Sustainable forest management (SFM) of tropical moist forests: the case of the Brazilian Amazon

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1 Introduction

The Brazilian Amazon, with an area of 3.2 million km^2, is the largest tropical forest in the world (Laurance et al., 2001; Uhl et al., 1997). Despite relatively poor-quality soils, the forest exhibits rich biodiversity and plays a central role in local, regional, and global climate regulation (Soares-Filho et al., 2010; Nobre et al., 2016; Exbrayat et al., 2017). However, the region is well-known for historically high deforestation rates; roughly 20% of the original cover is estimated to have been lost since the 1970s (Souza et al., 2013). While pasture for livestock represents the main land use after clearing (≈80%), mining and, more recently, dams are also of major environmental concern for the future of the rainforest (Almeida Prado et al., 2016; Tyukavina et al., 2017; Veríssimo and Pereira, 2014).

Logging is the third most important economic activity in the Brazilian Amazon, after industrial mining and cattle ranching (Veríssimo and Pereira,

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2014). Timber production is highly concentrated (88%) in the states of Pará, Mato Grosso, and Rondônia (Hummel et al., 2010; IBGE, 2017), which are also the states with the highest rates of forest loss in the region (PRODES, 2019). In 2016, according to official data, the timber sector in the Amazon generated a total gross income of USD 1.2 billion (BFS, 2019a; IBGE, 2017).

From a social perspective, the timber sector outweighs by far other economic sectors in the Brazilian Amazon. It employs nearly 200 000 people, 67 000 directly and 137 000 indirectly (Pereira et al., 2010), equivalent to 2% of the economically active Amazonian population. However, due to the increasing overexploitation of timber in regions close to the large markets and transportation routes, and the growing efficiency of measures against illegal logging, large wood-processing centers have experienced a significant downturn over the last decade, with a reduction of 60% in sawn-timber production between 1998 and 2016, from 28 M m^3 to 11 M m^3 (Lentini et al., 2003; Hummel et al., 2010; BFS, 2019a). The rise of alternative products for wood, the global economic crisis, and the government action affecting the supply of illegal timber in the market are seen as mainly responsible for this decline (Pereira et al., 2010). However, it has been the unsustainable forest-management practices and the failure to implement forest conservation measures that ultimately drove logging centers in the Amazon to a situation of imminent collapse (Rodrigues et al., 2009).

Conventional logging activities in the region remain poorly managed (Macpherson et al., 2010). Overexploited (logged) forests become much more susceptible to wildfires and proliferation of lianas (vines) and pioneer species (able to quickly colonize degraded areas), compromising the regeneration of timber species and hence the long-term sustainability of forest resources (Gerwing, 2006; Kukkonen and Hohnwald, 2009; Scabin et al., 2012; Schwartz et al., 2014; Vidal et al., 1997). As is the case in most tropical regions, logging in the Brazilian Amazon is often unplanned, causing considerable (and avoidable) damage to the structure and composition of the forest (Holm et al., 2014; Lindenmayer et al., 2012; Purvis et al., 2012; Putz et al., 2012; Ruslandi et al., 2012). Cutting cycles are often too short to allow forests to fully recover timber stocks before the next harvest (Cole et al., 2014; Dubayah et al., 2010). Estimates suggest that most of the processed wood in the Brazilian Amazon originates from illegally harvested areas (Brancalion et al., 2018; Cardoso and Souza Jr., 2017). As a result conventional, as well as illegal, logging practices (i) decrease carbon stocks (Mazzei et al., 2010; West et al., 2014) and (ii) compromise the timber potential of the residual forests (Macpherson et al., 2010; Valle et al., 2007; Vidal et al., 2016).

Tree mortality also increases after logging (Mazzei et al., 2010; Schulze and Zweede, 2006), mainly due to collateral felling damage to the residual stand (Asner et al., 2006). Nevertheless, mortality rates are much higher in areas of unplanned logging when compared to planned harvesting operations (Mazzei et al., 2010; Sist and Nguyen-Thé, 2002; Valle et al., 2007). Post-logging mortality rates tend to decrease with time (Sist and Nguyen-Thé, 2002; Valle et al., 2007; van Gardingen et al., 2006), reaching pre-logging levels after ≈10 years (Graaf, 1986; Jonkers, 1982; Mazzei et al., 2010). While mean annual mortality rates range from 1% to 2% after natural disturbance (Hartshorn, 1990; Mazzei et al., 2010), rates tend to be higher after logging, ranging from 2.6% in Indonesia (Sist and Nguyen-Thé, 2002) to 2.5% in Eastern Amazonia (Silva et al., 1995) and 1.6–2.2% in Central Amazonia (Higuchi et al., 1997).

In recent decades the adoption of good forest-management practices seems to be increasing in the region (Brienen et al., 2015; Gerwing, 2006; Macpherson et al., 2012; Mendes et al., 2013; Mori et al., 2009; Sabogal et al., 2007; Salimon et al., 2011; Schulze and Zweede, 2006). A study that assessed the adoption of 14 good forest-management practices among loggers in Bolivia, Brazil, and Peru found that, on average, Brazilian loggers adopted roughly half of them (Snook et al., 2009). The reasons for adoption included new forest-management regulations (e.g., pre-approval of management plans), intensification of field inspections by environmental law enforcement officials, and increased wood demand for well-managed, and often certified, forests (McDermott et al., 2015; Schulze et al., 2008b).

Tropical forest logging is implemented selectively (e.g., felling of 5–8 trees ha^{-1}), given that only a limited number of tree species in the Amazon have a commercial value (Asner et al., 2002; Barros and Uhl, 1995). Negative impacts from the selective logging of native trees on the residual forest stand can be reduced if good practice guidelines are employed, for example, reduced-impact logging (RIL) techniques (Putz et al., 2012; Vidal et al., 2016; West et al., 2014), or if the number of harvest trees of a given species is adjusted based on the number of individuals from that species left in the stand (Vidal, 2004). RIL-based operations cause lower damage to forest cover when compared to conventional logging, contributing to the maintenance of biodiversity and ecosystem services such as soil and fire protection (Bicknell et al., 2014; Edwards et al., 2014; Putz et al., 2012).

In this chapter we present an overview of forest-management practices and regulations in the Brazilian Amazon, followed by a discussion of the benefits and challenges of legal forest management in the region, from private to community-based enterprises. Lastly, we summarize the course ahead to ensure the sustainable management of the Amazonian rainforest.

2 Regulation of Brazilian forest management

Forest management in Brazil is regulated at the federal level by the national Forest Code (Law 12,651), enacted in 1965 and revised in 2012 (Freitas et al., 2018; Soares-Filho et al., 2014). The law is complemented by a series of normative instruments that establish the basis for the legal harvesting of primary Amazonian forests via forest-management plans. However, it was only in 1994 that the principles and guidelines for sustainable forest management (SFM) were formalized in Brazil (Decree 1,282):

> The management of the forest to obtain economic, social, and environmental benefits, respecting the sustainability mechanisms of the managed ecosystem considering […] multiple timber species, multiple non-timber products, and by-products, as well as other forest products and services.

Initial regulations set by the Brazilian Institute of Environment and Renewable Natural Resources (or IBAMA) assumed that a 30-year minimum harvesting cycle would ultimately ensure the long-term sustainability of forest management in Amazonia. However, emerging scientific evidence questioning the 30-year period led to revisions and new logging regulations (e.g., extended cycles for slow-growing species). Although the new regulations were implemented to promote more sustainable forest-management practices, they also caused concern among stakeholders from the timber sector, reportedly concerned about potential (significant) reductions in profit margins (Richardson and Peres, 2016; Schulze et al., 2005, 2008a; Sebbenn et al., 2008).

Normative Instructions 4, 5, and 12, published in 2006 by the Ministry of Environment, are currently the most important logging regulations in Brazil. They serve as the basis for the development of Sustainable Forest Management Plans (SFMPs) in Amazonia. Specifically, in addition to resolution 406 from the National Council for the Environment (CONAMA), these regulations established the technical procedures for writing, presenting, implementing, and assessing SFMP, including the need for a specific, pre-approved Annual Operational (harvesting) Plan (POA) for each harvesting season. Harvested wood volumes and products were also required to be reported in a Forest Origin Document (DOF), a document designed to accompany legally harvested timber throughout all steps of the production chain (Waldhoff and Vidal, 2015).

Normative Instruction 5 also defined two forest-management categories:

1. Low-intensity forest management, often community-based, with maximum allowed harvest volume of 10 m^3 ha^{-1}, 10-year minimum harvesting cycles, and restrictions on the use of heavy logging machinery
2. Full forest management, which allows for a maximum harvest volume of 30 m^3 ha^{-1}, 25- to 35-year minimum harvesting cycles, and no machinery restrictions

The maximum volume allowed under a 35-year cycle from the second forest-management category implies a general timber-recovery rate of 0.86 m^3 ha^{-1} $year^{-1}$ at the forest stand level. However, this rate contrasts with the findings from the scientific literature and it is unlikely to ensure the long-term sustainability of forest management (Macpherson et al., 2010; Mazzei et al., 2010; Vidal et al., 2016).

3 Good forest-management practices in Amazonian Brazil

Similar to other tropical regions, SFM in Amazonia generally follows standard good practice guidelines (Pokorny et al., 2006; Sabogal et al., 2009; Tenório, 2010; Uhl et al., 1997). The main guidelines are described below (Fig. 1 and Box 1):

- *'100% inventory' of all harvest trees*. The 'census' of merchantable trees is the basis of the POA and contains information about tree volumes,

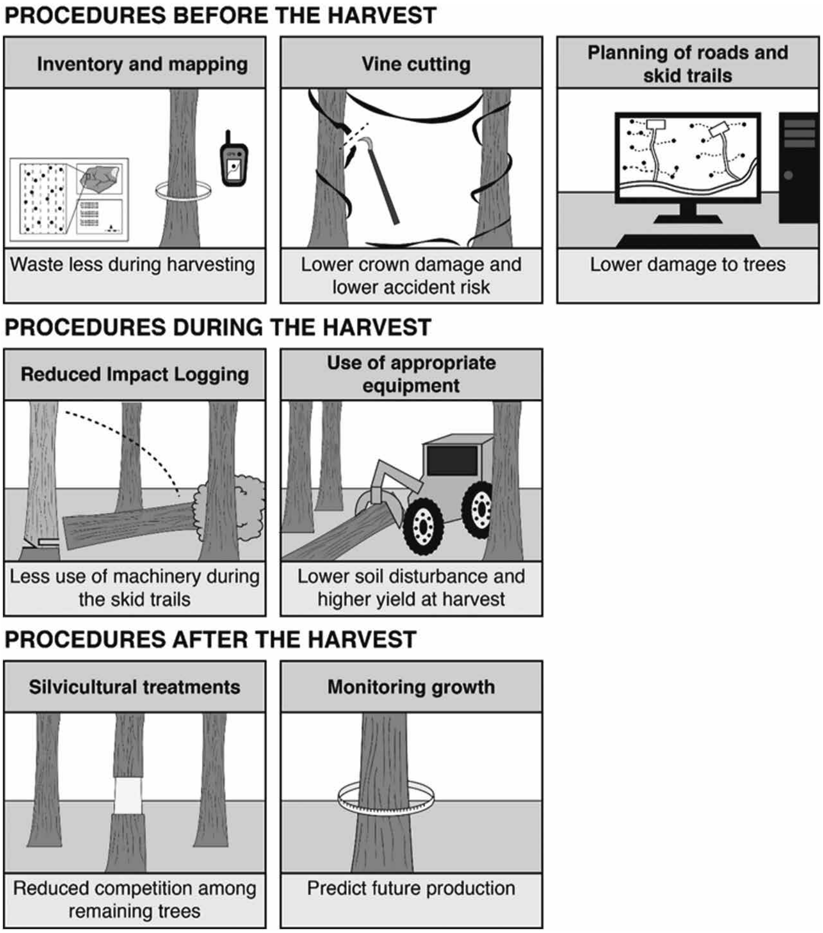

Figure 1 Guidelines for sustainable tropical forest management.

location, and topography. Census data is used to construct a map to guide pre- and post-logging activities (e.g., liana cutting, tree felling, and road, skid-trail and log-yard plan ning).

- *Harvest-block mapping*. According to current regulations, the forest area to be harvested is defined as a forest-management unit, which is divided into subunits, the annual production units (UPAs). Annual units are further divided into harvesting units (or blocks), which are the basis for logging planning.
- *Liana cutting*. Lianas are the common climbing plants in rainforests. Their presence makes harvesting difficult and can result in significant damage to the residual-forest stand as trees are felled. Liana cutting reduces collateral logging damage, wood waste, and accidents, and promotes better conditions for post-logging forest regeneration.
- *Road, skid-trail, and log-yard planning*. Infrastructure planning reduces costs and unnecessary damage to the forest.
- *Directional felling* aims to reduce damage to the harvested stem (reducing wood waste) and to the neighboring trees (collateral stand damage). It also facilitates wood removal from the forest, which can assist post-logging recovery due to reduced skidding damage. Studies suggest that directional cut can reduce waste of up to 1.7 m^3 ha^{-1} (Barreto et al., 1998; Gerwing et al., 1996).
- *Minimum-cutting diameters*. This approach has been traditionally adopted across tropical forests as an attempt to secure future timber provision. In Brazil, the standard minimum-cutting diameter is 50 cm, although it can vary based on local ecological assessments and tree species.
- *Additional restrictions on rare-species harvesting*. Forest-management plans must ensure that at least 3 trees/100 ha^{-1} from all species remain in the foreast after logging. This limit can increase to 4 trees/100 ha if the species is listed as vulnerable by the International Union for Conservation of Nature (IUCN).
- *Seed trees*. Minimum percentages of adult trees must remain in the forest after logging to maintain the genetic variability of the population. In Brazil, these numbers are 20% for the bigleaf mahogany (*Swietenia macrophyla* K.), 15% for vulnerable species (IUCN), and 10% for the other species.
- *Riparian-forest preservation*. In accordance with the national Forest Code, forests alongside streams, rivers, and lakes are critical for the protection of water resources and thus are ineligible for harvest.

Legal forest management of Amazonian forests in Brazil must follow an approved SFMP (BFS, 2019b). The technical procedures for the development of an SFMP can be divided into three phases:

1 design of the plan itself, which must be signed by a certified forestry professional
2 analysis of the plan by an approved environmental agency and its approval or rejection
3 implementation of the plan

These phases are shown in Fig. 2.

Before forest management can begin, a series of administrative procedures must be followed, starting with a land tenure assessment of the area (Normative Instructions 4, 5, and 12 from 2006, published by the Ministry of Environment; Waldhoff and Vidal, 2015). This analysis includes an assessment of the SFMP, POA, logging permit issued by the licensing agency, and the Forest Origin Document (Box 1).

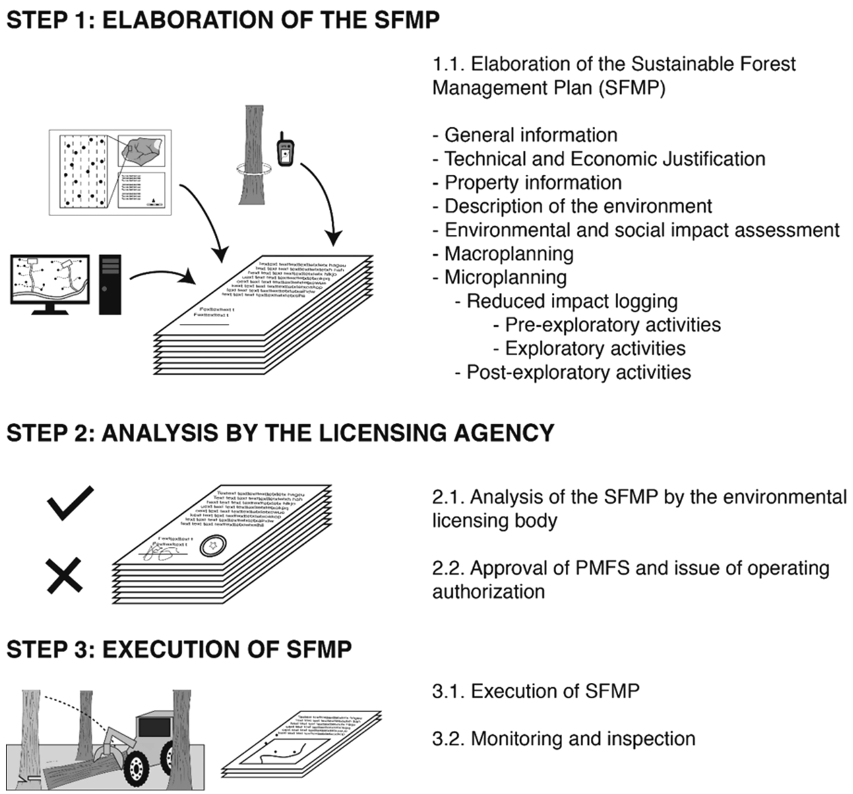

Figure 2 Steps for the development of a sustainable forest-management plan (SFMP) in the Brazilian Amazon.

Box 1 Legal procedures for sustainable forest management in the Brazilian Amazon

Step 1: *Authorization prior to the technical assessment* (APAT). Regulated by normative acts described before in this chapter, the APAT is the first step toward obtaining legal forest-management rights. In this step, an environmental licensing agency evaluates the legal and administrative feasibility of the forest-management plan. The APAT is issued after a property-level analysis, in which the location of 'legal forest reserves' (or Reserva Legais; RL), riparian forests (or Áreas de Preservação Permanente; APP), and deforested areas are checked. The proof that the certified forestry professional (i.e., forest engineer) responsible for the elaboration and submission of the SFMP has an active registry in the Regional Council of Engineering and Architecture (CREA) is also required for the issuance of the APAT.

Step 2: *Sustainable Forest Management Plan*. The SFMP is elaborated for a full management cycle (e.g., 25–30 years), with periodical revisions. The plan defines the harvesting periods and divides the forest into UPAs. The plan includes the installation of infrastructure and the forest inventory with estimates of the expected timber volume to be harvested per tree species. Satellite imagery of the property and the location of 'legal reserves' must be attached. The environmental agency verifies inconsistencies in SFMP, for example, conflicting ownership claims of the land. Inventory data and planned-harvesting volumes are also checked. In this step, the forest owner formally commits to not abandon the managed area during the forest-management cycle.

Step 3: A POA for each UPA must be approved by the environmental agency for every harvesting year and include forest-inventory information, a map, and a wood-waste management plan. In addition, the forest owner must disclaim the name of the companies purchasing the timber, as well as the volume and the destination of the wood.

Step 4: Once the management plan and/or the POA are approved, an environmental agency issues a 'license of operation', valid for a specific harvesting season. The license contains the volumes of each species to be harvested, the harvesting blocks to be managed, and its expiration date. The forest owner must report the timber volumes transported from the forest to the processing mills in an electronic monitoring system. The system is similar to a checking account, containing a limited quantity of approved 'timber-volume credits' for each tree species. Although transparent, and under continuous improvement, the electronic system is not completely protected from frauds, corruption, and illegality.

4 Private and community-based forest management in Amazonian Brazil

Forest-management activities can take place on private or public land. In this section, we describe three distinct forest-management systems in the Brazilian Amazon:

1 forest management in private lands (mainly conducted by companies)
2 management of public forest concessions
3 community- or smallholder-based forest management.

These are discussed in the following subsections.

4.1 Private-forest management

With the approval of the 2006 public forest management law (Brasil, 2006), states became responsible for the regulation of forest-management activities in the private land of <50 000 ha located entirely within their borders, excluding federal land and the growing of mahogany (separately regulated). Management of private forest land has been the most traditional type of forest management in the Brazilian Amazon. Despite the decline of logging activities in Amazonia in recent decades (Pereira et al., 2010), the abundance of timber resources and labor in the region still makes private-forest management an important business activity and a potential key driver of Brazil's green economy in the northern part of the country (C. L. S. Mori et al., 2009).

Historically, logging has been part of a set of strategies commonly adopted in the Amazon to secure land tenure status. Extensive 'forest mining' (i.e., predatory exploitation of commercially useful trees) often precedes forest conversion to alternative land uses (mainly low-productivity cattle ranching). The illegal supply of timber from these forest mining activities has most probably been responsible for the growth (and survival) of the Amazonian timber industry. Moreover, it has played a key role in the development of several municipalities in the region (now) connected by an official road system that was originally privately (and often illegally) constructed for timber transportation. This history contributed to the extremely low adoption of sustainable forest-management practices in the 1980s and 1990s. Widespread illegal logging activities also explain the resistance of Amazonian forest owners to comply with more restrictive forest-management regulations enacted in the middle 1990s. The larger private landowners were incentivized by the government to 'clean' forests for the promotion of regional development (Pedlowski et al., 1997).

Despite the unfavorable historical context, forest management remains as an important activity. In accordance with the national Forest Code, at least 80% of each private landholding in the Amazon must be a 'legal forest reserve' or Reserva Legais (RL). This makes it possible for forest management to still thrive where timber stocks have not been completely depleted even on properties focused on livestock production as an additional land-based activity. Ultimately, the promotion of legal forest management among Amazonian landholders will depend on effective incentives from the government and demands from consumers of forestry products.

4.2 Forest concessions

Forest concessions are a forest-management scheme conducted by selected organizations on public lands. Organizations are selected through public bidding, fulfilling a contract set by the government. In all cases, harvesting is only allowed based on an approved SFMP. In general, concessions in Amazonia are well-defined areas within protected areas that fall under the sustainable-use category (i.e., national, state, or municipal forests), in accordance with the National System of Protected Areas (SNUC). According to the public forest management law, the management rights of the concessionaire do not imply land ownership, access to mining, fishing, hunting, water-use, or other rights beyond what was set in the concession contract or the rights for the commercialization of 'carbon credits' (Brasil, 2006).

While the public forest management law was enacted in 2006, activities focused on the management of public forests in Brazil date back to the early 2000s. The first initiative involved a 'State Forest in Acre' in 2001 (Law 1426 of 2001). The experience learned from the acre experiment influenced the formulation of the 2006 policy which, in turn, enabled other states to create their own public forest-management regulations (although the federal government remains in charge of concessions in federally protected areas). The administrative framework responsible for concessions in Brazil consists of the Ministry of Environment (granting agency), the Brazilian Forest Service (management agency), IBAMA (licensing agency), and the National Council for the Management of Public Forests (advisory board).

The concession process consists of three phases (Balieiro et al., 2010; BFS, 2019b; Waldhoff and Vidal, 2015):

- pre-announcement
- announcement/bidding
- contracting

These phases are shown in Fig. 3. The public forests are eligible to become concessions if they meet specific criteria. These include possessing a valid Protected Area Management Plan, logging potential (i.e., valuable timber stocks and infrastructure), no presence of existing communities or potential for community use, and being listed as a 'potential concession area' by the Brazilian Forest Service (Brasil, 2006).

After the Public Forest Law was enacted, there was a widespread expectation among Amazonian stakeholders that forest concessions would gain scale and substantially increase the area under SFM in the region. Compared to the institutional, political, and economic context surrounding forest management in private lands, concessions were expected to be much

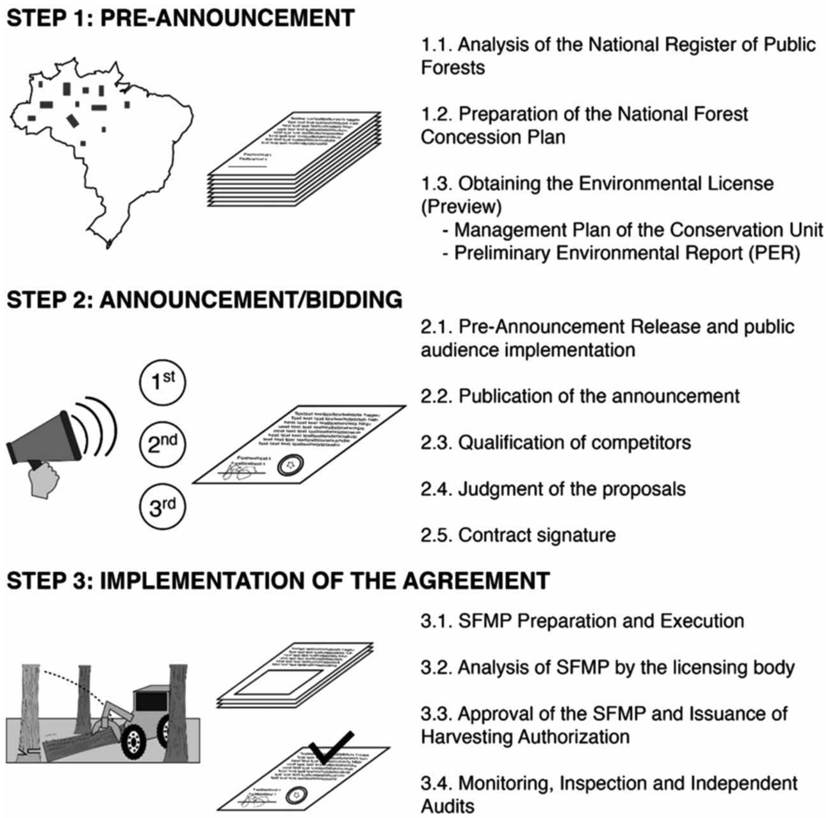

Figure 3 Steps for the creation of forest concessions in Brazil.

more attractive to investors due to their large size and clear tenure status. Moreover, many expected concessions to mitigate the problem of illegal timber supply. Estimates suggested that 20 Mha of forest under sustainable management would be needed to secure the long-term sustainability of the timber industry and the concessions would play a key role in achieving this objective (BFS, 2019a; FGV, 2016).

A number of factors help to understand the slow rate in granting forest concessions in Brazil. During the first four to five years after the Public Forest Law was enacted, there was an inadequate infrastructure in place. For example, few protected areas in the Amazon met the required criteria defined by the law to become concessions (e.g., completing a valid management plan or setting up an advisory council). This was the case for the Jamari National Forest, the first protected area included in a concession bidding process. The Brazilian Forest Service had also been recently created after the law was enacted and many of the concession procedures were still under development. In addition, that was the period when the management of environmental enforcement and licensing activities were being decentralized (from IBAMA to state-level agencies), which proved to be a long and difficult (but arguably necessary) process.

From the nongovernment stakeholder perspective, there was a widespread lack of understanding about processes and regulations relating to concessions. Entrepreneurs were unwilling to take the risks of being the first to apply. There was also the criticism of stumpage prices (prices per tree felled) which were seen as too high according to some stakeholders. Excessive bureaucratic procedures, reflecting government caution, resulted in extremely slow processes for granting concessions. Furthermore, a widespread misconception of the Public Forest Law led many local communities, nongovernmental organizations, and even the press to accuse the Brazilian government of 'trying to sell the Amazon to illegal timber companies'.

The process of granting concessions gained momentum after 2010 and covered an area of over 1 Mha by 2015, but some of the early problems persisted. There is still skepticism among timber companies about concessions and criticism of stumpage prices, while local communities and others still question the presence of concessions and potential unintended impacts on traditional indigenous community rights and livelihoods. Nevertheless, the main factor limiting the expansion of forest concessions in Amazonia is likely to be illegal logging.

In the light of this experience, the following recommendations were made during the 10th Anniversary of the Forest Concession Mechanism Workshop held in Brazil in 2016 IMAFLORA (2016) to promote Amazonian concessions:

1. identify ways to value and differentiate the concessionaire from traditional timber companies
2. reduce concession bureaucracy (e.g., the environmental licensing process, which is currently under the responsibility of multiple environmental agencies)
3. improve relationships with local communities
4. improve transparency and stakeholder communication
5. involve academia and local researchers to investigate the social, economic, and biological impacts of concessions
6. identify ways to strengthen and promote community-based forest management
7. support capacity-building initiatives for forest management

It is hoped these steps will simplify, strengthen, and accelerate the process.

4.3 Community-based forest management

Forest resources play a key role in the livelihood of many local communities in Amazonia and other tropical regions. In addition to the traditional use of forest resources (e.g., rubber, resins, fruits, seeds, medicines, and timber), new community-based forest-management (CBFM) schemes have gained momentum across the Brazilian Amazon in recent decades. Under these schemes, forest management is conducted by external agents such as the government, international, or local nongovernmental organizations, or a combination of the three (Sunderlin, 2006). Such a diversity of contexts, actors, objectives, and strategies make it difficult to define 'community-based forest management' in Amazonia (Amaral and Neto, 2005).

The Federal Program for Community and Family Forest Management defined CBFM as the 'implementation of management plans by "family farmers", agrarian-reform settlers, and traditional people and communities to obtain economic, social, and environmental benefits while respecting ecosystem sustainability' (Decree 6874 of 2009). The definition, although comprehensive, does not acknowledge the role of external actors nor distinguish subsistence from for-profit activities. For-profit management of native Amazonian forests dates to the country's colonial times, when Brazilwood (*Paubrasilia echinata*), the national tree of Brazil, was heavily marketed by Portuguese colonizers (Bueno, 1998).

There is a great potential for CBFM in Brazil. Communities are eligible to manage multiple types of protected areas and do not have to purchase logging rights from the government. Approximately 60% of the Amazon region is taken up by protected areas (≈235 Mha), of which 42% are indigenous lands (≈100 Mha) and 32% are protected areas under the sustainable-use category (≈77 M ha) (BFS, 2013). Estimates suggest that if half of the protected areas created by 2004 were under sustainable forest-management regimes, 5.6 Mm^3 of timber could be annually harvested, equivalent to 40% of the total 14 Mm^3 $year^{-1}$ produced in the region (Amaral and Neto, 2005; Pereira et al., 2010). Despite this potential, examples of successful CBFM activities are limited.

CBFM initiatives in Brazilian forests date to the mid-1990s. During 2009–2010 1213 CBFM initiatives were identified in six states of the Brazilian Amazon, 898 of those in Amazonas alone (BFS, 2010). Many of these activities were unauthorized, mainly due to the long distance from (and lack of ways to communicate with) the state environmental agency in Manaus (the state capital), limited government resources, and divergent interpretations of environmental regulations (Waldhoff and Vidal, 2015). Additional challenges relate to weak land-tenure systems, lack of capacity building for forest management among communities, and limited access to credit (Humphries et al., 2012; BFS, 2010; Hajjar et al., 2011).

CBFM could supply a significant share of the demand for Amazonian timber if effective enabling conditions were in place. It is essential for government agencies and nongovernmental organizations to be involved in the implementation of CBFM, especially when the forest is managed by third parties. The involvement of third parties is commonly found throughout the Amazon since most communities lack the required machinery, equipment, and skilled labor for forest management.

5 Sustainable forest management in Amazonian Brazil: challenges and strategies

Despite the large forest resources in Amazonia and other tropical countries, the opportunity cost of native forest management is often lower than other land uses, for example, soybean crops and palm oil plantations (Dang Phan et al., 2014). Moreover, a series of studies suggest that current logging regulations in Brazil are insufficient to secure the sustainability of forest-management operations (Macpherson et al., 2010; Valle et al., 2007). This section lists some of the challenges of forest management in Amazonia and strategies to support its long-term sustainability. These challenges include:

- *Species-specific minimum-cutting diameters* (MCD) set to assist the regeneration of commercial tree populations and sustain future timber stocks. The feasibility this strategy would depend on the existence of (i) a number of trees above the MCD in order to secure the profitability of the forest management and (ii) scientific information for the definition of species-specific MCDs (Lamprecht, 1989). Appropriate knowledge is the key to define appropriate species-specific MCDs, but it is still unknown for most tropical timber species.
- *Genetic depletion*. Evidence from the literature suggests unsustainable logging practices are linked to the genetic depletion of timber species in the Amazon (Sebbenn et al., 2008). It has been suggested that species respond differently to logging, which would imply the need for species-specific management regulations in order to mitigate genetic depletion.
- *Seed dispersal*. The long-term sustainability of forest-management activities could be augmented with improved seed-dispersal strategies. Directional felling can avoid residual trees from species with low-recruitment rates from being damaged during logging. In addition, recruitment rates could be improved if large trees from these species were harvested 2–3 years after the 'main' logging operation. During this interval, seeds from the unharvested species would benefit from reduced post-logging competition and could recruit a larger number of seedlings compared to the logged species;

- *Wood-processing efficiency*. Some studies have suggested the average wood-processing efficiency in the Amazon to be near 40% (Pereira et al., 2010), but the real number is thought to be much lower. Other studies found large sawmills in the region to have an average efficiency of 30%, but some could be less than 15% (Gerwing et al., 1996; Pereira et al., 2010). On the other hand, some sawmills – usually focused on small-wood products, such as wood flooring – can achieve much higher wood-processing efficiency (up to 85%). One of the possible reasons for the low wood-processing efficiencies across Amazonia is the strict international demands for high-quality wood products.
- *Land-tenure system*. Ownership remains one of the main unresolved bottlenecks in the Amazon (Fearnside, 2017). It was estimated that 32% of the supposedly private Amazonian lands lacked legal title documentation and only 4% of the private areas had titles validated by the National Institute of Colonization and Agrarian Reform (INCRA) in 2007 (Barreto et al., 2008). This situation has historically been an impediment for the legal forest management of private land. Ongoing government programs, for example, the national Rural Environmental Registry (CAR) and the Terra Legal (Duchelle et al., 2014), aim to improve the fragile Amazonian-tenure system.
- *Environmental agencies*. Organizations involved in forest management often lack trained staff, suffer from political and financial instability, misinterpret regulatory changes, and are overwhelmed by bureaucratic, administrative processes. Moreover, environmental agents are frequently involved in illegal licensing activities in the Amazon. The inefficiency of environmental agencies and licensing processes has become one of the main obstacles for the promotion of SFM in the region;
- *Illegal logging*. It is estimated that 44% (46 149 ha) of all native wood harvested between 2015 and 2016 in Pará state (the largest timber producer in Amazonian Brazil) was illegal. The economic viability of SFM in the region depends on improvements in governance and supply chain systems. Legally harvested timber cannot compete against illegally harvested timber because the large supply of the latter drives market prices down. Illegal logging is unlikely to be controlled solely by government efforts and without the engagement of consumers. Licensing, as well as the supply chain for forest-management operations, must be fully transparent, and national and international markets should demand legal, certified wood (Brancalion et al., 2018; Richardson and Peres, 2016);
- *Capacity building and training*. SFM requires specialized knowledge from different areas, both in the forest and in the office. The lack of trained labor to conduct forest-management activities can compromise management performance. Proper investment is needed for continuous training of

forest workers in activities such as the identification of native species, tree mapping, harvest planning, and machinery and equipment use (Lentini et al., 2009).

'Sustainability' has become a buzzword in environmental studies. Based on the work of Zarin et al. (2007), we suggest discussing forest management 'sustainability' based on the following criteria:

1 maintenance of forest cover and biodiversity over time
2 volumetric timber recovery (at both stand and species level)
3 maintenance of gene pools

Some aspects of sustainability are discussed below.

RIL techniques such as pre-harvesting maps, liana cutting, road and skid-trail planning, and directional felling have been demonstrated to improve stand-level volumetric recovery when compared to conventional logging (Keller et al., 2004; Valle et al., 2007; Vidal et al., 2016). Based on empirical data from RIL and conventional logging plots, West et al. (2014) reported that, on average, species common to both plots, and with 20–40 cm in diameter, grew faster after conventional logging than RIL. However, due to less collateral damage, the residual-forest stand subjected to RIL (considering all trees and species) recovered faster than its conventionally logged counterpart. However, evidence suggests that RIL alone is not enough to avoid long-term declines in volumetric recoveries (Dauber et al., 2005; Gourlet-Fleury et al., 2005; Kammesheidt et al., 2001; Phillips et al., 2004; Vidal, 2004). Moreover, species composition of managed forests is likely to change even if RIL guidelines are followed (Alder and Silva, 2001; Macpherson et al., 2012; Schulze and Zweede, 2006; Valle et al., 2007).

Given the length of harvesting cycles in the Amazon, most sustainability assessments of managed forests rely on simulation exercises. Using the CAFOGRON growth model based on logging intensities of 27–28 m^3 ha^{-1} $year^{-1}$, 4–6 trees ha^{-1}, and 30-year cutting cycles over a 200-year horizon, (Alder and Silva, 2001) found that forest management would only be sustainable if 66% of non-commercial species were included in the harvesting after the second cutting cycle. In a different modeling exercise, Valle et al. (2006) adapted the SYMFOR model, initially developed for Indonesian forests, to assess long-term effects of RIL and conventional logging on Amazonian forests. Results suggest the recovery of total and commercial volumes after RIL to be much faster than after CL (i.e., 10 and 30–40 years, respectively, in the former versus 35–40 and >60 years, respectively, in the latter). Nevertheless, evidence suggests that RIL techniques must be combined with additional silvicultural treatments and

Table 1 Estimated recovery of pre-logging timber volume of three Amazonian merchantable species after harvesting

	Timber recovery after harvesting (%)			
Tree species	30 years	60 years	90 years	120 years
Manilkara huberi (Ducke) Chev.	25	36	50	75
Hymenaea courbaril L.	20	52	61	117
Handroanthus impetiginosus (Mart. ex DC.)	4	9	11	18

Source: adapted from Schulze et al. (2005).

better logging regulations to secure lasting forest-management sustainability, at least at the stand level.

Most timber species in the Brazilian Amazon, and elsewhere, are slow growers. As a result, achieving sustainability in terms of volumetric recovery between harvesting cycles is even more challenging at the species level. Table 1 presents the estimated volume recoveries after harvesting for three popular Amazonian timber species, *Hymenaea courbaril* (jatobá), *Manilkara huberi*, and *Handroanthus impetiginosus*. Those estimates indicate that those species would require much longer harvesting cycles to fully recover than what is set by current logging regulations. Moreover, expected increases in the frequency of extreme droughts in Amazonia due to climate change could compromise even more post-logging timber recoveries, especially because large trees are suspected to suffer more from these events (Bennett et al., 2015; Bonal et al., 2016; Phillips et al., 2009; Vidal et al., 2016).

As mentioned earlier, current logging regulations in Brazil adopt a standard post-harvesting recovery rate of 0.86 m^3 ha^{-1} $year^{-1}$ (CONAMA Resolution 406 of 2009). The rate implies an oversimplified assumption that a 35-year cutting cycle would be enough to guarantee the recovery of 30 m^3 ha^{-1} (i.e., maximum-harvesting volume allowed) and, hence, the sustainability of forest management. A single standard rate for all managed forest in the Amazon is problematic because post-logging timber (and biomass) recovery is known to be a function of harvesting intensity (Rutishauser et al., 2015). Based on the 20-year data from a logging experiment in eastern Amazon, (Vidal et al. (2016) found a timber-recovery rate of 0.78 m^3 ha^{-1} $year^{-1}$ after RIL. If this rate was sustained, a 50-year period would be necessary for the residual stand to reach pre-logging timber volumes (given that in this case, the harvested volume was 38.6 m^3 ha^{-1}).

One strategy to sustain productivity levels in Amazonian forests would involve changing the current logging regulations to allow only the volume expected to be recovered within a cutting cycle to be harvested. Sound scientific evidence would be essential for the definition of standard recovery rates, which should ideally vary based on logging intensities. For illustrative purposes, we adopted the timber-recovery rates set by current logging regulations (and reported in Vidal et al., 2016) to set the maximum-harvesting volume under three distinct cutting cycles: 25, 30, and 35 years (Fig. 4). Under these scenarios, maximum-harvesting volumes would decrease from 21.5, 25.8, and 30.1 m^3 ha^{-1}, respectively (following current regulations), to 19.5, 23.4, and 27.3 m^3 ha^{-1}, respectively (based the recovery rate reported by the previous authors).

Many studies have questioned the extent to which forest-management techniques (e.g., RIL) can ensure that successive harvesting cycles will not alter diversity and undermine long-term timber production (Jennings et al., 2001; Sheil and Van Heist, 2000; Sist et al., 1998, 2003). While some advocates volumetric timber recovery at the forest stand-level to be sufficient (Alder and Silva, 2001), others argue that forest management should promote timber recovery at the species or species-group level (Vidal et al., 2016). Either way, given the growing issue of depletion of Amazonian timber stocks (Schulze et al., 2005; Sebbenn et al., 2008), forest companies should not be allowed to harvest more than the recovered volume between cutting cycles. At the same time, while it is well-acknowledged that current logging regulations must be revised to ensure sustainability objectives (Zarin et al., 2007), additional restrictions on harvesting volumes or the number of logged trees could compromise (even more) the financial feasibility of forest management in Brazil. Alternatively,

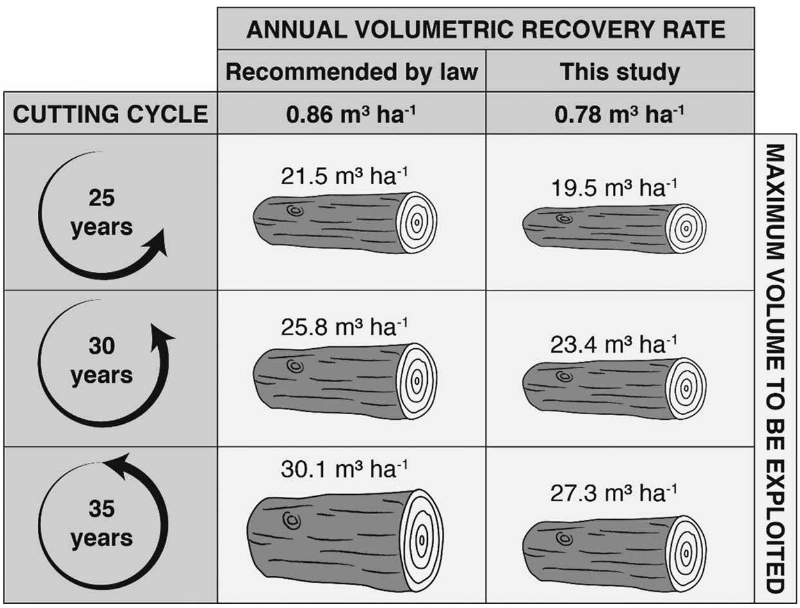

Figure 4 Estimated changes in timber recoveries based on the standard-recovery rate set by current logging regulations in Brazil and the rate reported in Vidal et al. (2016).

silvicultural strategies could help to sustain forest productivity levels in the long term.

Silvicultural treatments, for example, enrichment planting of timber species after logging and protection of future harvest trees, are two of the main strategies to increase timber productivity of the residual-forest stand (Peña-Claros et al., 2008; Wadsworth and Zweede, 2006) While these activities could increase timber volumes substantially and cover silvicultural costs (Peña-Claros et al., 2008), they would likely also reduce carbon stocks (at least in the short term) and tree diversity. In the Brazilian Amazon, enrichment planting is required for species with low regeneration rates, for example, Mahogany (*S. macrophylla*), Ipê (*Handroanthus* sp.), and Jatobá (*Hymenaea* sp.), but should be also incentivized for others.

6 Conclusions

Brazil has a complex system of regulations for the management of Amazonian forests. Legal harvesting operations struggle to compete against widespread illegal logging activities. Much of the hope for the expansion of legal, sustainable forest-management practices in the region relies on the improved promotion of unexploited forest concessions and CBFM, but those schemes will flourish only if the current bureaucratic processes are simplified and more locally applicable guidelines become available for CBFM activities.

Research has shown that even when forests are harvested following RIL guidelines, full recovery of pre-logging timber volumes often requires more time than set by current logging regulations (typically 25–35 years). Therefore, the promotion of post-harvesting silvicultural treatments is essential to secure the long-term sustainability of forest management in the Brazilian Amazon. Other strategies include the adoption of longer cutting cycles or the harvesting of lower volumes, potentially adjusted at the species or species-group level. However, if not properly designed, those strategies could undermine forest management and further stimulate illegal forest degradation and even deforestation. The marketing of alternative tree species may mitigate the overexploitation of current commercial species, but the implementation of this strategy relies on consumer acceptance and would require significant effort in creating demand for lesser-known tree species.

The way markets will adjust to changes in the Amazonian logging sector will define the future of forest management in the region. Current timber markets are mainly driven by consumers with little regard for forest sustainability. Demand for wood from well-managed forests will increase only if environmental awareness increases in Brazil and elsewhere. If that happens, nearly 30 Mha of Amazonian public forests, according to the Brazilian Forest Service, could be sustainably managed as forest concessions or as part of large-scale CBFM programs.

7 Where to look for further information

In Section 5 we have already discussed a little about some important points for research in the management of the Amazon rainforests. Prioritizing research we would recommend research related to:

Biological basis for advancing management. Forest communities are made up of hundreds of valuable or non-commercial tree species. These species compete for the same resource (light, water, nutrients, and space). These species require different characteristics of life history, as some grow quickly, produce seeds 1–2 decades after settling on the forest floor and die young. Other species are slow growing and need decades to reach the sexually mature stage and remain alive for centuries. In addition, each species has particular characteristics of pollination, production of seeds, seedlings and juvenile forms to reproduce and grow until adulthood. In this way, the different stages of the life cycle vary dramatically in relation with the resource conditions necessary for their survival and growth. All of these differences have implications for management in tropical forests. Therefore, studying the life cycles of timber species is fundamental and must be taken into account in order for crops to be more sustainable. For more details see Grogan et al. (2006).

Population genetics of species. The management of tropical forests changes the population size and spatial patterns of individuals within populations. This reduction in the size of populations, through forest management, can lead to genetic drift, which is characterized by the loss and random fixation of alleles and the increase of kinship and inbreeding within populations. Forest management reduces the adaptive, reproductive, and productive capacity of species through genetic drift. Forest management alters the spatial distribution of individuals within populations and can lead to changes in the density and behavior of pollinators, which can generate changes in crossbreeding levels, such as increased self-fertilization and, consequently, inbreeding. In the management of tropical forests, it is important to consider the genotypic constitution of individuals, which is responsible for differences in productivity, adaptation, and reproduction between individuals of a species. However, despite the great importance of individuals' genetic factors for the sustainable exploitation of a species, this component has been subjugated in management plans in natural tropical forests. In reality, there are no forest-management programs that consider the genetic component as one of the primary factors for the real effectiveness of sustainability. For more details see Bawa and Krugman (1990); Murawski (1995); Crow and Kimura (1970); Mettler and Gregg (1973); Ellstrand and Elam (1993); Falconer and Mackay (1997); and Sebbenn et al. (2000).

Species traceability through DNA is one of the priority research areas. With the current resources and control system, it is not possible to pinpoint with 100% security the origin of the vast majority of the commercialized wood, as well as tracing the final product to the tree that gave rise to it. As demonstrated by Brancalion et al. (2018) for the case of 'ipê' (a single species of the several that are commercialized), it is often not even possible to know whether the extracted trees really existed, which could be products of illegality. In addition, a considerable part of this illegality may be due to failures along the production chain, given that the State has a very limited inspection capacity and unsafe and efficient instruments/methods for verifying wood loads. On the other hand, several European countries, as well as the United States, have already adopted laws and programs to control wood entry, punishing companies that import illegal wood according to the legislation of the country of origin of the material. Thus, due to the stricter control of the entry of wood in these countries, access to these markets is increasingly limited, which requires the improvement of current technologies/procedures or the creation of new ones. In recent years, different diagnostic methods have been proposed and used to improve the traceability of timber products at different stages and scales, from taxonomic identification (in the field and along the production chain) to linking the individual to their area of origin that is legally granted for the purpose of extraction. However, as already highlighted by the authors, each method has its virtues and its technological and practical limitations. Despite these recent technological developments, including DNA-based forensic methods, in Brazil, the most used systems for traceability are still the identification painted on the log and the metallic or plastic platelets with bar codes or alpha-numerics. Thus, it is clear that there is a great weakness in the current control and monitoring systems. To worsen the situation, as recently demonstrated by Brancalion et al. (2018), the current system easily enables the 'legalization' of illegal wood, contributing in a dizzying way to unfair competition with legal enterprises, causing losses estimated at 477 million of the reais (only in the year 2009) arising from tax evasion in public accounts, such as tax evasion of state and federal taxes. For more details see, for example, EUROPEAN COMMISSION DG ENVIRONMENT 2008;EU Timber Regulation 2010; US Lacey Act 2008; Dormontt et al. (2015); Lowe et al. (2010); and Adeodado et al. (2011).

For more information on the topics discussed in this chapter you can consult:

- Brazilian Forest Service (www.florestal.gov.br)
- IBAMA (www.ibama.gov.br)
- ICMBio (www.icmbio.gov.br)
- Ministério do Meio Ambiente (www.mma.gov.br)
- Brazilian Agriculture Research Corporation (www.brazil.gov.br)
- IBIF (http://www.ibifbolivia.org.bo)

- CELOS (https://www.tropenbos.org)
- IWOKRAMA (https://iwokrama.org/)
- IIAP (www.iiap.org.pe)
- French Agricultural Research Centre for International Development (CIRAD) (http://ur-forets-societes.cirad.fr)
- Tropical managed Forests Observatory (TmFO) (https://www.tmfo.org)
- Imazon (http://imazon.org.br)
- IDESAM (http://idesam.org.br)
- IFT (http://ift.org.br)
- IEB (http://iieb.org.br)

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