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Greenhouse gas emissions during intermodal transport of timber exported from the Brazilian Amazon: a case study

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ABSTRACT: Approximately 92% of timber from the Brazilian Amazon is consumed domestically, mostly for use in construction. The main destination for this wood is the Southeast and South regions of the country, relying heavily on road transport, which is a significant source of greenhouse gas emissions. This study simulated carbon dioxide emissions associated with intramodal transport of this timber from forest management units to sawmills, ports, and international consumer markets, comparing values for transporting raw wood versus processed lumber to be used in long-lasting applications that serve as carbon reservoirs. Carbon stocks in the harvested wood were also calculated to estimate the balance of emissions sequestered during growth and pollution resulting from wood transport. A total of 7,388.57 t of CO_2 were generated during shipping, which included road (4,672.64 t), river (111.25 t), and maritime (2,604.68 t) routes covering over 48,000 km. In contrast, a total of 37,268.9 t CO_2 was sequestered and stored in the wood. We determined that transport emissions represented 19.81% of the stored carbon, indicating a significant mitigation of greenhouse gas emissions.
Keywords: Amazon rainforest; carbon balance; greenhouse gases; timber transportation.

Um estudo de caso das emissões de gases de efeito estufa durante o transporte intermodal de madeira exportada da Amazônia

RESUMO: Na Amazônia brasileira, cerca de 92% da madeira produzida é consumida internamente, com destaque para o setor da construção civil. As regiões Sudeste e Sul são os principais destinos, utilizando majoritariamente o transporte rodoviário, que contribui significativamente para as emissões de gases de efeito estufa. Este estudo simulou as emissões de CO_2 no transporte da madeira desde a unidade de manejo florestal até serrarias, portos e mercados consumidores. Foram comparadas as emissões do transporte de madeira bruta e processada, esta última usada em produtos de longa duração, como na construção civil, onde atua como estoque de carbono. Também foi avaliado o carbono armazenado na madeira extraída para estimar o balanço entre sequestro e emissão de CO_2. As emissões totais foram de 7.388,57 t CO_2, considerando trajetos rodoviários (4.672,64 t), fluviais (111,25 t) e marítimos (2.604,68 t), em um percurso total de mais de 48 mil km. Já o carbono armazenado somou 37.268,9 t CO_2, sendo as emissões equivalentes a 19,81% desse total, indicando mitigação relevante das emissões.
Palavras-chave: floresta Amazônica; balanço de carbono; gases de efeito estufa; transporte de madeira.

1. INTRODUCTION

In Brazil, timber is a product that has been transported over vast distances, mainly by road. This scenario may include various modalities to move a single shipment (waterways, rail and road, for example) until the cargo reaches domestic buyers or arrives at maritime transport terminals to be shipped to overseas markets. This process consumes significant quantities of energy and is a source of carbon dioxide emissions.

The transport sector in Brazil accounts for a large share of total greenhouse gas (GHG) emissions. One example in the area of forestry is depicted in research such as the work by Carmo (2016), which determined that transport is the most polluting phase in the supply chain. Transport was responsible for 47% of all the emissions quantified by the Brazilian Greenhouse Gas Emissions and Removal Estimation System (SEEG, 2020), which calculates GHG emissions from production and fuel use in the Brazilian energy industry, which is the sector with the highest historical increase. Cargo shipping alone is responsible for 40% of emissions.

Considering the importance of the transport sector in GHG emissions and the current intensification of climate change, it is critical to assess the most impactful activities as well as the goods that pollute the least, bearing in mind commitments to mitigate future impacts.

One such commitment in international climate policy is the 1997 Kyoto Protocol, which proposed a system for a verifying and monitoring GHG emissions as well as quotas for each country, focusing on developed nations and calculating carbon dioxide equivalents (CO_2eq) from the main known GHG released into the atmosphere, namely CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6) (UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 2008).

During the most recent agreement (during COP26), Brazil made a new commitment to mitigate 50% of the country's GHG emissions by 2030 compared to 2005 levels to help limit global warming to 1.5 ºC. At the same time, deforestation (denoted as "changes in land use") is strongly associated with these emissions, illustrating the difficulty Brazil faces in fulfilling this obligation (WRI, 2021).

Within the scenery of climate change, environmental and ecological aspects will be strongly affected, with repercussions in the supply of raw materials for the production of consumer goods, food and energy. Because the Brazilian economy is highly dependent on renewable natural resources, it is essential to analyze CO_2 emissions from logistics to define potential reductions, as environmental impacts more significantly affect production flows. Multimodal cargo transport, as highlighted by Vettorazzi et al. (2017), can be one way of reducing negative environmental impacts and total costs of this activity, despite higher energy use.

One study assessing the integration of the rail modality into cargo shipping found that intermodal transport reduced atmospheric CO_2 emissions, mainly on long routes, which are very common in Brazilian cargo transport (Craig et al., 2013); this study found a decrease of up to 46% in harmful emissions. However, the rail and waterway infrastructure in Brazil is insufficient for transporting several types of commodities, which results in widespread use of road transport even when long distances are involved (VETTORAZZI et al., 2017).

The transport phase in the timber production chain reduces the net stock of carbon in the transported wood (where the tree previously fixed the carbon during growth). Because burning fossil fuels results in atmospheric CO_2 emissions, some authors have noted that there may be a limit beyond which CO_2 emissions from transport exceed the amount of carbon stored within the wood (GUSTAVSSON et al. 2011). This timber, especially when it is sawn and utilized in applications with long useful lives, such as home construction, can be considered a carbon stock. The average carbon content in the wood of Amazonian tree species has been estimated at 49%, according to the Intergovernmental Panel on Climate Change (2019).

With this in mind, this present study investigated the balance between pollutant gas emissions from multimodal transport of wood obtained through reduced-impact forest management, as well as the net carbon stock fixed by the trees in the forest. We considered emissions from timber extraction within the forest management area until the resulting lumber arrived in consumer markets outside Brazil.

2. MATERIALS AND METHODS

2.1. Study area

The data for this analysis were obtained for native wood resulting from sustainable forest management in the Jamari National Forest. This conservation unit includes the municipalities of Candeias do Jamari, Itapuã do Oeste and Cujubim in the Brazilian state of Rondônia and spans 225,799.75 hectares (Figure 1). It contains 25 annual production units (APUs) managed for timber production during the concession; APU 12, which contains 2,445 hectares, was felled in 2019 and was the focus of this study.

The roads within the national forest are in poor condition. It is located about 4 kilometers to the west of the BR-364 national highway (AMATA, 2009).

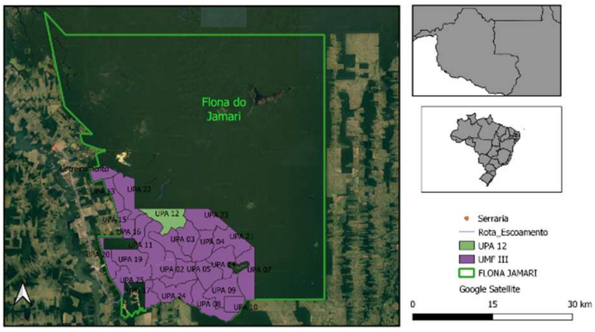

Figure 1. Location of Forestry Management Unit III within the Jamari National Forest in Rondônia, Brazil.
Figura 1. Localização da Unidade de Manejo Florestal III na Floresta Nacional do Jamari, em Rondônia, Brasil.

2.2. Calculation of carbon within the wood

Using forest inventory data provided by the company that holds the timber concession, the carbon stock in transported logs was calculated from the diameter at breast height (DBH), height and volume for each species. We also obtained basic data on density for each species from the literature, namely the database provided by the Brazilian Forest Service and IPT (2021), to estimate the mass of the logs in kilograms, an important parameter for determining carbon content (Table 1).

Using the basic density values presented in Table 1 and the volumes for each tree (obtained from the forestry inventory), we used Equation 1 below to estimate dry mass (at 0% humidity) for each species.

$$D_b = \frac{M_{dry}}{V} \qquad (01)$$

where: D_b: average basic density per timber species, in t/m³; M_{dry}: dry mass for each individual, in tons; V: wood volume obtained after forestry inventory measurement, in m³.

In order to estimate the amount of carbon contained in the biomass (Equation 2), we first calculated the dry mass of the wood in kilograms, assuming a 40% moisture content (HIGUCHI; CARVALHO JUNIOR, 1994). The remaining dry mass was then considered to contain 49% carbon, with the remainder consisting of extractives and other compounds, as per the Intergovernmental Panel on Climate Change (2006) guidelines.

$$EC = M_{dry} \times 0.49 \qquad (02)$$

where: EC: net carbon stock, in tons.

To estimate the quantity of CO_2 that was absorbed and incorporated into the timber, the net carbon stock obtained using Equation 2 was multiplied by 44/12 (the molecular weight of the carbon molecule is 12, and CO_2 is 44), as shown in Equation 3 below.

$$E_{CO_2} = EC \times (44/12) \quad (03)$$

where: E_{CO2}: net carbon dioxide stored, in tons.

Table 1. Timber species harvested from Annual Production Unit 12 within the Jamari National Forest, and density values for calculating carbon stock.
Tabela 1. Espécies madeireiras colhidas na Unidade de Produção Anual 12 da Floresta Nacional do Jamari e valores de densidade para cálculo do estoque de carbono.

Family	Species (scientific name)	Vernacular name (Brazil)[1]	Basic density (kg/m³)
Sapotaceae	*Pouteria guianensis* Aubl.	*Abiurana*	830
Leguminosae	*Hymenolobium excelsum* Ducke	*Angelim-pedra*	600
Vochysiaceae	*Qualea paraensis* Ducke	*Cambará-rosa*	640
Meliaceae	*Cedrela fissilis* Vell.	*Cedro-rosa*	390
Leguminosae	*Dipteryx odorata* (Aubl.) Willd.	*Cumaru*	870
Lecythidaceae	*Couratari stellata* A. C. Sm.	*Embireira*	650
Leguminosae	*Dinizia excelsa* Ducke	*Faveira-ferro*	830
Boraginaceae	*Cordia goeldiana* Huber	*Freijó*	480
Leguminosae	*Apuleia leiocarpa* (Vogel) J.F.Macbr.	*Garapeira*	750
Moraceae	*Bagassa guianensis* Aubl.	*Garrote*	700
Moraceae	*Clarisia racemosa* Ruíz & Pav.	*Guariúba*	560
Bignoniaceae	*Handroanthus incanus* (A.H. Gentry) S. O. Grose	*Ipê-amarelo*	820
Bignoniaceae	*Handroanthus impetiginosus*,. (Mart.ex DC.) Mattos	*Ipê-roxo*	870
Leguminosae	*Hymenaea oblongifolia var. palustris* (Ducke) Y.T.Lee & Langenh.	*Jatobá*	760
Leguminosae	*Hymenaea intermedia* Ducke	*Jatobazinho*	760
Lecythidaceae	*Allantoma decandra* (Ducke) S.A.Mori, Y.-Y.Huang & Prance	*Jequitibá*	600
Anacardiaceae	*Astronium lecointei* Ducke	*Muiracatiara*	790
Moraceae	*Brosimum rubescens* Taub.	*Muirapiranga*	835
Caryocaraceae	*Caryocar villosum* (Aubl.) Pers.	*Pequiá*	630
Leguminosae	*Peltogyne excelsa* Ducke.	*Roxinho*	810
Leguminosae	*Bowdichia nitida* Spruce ex Benth.	*Sucupira-amarela*	740
Leguminosae	*Diplotropis rodriguesii* H.C. Lima	*Sucupira-preta*	740
Lecythidaceae	*Cariniana micrantha* Ducke	*Tauari-vermelho*	580

[1]The vernacular names associated with the scientific nomenclature were obtained from the REFLORA virtual herbarium (REFLORA 2022).
[1]Os nomes vernaculares associados à nomenclatura científica foram obtidos do herbário virtual REFLORA (REFLORA 2022).

2.3. Calculation of carbon dioxide emissions from transport

Emissions of CO_2 were calculated for every phase of wood transport, over roads as well as water routes, considering the distance between origin and destination and the volume of transported timber (Figure 2). Journey sequencing was performed for this analysis, and considered route (listing origin and destination), distance, transport type/mode and ordinal stage (in ascending order, from primary to quaternary). The first stage of transport (primary) covers the trip from the forest management area to the sawmills by road, performed in this study by the public national forest. Primary and secondary timber processing takes place at these sawmills in the towns of Itapuã do Oeste, Ariquemes and Candeias do Jamari, and the wood also dries for trade. In the second stage (secondary transport), the processed wood is moved over the road to Porto Velho, the capital of Rondônia. The third stage (tertiary transport) takes place in two different ways: 50% of the lumber is shipped from Porto Velho to Manaus over water via ferry, and the other 50% moves by road to the port of Paranaguá in Paraná state. The final stage is quaternary transport, as this wood is shipped by sea; the wood in Manaus is sent to the port of Rotterdam in Holland (3,518.8 m³) or the Chinese port of Shanghai (879.7 m³), while the remaining 50% at the port of Paranaguá is shipped to Rotterdam (4,398.6 m³).

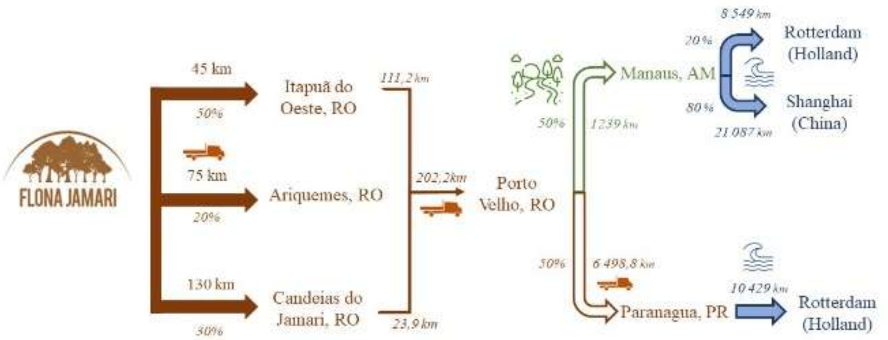

Figure 2. Intermodal flow of wood transport from APU 12 in the Jamari National Forest, showing distance from start to finish and percentage of wood transported to each destination.
Figura 2. Fluxo intermodal de transporte de madeira da APU 12 na Floresta Nacional do Jamari, mostrando a distância do início ao fim e a porcentagem de madeira transportada para cada destino.

It is important to note that although the wood was shipped to Europe and Asia, this study did not determine which individual countries actually consumed this timber. Instead, we examined the busiest markets for tropical wood sales to define a simulated route for Europe in Rotterdam and for the Asian continent from Shanghai.

Round-trip truck emissions were considered in the primary and secondary stages, considering that no other products were included as loads going in the same trip. One characteristic of wood transport is that the trucks travel in only one direction due to the specific nature of the load and freight exclusivity (Seixas, 2001); however, emissions from the returning, empty vehicles are lower than for loaded trucks.

For the tertiary and quaternary stages, however, only the outbound trip was considered, since for shipping via both rivers (from Porto Velho, Rondônia to Manaus, Amazonas) and roadways (from Porto Velho, Rondônia to Paranaguá, Paraná), we assumed another load would be available for the return trip. And quaternary transport takes place in cargo vessels, where other products are shipped during the same trip.

We utilized the following CO_2 emission factors described by Leal Junior et al. (2015) for diesel vehicles in order to determine the quantity of CO_2 per transported ton per traveled kilometer (kg/t.km): 0.11917 for road freight and 0.018 for waterborne shipping. When rail was also used, the factor was 0.0346 kg/t.km.

With this data, emissions were calculated for each transport phase using Equation 4, based on work by Vettorazzi et al. (2017).

$$E_{jk} = \sum(Fe_i \times D \times Q_{jk}) \quad (04)$$

where: E_{jk} = total CO_2 emissions for municipality of origin j and destination k, in kg; Fe_i = CO_2 emission factor for transport modal i, in kg/t.km; D = distance traveled, in km;
Q_{jk} = quantity of transported wood per municipality of origin j and destination k, in tons.

The sum of total emissions for all the phases resulted in total emissions for transport of the timber from the harvested stands.

2.4. Balance between stored and emitted CO_2

The carbon balance was calculated by determining the amount of CO_2 emissions that were stored in the transported wood and total emissions from primary, secondary, tertiary and quaternary transport (Equation 5). More details about this calculation method can be found in Lima (2022).

$$B_{CO2} = E_{CO2} - \sum E_{jk} \quad (05)$$

where: B_{CO2} = balance between the CO_2 emissions stored as carbon in the transported wood and emissions from transport, in kg; $\sum E_{jk}$ = sum of emissions from primary, secondary, tertiary and quaternary transport, in kg.

3. RESULTS

According to our calculations based on the forest inventory data, an estimated 37,268.9 t of CO_2 were stored in the total volume of wood harvested from APU 12, yielding a ratio of 15.24 t CO_2 stored per hectare, the equivalent of 8.48 t biomass/ha. Considering the carbon fixed by entire trees, the forest stored 71,670.8 t CO_2, the equivalent of 29.31 t CO_2/ha. For sawn lumber, we determined that the remaining wood volume stored 13,370.5 t CO_2, which is the average yield of the wood.

As for transport, we found that in the primary stage (from the forest management unit to the three sawmills), a total of 32,156.00 tons of logs were hauled exclusively by road, the transport modal with the most emissions impact. This quantity was distributed over 253 trips from the Jamari National Forest to Itapuã do Oeste (50%), Ariquemes (20%) and Candeias do Jamari (30%). Total emissions from this first phase were 586.30 t CO_2, corresponding to 1.49% of the net CO_2 stock and 1.02% of the total wood transport journey. Once the logs reached the sawmills, a total volume of 8,797.1 m^3 of lumber was produced, representing a volumetric yield coefficient (CRV) of 30.49%.

Secondary transport also took place entirely by road, over a total of 674.60 km, emitting 223.03 t CO_2. This corresponded to 1.38% of the total journey distance and 0.66% of the net stock consumed in this phase, representing lower emissions over a longer distance compared to primary transport, where the loads were 3.1 times larger in terms of mass. The significant impact of road transport on CO_2 transport emissions is clearly seen in the results for tertiary shipping (Table 2). The long road journey of 6,498.8 km from Porto Velho to the port of Paranaguá emitted 97.20% more CO_2 than transporting the same volume of wood 1,239 km over water from Porto Velho to Manaus (5.2 times shorter distance).

The simulation for shipping the lumber to the foreign consumer markets, which accounted for 81.80% of the total distance the load was shipped, yielded 2,604.68 t of CO_2 emissions. This value is lower than the emissions from tertiary transport, which was responsible for 15.80% of the total transport distance, reinforcing the impact of polluting atmospheric emissions from long-distance roadway shipping.

The sum of results was 7,381.19 t CO_2 of total emissions from intermodal transport of the wood harvested from the forest management area in the Amazon to the foreign consumer market (Table 3), corresponding to 19.81% of the net CO_2 stored in the harvested timber. When tree parts other than logs (crown, roots, etc.) are considered, this value comes to 10.30%.

Table 2. Tertiary transport emissions for 50% of the lumber shipped via water and 50% via road.
Tabela 2. Emissões do transporte terciário para 50% da madeira transportada por via aquática e 50% por via rodoviária.

Porto Velho → Manaus (one way, by water) (t CO_2)	Porto Velho → Paranaguá (one way, by road) (t CO_2)	Total tertiary transport emissions (t CO_2)
111.25	3,863.31	3,974.56

Table 3. CO_2 balance results for fixed CO_2 and emissions from primary, secondary, tertiary, quaternary and total transport.
Tabela 3. Resultados do balanço de CO_2 para CO_2 fixo e emissões do transporte primário, secundário, terciário, quaternário e total.

Fixed CO_2 (t)		CO_2 from transport emissions (t)			
In the forest	In the logs	1st	2nd	3rd	4th
71,670.80	37,268.81	586.30	223.04	3,974.56	2,604.68
		Total 7,388.58			

These results depict wood transport in this scenario as relatively 'clean,' considering that less CO_2 is emitted than the quantity fixed in the wood. In this way, much of the carbon fixed by the trees managed in the Jamari National Forest can remain sequestered after the wood is used, particularly in more durable applications.

4. DISCUSSION

Calculation of CO_2 stocks in transported timber is useful when describing wood removed from only a part of a managed forest and when utilizing accurate data from the literature on the biomass in the living aerial portion of trees from different regions of the Brazilian Amazon. Nogueira et al. (2008) determined a value of 253.8 t of dry biomass/ha, the equivalent of 3.34% considering only the biomass from the logs extracted from the forest. Part of the carbon in this harvested timber remains stored in the wood over the life of the resulting products (which are often durable). At the same time, significant amounts of CO_2 will be absorbed by natural regeneration after harvesting, which occurs more intensely in the clearings that result after felling (even when forests are managed to reduce impact), and in deactivated roads and storage areas after activities conclude.

Atmospheric emissions of GHG may be one factor considered by forest managers in decision-making, according to Moroni (2013); this author also suggests landscape conservation to provide 'carbon pools' and encourages society to seek alternatives for materials associated with greater emissions.

Note that in reduced-impact harvesting in tropical forests, trees are strategically felled to permit regeneration of other individuals and the forest remains standing for future decades. This leads to a carbon increment in this area, particularly in the first years following harvesting when regeneration is more accelerated.

As part of their GHG accounting frameworks, some countries like Australia consider the carbon within wood products as carbon credits (stock increase) in their national inventories (RICHARDS et al., 2013).

Several authors, including Brandão et al. (2012) and Smith et al. (2014), have noted the importance of sustainably managed wood in mitigating the global effects of climate change, since 'anthropogenic reserves' accumulate carbon for relatively long periods in wood instead of in the atmosphere. These anthropogenic reserves are wood products in use, which can last for 5 to 100 years (BRUNET-NAVARRO et al., 2017), and the carbon may be stored even longer after disposal. However, the mitigation potential for managed forests depends primarily on how much carbon is stored in the wood or associated with losses in processing, which span from felling to the final application (ALICE-GUIER et al., 2020).

4.1. Volumetric yield coefficient

Even without specific data about sawmill residuals, we can assume that part of the net carbon stock is lost during the milling process. The management plan includes energy production from the resulting by-products via cogeneration for pellets and charcoal, depending on prices and demand in local and overseas consumer markets (AMATA, 2007), a beneficial use of existing raw materials.

The CRV obtained for Amazonian wood in sawmills tends to vary between species. In a survey of 2,570 companies in 72 wood processing centers in the Legal Amazon region, Lentini et al. (2003) found an average CRV of 38.2%, while Pereira et al. (2010) calculated values ranging from 38% to 42% in the biome.

Log attributes such as cavities (even when small), rotten spots, tortuosity, tapering and variations in the sapwood region affect the net volume that the sawmill can actually consume. Most of the wood used by mills is the heartwood in the center of the log; this wood is colored differently from the whiter sapwood surrounding it, which mostly goes unused and in several species is essentially waste after milling. The heartwood (also known as wood fillet) is considered more resistant to boring insects and fungi and more durable. In certain species where the difference between heartwood and sapwood is more subtle, CRV values are higher and less waste is generated.

4.2. Emissions by transport modal

According to Correa; Ramos (2010), fuel consumption for the road modal is less efficient per transported ton, while water and rail are more suitable for transporting loads with low added value over long distances, maximizing fuel consumption efficiency per transported ton.

In this present study, no exact information was available about fuel consumption for each transport modal, and we consequently did not compare efficiency. The base data on average emission factors by modal was obtained from the Painel Brasileiro de Mudanças Climáticas (PBMC, 2013). However, for a better comparison of tertiary transport modes, we calculated emission factors in kg of CO_2 for each ton transported one kilometer, which yielded 0.009 kg CO_2/t.km for water transport and 0.060 kg CO_2/t.km by road, demonstrating that road transport produced more pollution.

Transport of wood with moisture levels in balance with air humidity is regarded by Campos et al. (2011) as ideal, considering the greater mass in green wood. However, some species are loaded only days after cutting in line with sawmill preferences to process wood with higher moisture content, and also to avoid potential losses in the field from xylophagous agents. Moreover, the flow of logs from the production unit depends on the rainy season in the Amazon, with management and transport only taking place during the dry season, considered the 'Amazonian summer,' when such activities are legally permitted. During the remainder of the year, frequent rains affect conditions on the roads, which, for the most part, are unpaved and not authorized for this type of transport.

According to the Ecological Transport Information Tool (2011), high-density loads may produce nearly double the emissions of low-density loads due to volume limitations related to vehicle weight capacity. This is an important aspect for the road modal, considering that trucks hauling native species tend to be overloaded, fleet maintenance is critical, and road network quality and paving require improvement and investments, as described by Lima (2014).

Emissions were calculated for hauling by road as well as water per m^3 of the total volume per species transported 1,000 km, and showed higher CO_2 emissions values for denser species. For example, road transport of *cumaru* (with a green density of 1.25 t/m^3) yielded 0.15 t CO_2/m^3 emissions, while this value was 0.07 t CO_2/m^3 for *freijó* (density of 0.60 t/m^3).

4.3. Balance between CO_2 emissions and stocks

Other studies have also demonstrated a positive carbon balance for the same shipping trajectory for tropical wood: in a similar analysis, Campos et al. (2011) found that 58% of the initial carbon stock was maintained.

While we also calculated the quantity of carbon stored in all non-log portions of the harvested trees, we considered it most appropriate to consider only the amount stored in the lumber as a long-lasting reservoir. Even so, and despite room for improvement in this process, this transport can still be considered clean. It is important to note, however, that we only calculated carbon emissions from shipping: analysis of other forestry operations within this supply chain is also important to more comprehensively determine whether the carbon balance is positive for wood extraction as a whole.

For example, Carmo (2016) analyzed GHG concentrations for 85 diesel-motor machines used in eucalyptus and pine forests for forestry activities, harvesting, log transport, administration, protection, construction and road maintenance to determine the carbon balance in these forests. Because forestry and logging require a variety of machines and phases involving fossil fuels for these activities, as well as management (such as employee trips), a broader exploration of all phases would more accurately depict the carbon balance for the entire production chain.

5. CONCLUSIONS

In this study, we calculated the balance between CO_2 emissions from the intermodal transport of wood resulting from managed forests to foreign consumer markets. We determined the relative percentage of net carbon stocks that were previously fixed by trees in the forest. Within this scenario, which considered only transport, the resulting CO_2 emissions did not exceed the quantity stored in the wood. The percentage of emissions equivalent to the CO_2 previously fixed by the tree during growth was 19.81%.

Our analysis of the various shipping stages confirmed findings from several studies in the literature, which determined that road shipping has a greater negative environmental impact than rail or water. This modal generates the highest CO_2 emissions values per ton shipped, and the significant distances can result in large-scale emissions into the atmosphere. And while the overseas leg of the journey to reach the simulated foreign consumer markets accounted for 81.80% of the total shipping distance and 2,604.68 t of CO_2 emissions, this value was lower than emissions from the tertiary stage of transport (corresponding to only 15.80% of the total distance), reinforcing the importance of GHG emissions from long-distance shipping by road.

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