proposals to list the species on Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Snook 1996; Lugo 1999). An Appendix II listing requires cooperation between producer and consumer nations to verify that internationally traded individuals or volumes of listed species have been harvested legally and in a manner nondetrimental to their role in ecosystems where they naturally occur (Blundell 2004). This debate echoed fears from the late 19th and early 20th Century that commercial stocks of mahogany might be nearing depletion in Mexico and Central America. Discovery during the early 1900s of extensive mahogany populations in lowland western Amazonia and during the 1940s of populations in the southern reaches of the Brazilian state of Pará were a great relief to luxury timber industries in the U.S. and Europe facing depletion of Central American supplies (Record 1941; Hoy 1946; Lamb 1966).

Almost a century later, the CITES Appendix II debate hinged on whether South American mahogany stocks were in turn nearing exhaustion due to unsustainable industry practices. Mahogany's extraordinary value—it is currently worth up to US$1800 per cubic meter of sawn wood at the point of export in Peru (ITTO 2009)—encouraged loggers to fell and remove every tree that could be located and transported out of remote forests, including trees smaller than legal minimum diameter cutting limits (MDCL; Veríssimo *et al*. 1995; Grogan & Schulze 2008). In southeast Amazonia, forests logged for mahogany typically lost 93–95% of trees larger than 45 cm diameter and 31–47% of trees smaller than this (Grogan *et al*. 2008). After the loss of almost all reproductively mature trees, population recovery is hampered by barriers to seedling regeneration where forests escape conversion to other land uses (Grogan & Galvão 2006), and by re-entry logging whereby trees missed during the first harvest are discovered and removed. While mahogany can persist as juveniles and pole-sized trees in logged forests, commercial stocks rarely recover to pre-harvest levels (Grogan *et al.* 2002; 2008).

Effective public policy regulating trade in wildlife populations occurring across national boundaries requires basic knowledge of historic and current range and stocks (CITES 2009). Calvo & Rivera (2000) updated historic and current range estimations for mahogany in Mexico and Central America, finding that mahogany's original geographic range of 41 million ha had contracted in the mid 1990s by 61%. Lamb's (1966) range map for mahogany in South America, based on anecdotal reports and his extensive travels, estimated an historic range of 342 million hectares tracing an arc through the seasonally dry tropical forests of six countries from Venezuela to Bolivia (Martinez *et al*. 2008). This map, while useful, overestimated mahogany's distribution in some regions and offered no information regarding stocking densities.

In this article we revise Lamb's historic range map for mahogany and estimate the extent to which commercial stocks have been depleted in South America using satellite data, expert surveys, and sawmill processing center data from Brazil. Our methods offer a relatively cheap alternative to costly and time-consuming regional and national inventories that are difficult to implement across vast stretches of the Amazon Basin for timber species occurring at low landscape-scale densities like mahogany. We summarize the history of mahogany's exploitation during the past century, discuss the public policy implications of these results for mahogany and similar high-value tropical timber species, and describe recent institutional and management initiatives that could conserve surviving populations by encouraging sustainable use.

Brief history of exploitation

Mahogany from Venezuela and Colombia augmented Central American supplies exported by Spain during colonial times. Exports from Venezuela to the United States began as early as 1908; sawn timber production from Venezuela peaked in 1971 but has declined ever since due to loss of forest cover and over-exploitation where forests remain. Expansion of agricultural frontiers in Colombia led to extensive deforestation and loss of habitat during the first half of the 20th Century, while industrial logging depleted most remaining commercial populations by the late 1960s (Martinez *et al*. 2008). Easily accessible mahogany populations growing along western Amazon River tributaries in Peru and Brazil were logged out by the early 1950s (White 1978; Grogan *et al*. 2002). Ecuadorean populations were largely depleted during the decade following mahogany's "discovery" there in 1985 (Martinez *et al*. 2008).

The expansion of highways in Brazilian Amazonia during the 1960s and 1970s opened access to high-density populations in south Pará and Rondônia, sparking a "mahogany rush" (Browder 1987). An estimated 5.7 million m^3 of sawn mahogany timber were produced from Brazil between 1971 and 1992, with 75% of exports going to the United States and the United Kingdom. As regional

stocks became depleted and public outcry grew over rampant illegality and corruption in the mahogany industry, a federal moratorium on the harvest, transport, and commercialization of mahogany essentially shut down Brazilian supplies in 2001 (Grogan *et al*. 2002). The decline of Brazilian stocks during the 1990s caused Bolivian populations to come under heavy exploitation pressure, with Bolivia becoming the world's leading exporter by 1996. Stripped of mahogany in less than a decade, Bolivia now supplies less than 10% of international trade. After the Brazilian moratorium in 2001, Peruvian exports spiked, and Peru took over as the world's major supplier of sawn mahogany timber (Kometter *et al*. 2004; Grogan & Schulze 2008).

Methods

To describe mahogany's historic geographic range and current status in South America, we revised Lamb's (1966) range map based on national surveys of experts familiar with the species at local and regional scales. Experts drew upon various sources of information to complete the survey, including available inventory data, field, and research experience, and published literature (see Kometter *et al*. 2004 for detailed methods). We then measured forest cover within the revised range on a 500-m grid using MODIS satellite images collected in 2001 (GLCF 2003), differentiating deforested (<65% forest cover) from historically nonforested areas using data collected in 2000 by the European Union's scientific and technical research laboratory, the Joint Research Centre (JRC 2003). We also determined the area within mahogany's revised historic range under protected status, that is, where all types of logging are restricted (IUCN protected area categories I and II, in nature reserves, wilderness areas, and national parks), and inside Indigenous Lands.

To determine the extent of mahogany's forested range lost to predatory logging (Veríssimo *et al*. 1995), we subdivided the revised range into units along coherent political and/or geographic boundaries and interviewed local experts regarding the current status of mahogany within each unit, including approximate density of commercial populations. Concordance among independent respondents was high ($r > 0.87$), indicating that the data are robust (Kometter *et al*. 2004).

This approach could not be implemented in Brazil because experts proved reluctant to respond to surveys after a federal moratorium shut down mahogany exports in 2001. To estimate the extent of commercial depletion in Brazil, we overlaid mahogany's revised historic range with the location of major Amazonian sawmill centers and estimated the forest area exploited for mahogany based on maximum log transport distances that the mills reported in 1998 (Nepstad *et al*. 1999; Lentini *et al*. 2005). These distances, ranging from 34 to 300 km (125 ± 64 km SD, $n = 77$), represent financially acceptable transportation costs compared to the high value of mahogany. Given that Veríssimo *et al*. (1995) reported mean mahogany transport distances of 245 km (± 130 km SD) in southeast Pará in the early 1990s, we consider these single-year distance reports of generally less than 200 km to represent highly conservative estimates of the total area exploited for mahogany. Our analysis is also conservative insofar as it does not account for logging during the 3-year period after 1998 until the 2001 moratorium, for illegal logging which occurred after the moratorium went into effect, or for logging in western Amazonia (Acre, Amazonas) during the 1930s and 1940s that eliminated riverine populations (Grogan *et al*. 2002).

Results

Expert respondents revised Lamb's (1966) estimate of mahogany's historic range in South America from 342 to 278 million hectares (Table 1; Figure 1). Revisions were most pronounced in Venezuela, Bolivia, and Brazil, where Lamb's range overlapped extensive areas of savanna, *cerrado*, and scrub woodland habitats that are unsuitable for mahogany. Brazil alone accounts for 57% of the revised historic range.

By 2001 approximately 58 million hectares (21%) of the revised historic range had been lost to deforestation, with the greatest reductions occurring in Venezuela, Colombia, and Brazil (Table 1). Based on expert surveys and, in Brazil, timber processing centers (Figure 2), we estimate that an additional 125 million hectares of forests containing mahogany have been logged, further reducing the current commercial range to 94 million hectares or 33.9% of the revised historic range (Table 1; Figure 3). Total estimated losses were highest in Venezuela and Colombia (11% range remaining) and lowest in Peru (49% remaining). Our conservative method based on sawmill data estimates that mahogany's historic range in Brazil has contracted by at least 65%.

Expert surveys and published reports indicate that most surviving commercial stocks are extremely low-density populations in the most remote regions where loggers have yet to exploit primary forests, especially in western Brazil. While typical commercial stands in southeast Amazonia occurred at densities ranging from 0.27 to 0.39 trees ha^{-1} > 60 cm diameter before they were logged out, surviving populations in southwest Amazonia occur at much lower densities, generally < 0.10 trees ha^{-1} (Grogan *et al*. 2008). The best available landscape-scale

Table 1 Historic range of mahogany in South America, range that remains forested based on 2001 satellite data, and range that still has commercial populations based on expert surveys and, in the case of Brazil, sawmill processing center data. Areas are given in millions of hectares in all tables

Country	Historic range (m ha)	Percent historic range	Remaining forest cover (m ha)	Percent loss of forest cover	Current commercial range (m ha)	Current range as % of historic range
Venezuela	9.3	3.4	2.4	74.2	1.0	10.8
Colombia	18.1	6.5	9.1	49.7	2.0	11.0
Ecuador	6.8	2.4	6.3	7.4	1.8	26.5
Peru	54.8	19.7	52.7	3.8	27.0	49.3
Bolivia	29.9	10.8	27.5	8.0	7.0	23.4
Brazil	158.8	57.2	121.4	23.6	55.3	34.8
Total	277.7	100.0	219.4	21.0	94.1	33.9

estimate of densities for surviving commercial stands in Peru is 0.0167 trees ha^{-1} (UNALM-FCF 2007; Grogan & Schulze 2008). That is, the richest commercial stands have already been logged. The one-third of mahogany's range that possibly remains thus contains much less than one-third of original commercial stocks.

Nearly 7% of mahogany's revised historic range in South America was under legal protection in 2001 (Table 2), and an additional 15% lay within legally recognized Indigenous Lands (Table 3). Forest cover maps confirm that deforestation affects much lower percentages of protected areas compared to the overall range (4.8% vs. 21%; see Bruner *et al*. 2001), while Indigenous Lands are also highly effective at curbing deforestation (10% vs. 21%; see Schwartzman & Zimmerman 2005). In Ecuador, Peru, and Bolivia, 14–16% of mahogany's

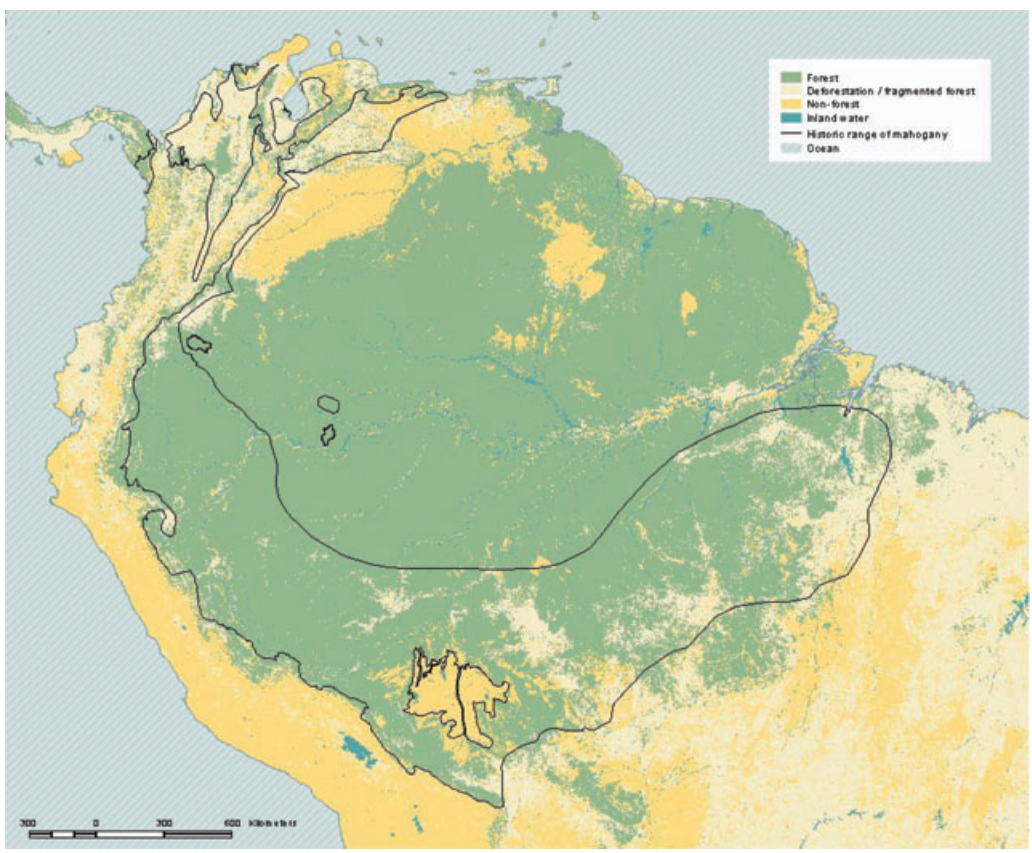

Figure 1 Historic range of mahogany in South America overlaid on forest cover based on 2001 satellite data.

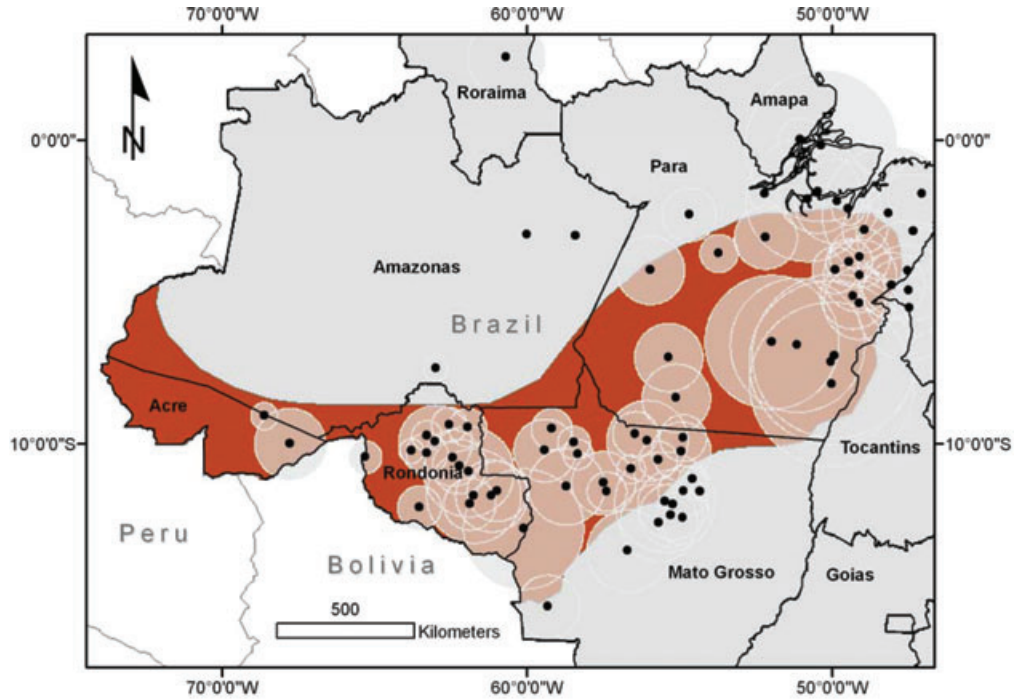

Figure 2 Distribution of sawmills in Brazil (black points) within the historic range of mahogany (darkened area). Circles indicate the maximum log transport distances reported by sawmills in 1998 and within which we assume mahogany is commercially extirpated.

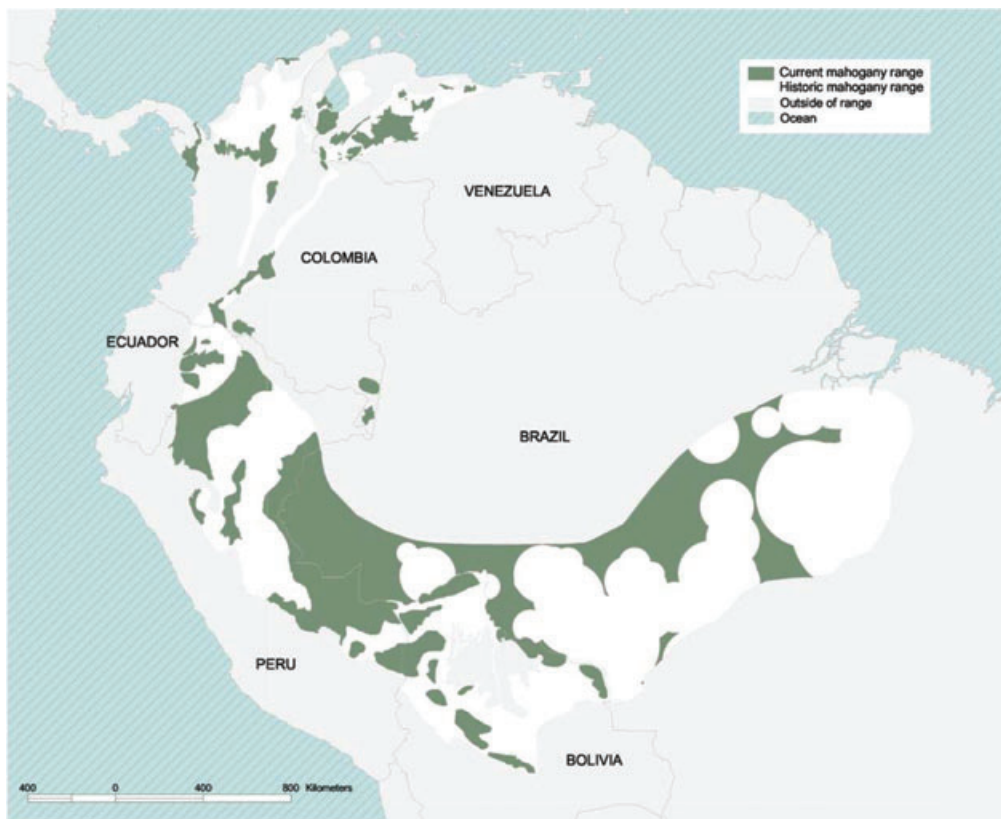

Figure 3 Distribution of existing commercial populations of mahogany in South America, shown by the darkened area within its historic range.

Table 2 Range of mahogany within legally protected areas (IUCN protected area categories I and II) in South America

Country	Historic range (m ha)	Range in protected areas (m ha)	Forest cover loss in protected areas (m ha)	% Range in protected areas deforested	% Range protected and forested
Venezuela	9.3	0.1	0.06	64.0	0.4
Colombia	18.1	2.1	0.13	6.3	10.9
Ecuador	6.8	1.1	0.004	0.4	16.1
Peru	54.8	7.8	0.16	2.1	13.9
Bolivia	29.9	4.2	0.37	8.9	12.8
Brazil	158.8	3.1	0.07	2.4	1.9
Total	277.7	18.4	0.80	4.3	6.3

historic range remained protected and forested. In Brazil, an estimated 22% of mahogany's historic range lay within Indigenous Lands and remained forested. However, in reality, throughout mahogany's range, its high value ensures that neither category of protected status affords real protection against illegal logging. This means that commercial populations cannot be assumed to survive where forests persist under protected status or within Indigenous Lands (Veríssimo *et al*. 1995; Greenpeace 2001; Grogan *et al*. 2002; Fagan & Shoobridge 2005, 2007).

Discussion

Empirical information on the geographic range and commercial status of high-value timber species in the neotropics is rare and fragmentary (Grogan & Schulze 2008; Grogan *et al*. 2008; Schulze *et al*. 2008a,b). This lack of information can cripple international public policy debates considering regulatory responses to unsustainable harvests (Blundell 2004). Facing this problem, we developed a rapid qualitative method for assessing historic range, presence, and stocking of mahogany in South America. This research protocol could be applied to other timber species facing heavy exploitation for which available information is inadequate for policy debate (Schulze *et al*. 2008a,b). Our method could advance international policy debates such as listing proposals for CITES Appendices by clarifying the commercial and conservation status of high-value timber species about which little information is available. For example, recent proposals to list *Cedrela* spp. and *Dalbergia* spp. on CITES Appendices made little headway for lack of adequate information about distribution, density, and rate of exploitation (CITES 2007).

Compared to field-based national inventories, the cost of our work was relatively inexpensive at $93,000. For example, an inventory of mahogany in Peru initiated in 2007 with funding from the International Tropical Timber Organization (ITTO) was estimated to cost $528,000 (ITTO 2005). A high level of concordance among expert respondents assessing identical geographic areas indicates consistent application of knowledge and experience, confirming the utility of this approach (Murray *et al*. 2009). While we do not suggest substituting our method for quantitative inventories, results reported here complement available field data and provide an informed best

Table 3 Range of mahogany within Indigenous Lands* in South America

Country	Historic range (m ha)	Range in Indigenous Lands (m ha)	Forest cover loss in Inidgenous Lands (m ha)	Percent of Indigenous Lands deforested	Percent range in Indigenous Lands and forested
Venezuela	9.3	–	–	–	–
Colombia	18.1	0.2	0.07	35.7	0.7
Ecuador†	6.8	–	–	–	–
Peru	54.8	1.0	0.05	5.1	1.7
Bolivia	29.9	2.1	0.08	3.7	6.8
Brazil	158.8	38.6	4.0	10.4	21.7
Total	277.7	41.9	4.2	10.0	13.6

*There is some overlap with protected areas in cases where Indigenous Lands are also designated as protected and fall within IUCN protected area category I or II.

†In Ecuador there is no official record of Indigenous Land boundaries. Legal demarcation of these lands was in process as this article was being written.

estimation of mahogany's current status until detailed inventories can be implemented.

These results reinforce concern over the critical status of mahogany in South America. We found that the previously accepted range estimate was too large by 64 million ha. Meanwhile a fifth of the revised historic range had been lost to deforestation by 2001, while an additional third of the geographic range had been selectively logged for mahogany. In fact, our estimation of the extent of commercial exploitation in Brazil considerably understates the reduction in mahogany's range and stocks there. Only 20% of sawmill operators were still processing mahogany within their range of operations in 1998 when the survey was conducted (Lentini *et al*. 2005); moreover, mahogany populations can be assumed to be commercially extirpated from forests within its range where only lesser-valued timber species are being logged (Veríssimo *et al*. 1995; Grogan *et al*. 2002). Extensive riverine populations in Acre and southwest Amazonas were logged during the early and latter decades of the 20th Century, but do not appear "logged" by our method because no sawmill processing centers were active in these regions in 1998. Accounting for these issues would likely reduce our estimate of the remaining unexploited range to less than 20% of the original revised range in Brazil.

Looking forward, the fate of remaining mahogany stocks in South America will depend on strengthening and enforcing policy initiatives such as the CITES Appendix II listing, and on transforming current forest management practices into sustainable production systems.

The situation in Brazil and Bolivia is encouraging. In Brazil, strict forest management guidelines regulating mahogany harvests were implemented in 2003. A scientific advisory committee must evaluate proposed management plans for mahogany harvests, including field verification, on behalf of the Brazilian CITES Scientific Authority. These new technical standards combined with the remote location of most remaining mahogany stocks have dramatically slowed industrial logging of mahogany in Brazil: only one timber company has legally harvested mahogany for export sale since 2003 (79 m^3 in 2006; C. Melo, personal communication). In Bolivia, Forestry Law No. 1700 passed in 1996 strengthened technical, operational and regulatory frameworks, and is credited with conserving surviving mahogany populations through improved management (Mejía *et al*. 2008).

A combination of international, bilateral, and domestic policy initiatives has stabilized the situation for mahogany in Peru since export volumes reached 52,138 m^3 in 2002 (Grogan & Schulze 2008). In response to the CITES Appendix II listing, the Peruvian government gradually reduced annual export quotas to 3,071 m^3 in 2007 (INRENA 2007; Mejía *et al*. 2008). As mentioned, a national inventory of remaining mahogany stocks was initiated in 2007 (Lombardi & Huerta 2007). Legislation establishing a roundwood (standing tree)-to-sawnwood conversion factor for the wood processing industry made it easier to assess the impact of mahogany export volumes on natural populations (Tomaselli & Hirakuri 2009). The 2007 Peru–U.S. Free Trade Agreement (FTA) included an annex on forest sector governance explicitly mandating both parties to implement a series of measures for mahogany, including verification of annual operating plans, nondetrimental export quotas, and physical audits. A CITES Significant Trade Review initiated in April 2008 addressed issues of legal sourcing and nondetriment in Peru without halting exports. An additional bilateral public policy instrument relevant to mahogany is the recently amended U.S. Lacey Act, which allows the U.S. government to seize timber that was harvested illegally, even if the importer had no knowledge of its illegality.

For trade in tropical timber species to be sustainable over time, logging industries must adopt best-management practices that reduce damages and encourage population recovery. Technical guidelines for mahogany production have improved since the late 1990s in the principal South American producer nations. The MDCL for mahogany was raised from 45 to 60 cm in Brazil in 2003; MDCL is 70 and 75 cm in Bolivia and Peru, respectively. Loggers are required to retain at least 20% of commercial-sized mahogany trees during harvests in Brazil and Bolivia; there is no retention rule in Peru (Mejía *et al*. 2008). Minimum density rules for commercial-sized trees in Brazil and Bolivia are intended to prevent reproductive isolation and population collapse in logged areas. In Brazil, forest managers are required to supplement low background levels of natural seedling regeneration with enrichment plantings in logging gaps and landings. Results from experimental enrichment plantings of mahogany have been promising (Lopes *et al*. 2008; Keefe *et al*. 2009), but financial costs and benefits of this approach at operational scales have yet to be evaluated. In Bolivia, harvest simulations based on long-term silvicultural research suggest that sustainable harvests of mahogany will require increasing the cutting cycle length beyond the current minimum of 20 years, reducing harvest intensity below the current 80%, and active management intervention aimed at maintaining optimal growing conditions for seedlings, saplings, and surviving trees (Verwer *et al*. 2008).

More broadly, it is essential that range nations maintain a functioning network of protected areas containing intact and viable populations, facilitating long-term maintenance of genetic and phenotypic diversity regardless of logging's impacts (Gullison *et al*. 2000).

Protected areas could serve as a source of seeds and seedlings for enrichment plantings in forests where logging has eliminated commercial populations. Incentives to forest-based Indigenous Amerindian communities to protect mahogany and other tree species rather than allow its over-exploitation would serve the dual goals of conservation and minimizing conflict. These goals can only be achieved with support and investment from importing nations whose consumer desires drive exploitation of high-value species and associated loss of habitat.

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