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Improving sustainable tropical forest management with voluntary carbon markets

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Abstract

Purpose

Due to a rapidly changing climate, voluntary carbon markets are gaining momentum and should be leveraged to improve and expand tropical sustainable forest management plans, limiting carbon emissions and enhancing critical carbon sinks. By sequestering more carbon than any other terrestrial ecosystem — ~1 Pg C yr^{-1} — tropical forests provide crucial natural climate solutions and opportunities in the evolving voluntary carbon market.

Methods

Here, we argue that some issues with the current sustainable management of tropical forests can be addressed using carbon-focused sustainable forest management (SFM+C) to leverage financial resources for tropical forest carbon storage and sequestration. We suggest an extended harvest cycle in SFM+C and calculate an associated potential increase in aboveground carbon stocks of commercial timber of 1.26 Mg C ha^{-1} after each cycle in the Brazilian Amazon.

Results

The additional carbon storage due to a longer harvest cycle can generate carbon credits worth 152.6 (SD 9.2) US dollars per hectare in 40 years. Considering an average cost of 180 BRL per m^3 of commercial timber delivered to the sawmill, an SFM+C plan with a 40-year cycle could generate 28.7% (SD 2.5) more profit than 35-year cycles by combining timber and carbon revenues.

Conclusion

A robust carbon price could incentivize the further extension of harvest cycles, providing a monetary return that offsets the opportunity cost intrinsic to harvesting under longer cycles. Finally, we highlight research needs to support tropical SFM+C, which can be part of a global collective effort to limit global warming to below 2°C above pre-industrial levels.

Keywords: Amazon forests, forest carbon stock, climate change, natural climate solutions, reduced-impact logging

Due to a rapidly changing climate, voluntary carbon markets are gaining momentum and should be leveraged to improve and expand tropical sustainable forest management plans — i.e., those following national regulations, including reduced-impact selective logging that minimizes damage to the standing forest (MMA 2009), limiting carbon emissions and enhancing critical carbon sinks (Numazawa et al. 2017; Pinard and Putz 1996; Putz and Pinard 1993). The number of carbon credits or metric tons of carbon dioxide (CO_2) bought, traded, and retired voluntarily is increasing (Kreibich and Hermwille 2021), connecting natural ecosystems and climate finance. With global atmospheric CO_2 concentration rising at an estimated rate of 3.40 ppm year^{-1} (NOAA, 2020), the carbon market provides a mechanism to couple voluntary efforts to halt new and drawdown past carbon emissions with the carbon storage and sequestration potential of the world's ecosystems. By sequestering more carbon than any other terrestrial ecosystem (Cook-Patton et al. 2020) — approximately 1 Pg C yr^{-1} (Mitchard 2018) — tropical forests provide crucial natural climate solutions (Griscom et al. 2017) and opportunities in the evolving voluntary carbon market (Sools et al. 2021). However, ongoing deforestation (i.e., forest conversion to another land cover or the long-term reduction of tree canopy cover below 10%; FAO, 2007) and degradation (i.e., temporary or permanent deterioration in forest cover, composition, function, and ecosystem services; FAO, 2007; Longo & Keller, 2019) undermine the integrity and climate mitigation potential of these forests (Kruid et al. 2021), and highlight the urgent need for improved management of tropical forests (Ellis et al. 2019; FAO 2020; Kraxner et al. 2017; Merry et al. 2009; Sist et al. 2021), including for carbon sequestration benefits (Koh et al. 2021; Mitchard 2018).

Forest management that does not follow reduced-impact logging guidelines designed to reduce carbon emissions and damage to the remaining stand (The Nature Conservancy, TerraCarbon LLC 2016; Zalman et al. 2019) can degrade tropical forests (e.g., Johns et al., 1996; Romero et al., 2020). The degraded forest area has now overcome deforested area in the Amazon (Matricardi et al. 2020), the world's largest tropical forest with ~123 Pg C of above- and belowground biomass (Malhi et al. 2006). Further, deforestation continues to result in carbon emissions (Qin et al. 2021). For example, in 2021, Brazil's National Institute for Space Research reported ~22% more clearings in Amazon forests compared to 2020, despite Brazil's commitment to the Paris Agreement on Climate Change to eliminate illegal deforestation by 2030. Illegal logging is, in fact, a solid barrier to the promotion of sustainable use and conservation of Amazon forests in the global timber market (Brancalion et al. 2018).

At the same time, in Brazil, the legislation establishes permissions, obligations, and restrictions for wood removal from Amazon forests under sustainable forest management (SFM) plans (MMA 2006, 2009). SFM plans enable faster post-harvest recovery of forest biomass compared to conventional logging (Rutishauser et al. 2015; Vidal et al. 2016; West et al. 2014) and provide a mechanism to avoid conversion to monocropping systems and widespread illegal logging and consequent carbon emissions (Kleinschmit et al. 2021; Santos de Lima et al. 2018; Sist et al. 2021). Carbon stocks in tropical forest soils (~155 Pg C; Pan et al., 2011; ~36 Pg C in the top 100 cm of Brazilian Amazon soils; Gomes et al., 2019) can also be maintained with SFM that limits machinery access into the stand (Barros and Fearnside 2016; Berenguer et al. 2014; Bomfim et al. 2020; Pinard and Putz 1996; Putz et al. 2012; West et al. 2014) and silvicultural practices (e.g., liana cutting; Peña-Claros et al., 2008) that decrease the impact associated with tree felling (Johns et al. 1996). Selective logging that does not limit machinery impact on tropical forest stands can decrease soil carbon stocks for up to 50 years (Chiti et al. 2016). Despite SFM's proven benefits, especially relative to conventional logging (e.g., Pinard & Putz, 1996), revising it before expanding across the tropics is imperative, especially under a changing climate.

The incipient voluntary carbon market incentivizes carbon-focused sustainable forest management (SFM+C) by capturing financial resources required to leverage tropical forest carbon storage and sequestration potential (Ellis et al. 2019; Putz and Pinard 1993; Sasaki et al. 2012). SFM+C is an opportunity to improve current tropical SFM plans (e.g., Piponiot et al., 2019) and tackle climate change by increasing tropical forest carbon sequestration while ameliorating degradation, protecting biodiversity and ecosystem services (MacDicken et al. 2015), and generating inclusive livelihoods to forest populations (de Toledo et al. 2017). This coupling could be possible by adapting SFM to carbon-inclusive strategic planning, which requires substantial alignment between project- and national-level carbon accounting (West et al. 2020). Although there are numerous limitations to current SFM plans that should be addressed, there is an urgent need to improve management by considering the role that site characteristics (e.g., soil properties), tree species traits (e.g., growth rate, wood density), and extended harvest cycles can play in mediating the effects of climate change on managed forests.

Current tropical SFM plans, such as those in the Brazilian Amazon, fail to fully account for species- (e.g., Romero et al., 2020) and site-specific tree growth (de Miranda et al. 2018) and mortality dynamics (Rosa et al. 2017). Instead, the Brazilian legislation establishes one sole minimum logging diameter (DBH or stem diameter at 1.3 m above the ground ≥ 50 cm) and a harvest cycle of 25–35 years. These numbers are based on a single legally-established tree growth rate of 0.86 m^3 ha^{-1} y^{-1} and maximum cutting intensity of 30 m^3 ha^{-1} for the whole forest (MMA 2006, 2009). Current SFM relies solely on the natural regrowth of commercial (and not-yet-commercial) tree species (Bomfim et al. 2020; Kozlowski 2002). Further, uncertainty exists regarding the capacity of the selective group of commercial tropical tree species (David et al. 2019) to support (e.g., grow fast enough) the continuity of future harvest cycles under a changing climate, which has been affecting the natural dynamics and functioning of forests (McDowell et al. 2018). Tropical SFM+C represents an opportunity to overcome these and other challenges to current SFM and align with state-of-the-art tropical forest and soil science under a changing climate perspective (Figure 1a). Tropical SFM+C could benefit from a more nuanced approach to management that accounts for variation in tree functional diversity (e.g., Sakschewski et al., 2016) and soil properties to determine site- and species-specific harvest cycles, minimum logging diameter, cutting intensity, and post-harvest management.

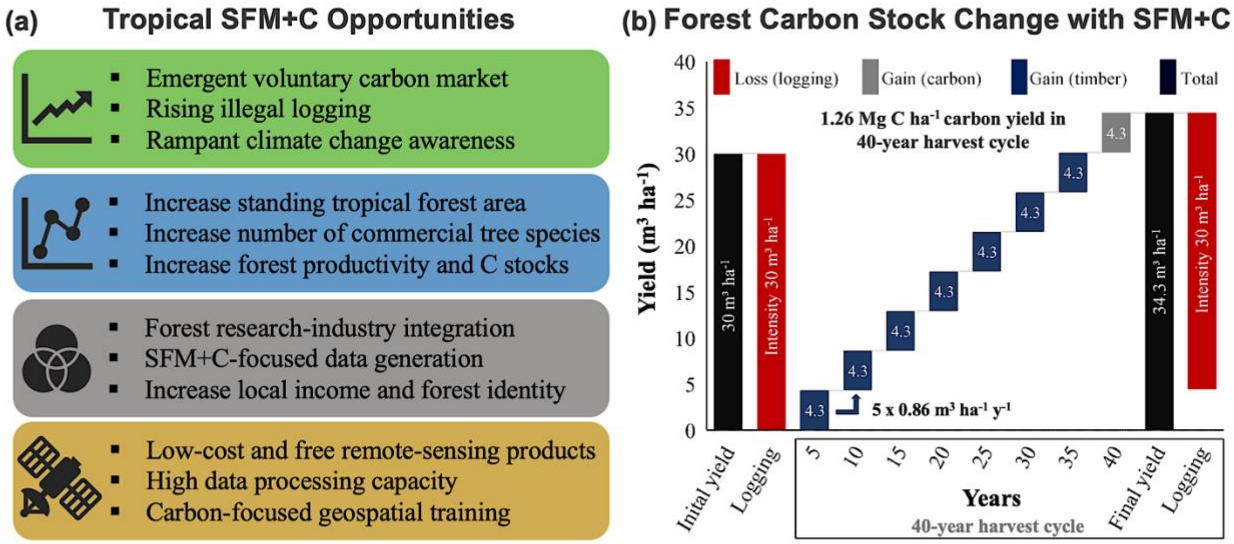

Figure 1 (a) Opportunities for tropical SFM+C, including **(b)** estimated changes in Brazilian Amazon forest aboveground carbon stock by increasing the harvest cycle from 35 to 40 years. "**Initial yield**" is the maximum legally allowable stock of commercial timber (30 m^3 ha^{-1}) in the first harvest entry. "**Logging**" indicates the cutting intensity to remove the "initial yield"; in this case, the maximum legally allowable value of 30 m^3 ha^{-1} was used. "**Yield**" (in m^3 ha^{-1}; y-axis) is the amount of timber grown over time, which depends on the legally established average tree growth rate of 0.86 m^3 ha^{-1} y^{-1}; under Brazilian law, this value is calculated by dividing the maximum cutting intensity of 30 m^3 ha^{-1} by the harvest cycle of 35 years; MMA, 2009). "**Harvest cycle**" is the time in years between successive harvest events (x-axis). "**Loss (logging)**" – red bar – is the amount of timber removed from the forest in each harvest cycle. "**Gain (timber)**" – dark blue bars – is the mean annual commercial tree growth, for the entire forest stand, destined for regularly replacing the amount of timber harvested, where "**Gain (carbon)**" – gray bar – represents the amount of carbon stored as aboveground biomass of commercial trees. The post-logging forest recovery per year was assumed to be linear with time (Numazawa et al. 2017; Rutishauser et al. 2015). The carbon additionality of 1.26 Mg C ha^{-1} was calculated as (600 kg/m^3 × 490 g C/kg × 0.86 m^3/ha/year × 5 years)/1000000.

A turn toward SFM+C that considers species and site characteristics reflects empirical studies indicating differential tree growth and replacement rates across commercial species in African and Amazonian forests (Brienen and Zuidema 2006; de Miranda et al. 2018; Groenendijk et al. 2014; Therrell et al. 2007). Romero et al. (2020a) showed that C stocks in commercial Amazon logs vary from 5.4 to 224.9 kg C ha^{-1}, reflecting a wide variety of species-specific functional traits such as wood density (Phillips et al. 2019) and growth rates. *Manilkara elata* saplings (i.e., 5-cm DBH), for instance, require over 600 years to reach a 50 cm diameter, the minimum required for harvesting (Ferreira et al. 2020). Tree growth also varies with climatic extremes like extended drought (Amissah et al. 2018; Brodribb et al. 2020; Fontes et al. 2020) and soil properties that contribute to carbon and phosphorus retention, like texture (Soong et al. 2020; Turner et al. 2018). As a result, providing timber from slow-growth tree species or species growing on low-productivity sites for future harvest cycles may not be sustainable even under SFM plans.

To improve and better position tropical forestry to contribute to natural climate solutions (De Ridder et al.

2013; Ferreira et al. 2020; Leoni et al. 2011), SFM+C plans can extend current harvest cycles (Roopsind et al. 2017). While targeted research is needed to guide the elaboration of species- and site-specific forest regulation in SFM+C, extending the harvest cycle corroborates studies suggesting that 40+ years (or to > 60 years; (Roopsind et al. 2017; Rutishauser et al. 2015; Sist et al. 2021) are appropriate for reducing emissions from deforestation and forest degradation (REDD+) in SFM plans (Numazawa et al. 2017; Sasaki et al. 2012). This would ultimately benefit forest growth and carbon sequestration and generate carbon credits for evolving voluntary markets. This carbon finance can, in turn, strengthen the economic viability of SFM+C harvest operations, leading to more carbon permanence (Sools et al. 2021).

Extending the harvest cycle from the current maximum of 35 to 40 years, for instance, would decrease century-scale logging frequency and represent potential additionality of around 1.26 Mg C ha^{-1} sequestered as (aboveground) commercial timber after each harvest cycle (Figure 1b; Supporting Information Table 1 includes the forest timber and carbon calculation details). This estimate is the product of the legally-established tree growth rate of ~0.86 m^3 ha^{-1} y^{-1} (MMA, 2009), the mean wood density of 600 kg m^{-3}, and the mean carbon concentration of 49% (Romero et al. 2020a, b). This additional carbon storage in commercial trees due to a longer harvest cycle can generate carbon credits worth 152.6 (SD 9.2) US dollars per hectare in 40 years — assuming the January 2021 weighted carbon credit price of 34.99 US dollars from the IHS Markit Global Carbon Index and discount rates between 2 and 10% (Emmerling et al. 2019; Koh et al. 2021) (Supporting Information Table 2 includes the carbon credit calculation details). Considering an average cost of 180 BRL per m^3 of commercial timber delivered to the sawmill for an internationally-certified company, an SFM+C plan with a 40-year harvest cycle could generate 28.7% (SD 2.5) more profit than 35-year cycles by combining timber and carbon revenues (see Supporting Information Table 3 for calculation details). A robust carbon price could incentivize the further extension of harvest cycles, providing a monetary return that offsets the underlying opportunity cost intrinsic to harvesting under longer cycles. We expect high-quality carbon prices to rise sharply as the global economy seeks to avert the climate crisis.

To meet the requirements of SFM+C, field-based, management-focused research in tropical forests is a critical need. Site- and species-specific baseline carbon sequestration information is key to develop SFM+C plans that consider, and accommodate within planning and operations, the different rates at which trees grow due to the soils and their vulnerability to extreme weather events under climate change. Uncertainty exists regarding which commercial tree species are most vulnerable to extended drought or the compounded effects of multiple disturbances changing in frequency and intensity. It is also essential to understand how species with different carbon densities can be leveraged in SFM+C. Revised allometric equations for volume, biomass, and carbon (Romero et al., 2020b) would contribute to SFM+C. Bioeconomic studies can apply appropriate models (e.g., Hartman model; Indrajaya et al. 2016) to analyze the potential of voluntary carbon markets and REDD+ to induce carbon sequestration in tropical forests under SFM+C. Finally, research needs to address uncertainties regarding additionality, permanence, and leakage in SFM+C carbon accounting, especially considering how changing climate may alter standing forests' growth rates and carbon integrity. Future research efforts are possible through effective research-industry-government collaboration to generate open and reproducible data management workflows.

A new era of SFM+C requires measurement, reporting, and verification (MRV), which can benefit from recent technological advances in remote and field monitoring, most of which are available at low cost. Relevant examples are the increasing availability of high resolution and near real-time satellite images, such as those made freely available by Norway's International Climate and Forests Initiative Imagery Program; uncrewed aerial vehicles (UAVs/drones) imagery to estimate harvested volume (Locks et al. 2017); and terrestrial and airborne lidar to estimate canopy and understory damage from logging operations (Dalagnol et al. 2019; Roşca et al. 2018). Another game-changing technological advance for remote monitoring is the cloud-computing platforms such as Google Earth Engine (Gorelick et al. 2017), which allowed for robust and automated selective logging detection using remotely sensed images (e.g., Hethcoat et al. 2019, 2020). While using these technologies that enable MRV at large scales requires coordination among research institutions, funding agencies, and field operators, partnerships among these stakeholders would fill training and data collection gaps.

Overall, the SFM+C framework can be part of a global collective effort to limit global warming to below 2 degrees Celsius above pre-industrial levels (Rogelj et al. 2018). Emissions reductions achieved through SFM+C plans with an extended harvest cycle can benefit from carbon revenues from voluntary markets. An increasing number of companies worldwide looking to reduce their carbon footprints voluntarily are willing to fund efforts like SFM+C by purchasing carbon credits. In addition, forest managers in internationally-certified logging companies already capitalize on sustainable management certification schemes — e.g., Forest Stewardship Council (FSC) — thereby lowering the threshold for carbon certification in FSC-certified areas (Sools et al. 2021). While leakage is a risk with avoided deforestation, SFM+C ensures local jobs and, especially if adopted widely, lowers leakage risk (Sools et al. 2021).

SFM+C plans can also benefit from results-based payments of the REDD+ program under the United Nations Framework Convention on Climate Change (UNFCCC) (Indrajaya et al. 2016; MMA 2018; UNFCCC 2021). All private and concession tropical forests managed under SFM+C could align with the country's commitment to climate change mitigation under the UNFCCC, making sure to avoid double counting of carbon additionality and avoided emissions. Brazil, for instance, has committed to reducing greenhouse gas emissions by 37% in 2025 and 43% in 2030 (BRAZIL 2020). Therefore, if Brazil makes a policy change to expand tropical forest areas under SFM+C to help reach its intended Nationally Determined Contribution, voluntary markets could financially support SFM+C beyond the country's limit. Because of the accelerated rate under which our climate is changing due to greenhouse gas emissions over the past fifty years, the clock is ticking, and tropical forestry should take advantage of climate finance and the emergent voluntary carbon market to advance the sustainable management of tropical forests. Ultimately, species- and site-dependent SFM+C plans, with a proper carbon verification standard, can be tested, improved, and replicated across the tropics, reinforcing the central role of working tropical forest lands in mitigating climate change.

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