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Logging residues for charcoal production through forest management in the Brazilian Amazon: Economic gains and forest regrowth effects.

Camila T D Numazawa[1], Andrey Krasovskiy[2], Florian Kraxner[2], and Stephan A Pietsch[2]

[1] Civil Engineering Graduate Program, Polytechnic School, University of São Paulo, Sao Paulo, Brazil
[2] Ecosystems Services and Management Program (ESM), International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

E-mail: numazawacamila@gmail.com

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Abstract

Sustainable forest management practices can potentially reverse loss of forest cover due to deforestation, while concomitantly preserving and maintaining biodiversity, and stimulating jobs, income, and forest services. Recent studies found that significant logging residues (i.e., leaves, branches, and buttress roots) suitable for bioenergy production were often left in the felling area, triggering risks of forest fires and increased CO_2 emissions due to wildfires or decomposition processes. For impact assessment of forest management practices, we collected primary harvesting data and estimated net primary productivity (NPP) and net ecosystem exchange (NEE) for 13 forest plots in the Brazilian Amazon. We applied a process-based forestry growth model (BGC-Man) to analyze the impacts on forest dynamics of selective logging and removal of logging residues, subject to landscape, soil texture, and daily weather. We explored the following selective logging scenarios: the Legal Reserve (i.e., reference) scenario, a scenario with one cutting cycle over the whole period, and a scenario with three timber rotation periods of 30 years. Two of the later scenarios were complemented with harvesting of the woody logging residues (LR; $Ø\geq10$ cm) for charcoal production. For each scenario, we computed forest NPP and NEE over a 120-year time horizon. Results suggest that using woody logging residues (i.e., 77% of total LR) for charcoal production would result in an economic gain equivalent to 24-46% of the timber price. Our findings indicate that under scenarios where LR were removed, forest NPP recovered to the reference level and even higher, while income and jobs from harvesting LR for charcoal production were generated. We conclude that sustainable forest management could enhance forest productivity and deliver economic benefit from otherwise unexploited logging residues.

Keywords: sustainable forest management, charcoal production, BioGeoChemistry Management (BGC-MAN) model.

1. Introduction

Sustainable forest management (SFM) in the Amazon forest has been proposed as a way of preserving and maintaining biodiversity, while at the same time generating jobs, providing income and forest services, and avoiding forest degradation[1-4]. As most of the forest remains intact, the application of SFM would not only prevent global land-use change and the illegal removal of natural resources, but also preserve terrestrial carbon stocks[5].

Sustainable forest management practices were also established as a way of creating economic alternatives for the inhabitants of the region and to improve livelihood conditions, especially for poor forest dwellers[6]. Achieving both environmental and socioeconomic benefits is key for sustainable development and the greenhouse gas balance[7].

Prior studies have shown that management as stipulated by the Brazilian Forest Code Regulations generates a significant amount of logging residues (LR) which are often left in the felling area[1,2,8]. Logging damage and wood waste from harvesting operations are thus left to decay, which further contributes to CO_2 emissions, and increases the risk of forest fires[9–13].

In planted forests all the biomass loss originates from harvested trees, whereas under selective logging practices, residues from logged trees make up only about one-quarter of the total biomass loss[14,15]. For every tonne of commercial stem harvested from planted forests in Brazil, 0.6 tonnes of residues (Ø≥10 cm) are produced[16], while under selective logging around 2.5 tonnes of residues are produced per tonne of commercial stem (Ø≥10 cm) in the Amazon[17].

LR play an important role in the forest structure and as a functional unit of the forest ecosystem[18]. The residues improve soil fertility in the tropical forest[19] helping to sustain nutrients and to maintain an appropriate level of soil organic matter and biological cycling[9]. Removing residues can thus impact the nutrient balance in the forest. However, larger pieces (Ø≥10cm) of fallen dead wood are considered to be a poor nutrient source in comparison with litterfall[20] and take a long time to decay[9,21,22].

A potential legal use for LR under the Brazilian Forest Code is charcoal production, which delivers benefits as a forestry co-product. Making use of the LR originating from SFM for charcoal could help mitigate deforestation and increase forest and land restoration. The charcoal produced (as biochar) could be used as a soil amendment for both carbon sequestration and soil health benefits[23–26].

It is therefore important to understand the impacts of residue removal and to assess the economic benefits of charcoal co-production.

The objective of our study was to assess the long-term forest regrowth dynamics in terms of net primary productivity (NPP) and the net ecosystem exchange (NEE) accumulated over a 120-year time horizon under five different selective logging scenarios in order to quantify the impacts of harvesting LR for charcoal co-production on the economic benefits of sustainable forest management practices in the Brazilian Amazon.

2. Materials and Methods

2.1 Site descriptions

The 13 study sites were located in the primary forest in the State of Pará, Brazil. This state has been one of the main producers of tropical timber in Brazil, accounting for between 45% and 60% of the market[27–29]. Fifty-one percent of the timber companies in the Brazilian Amazon are located in Pará and generate 48% of jobs in the Amazonian timber industry[30]. It is estimated that Pará has one of the highest spatial distributions of aboveground standing biomass of all dense forests (200 to > 400 Mg ha^{-1})[31].

The study area covered around 1,000 square kilometers, and the distances between study plots exceeded 450 km. The forests considered were logged by different landholders between 2002 and 2016, and the size of the plots (n=13) varied from 200 ha to 5,674 ha, amounting to a logged area of over 30,785 ha. Logging intensities ranged from 15 m^3 ha^{-1} (under reduced-impact logging) to 30 m^3 ha^{-1} (the maximum volume allowed under the Regulations). The total volume of harvested wood was 854,298 m^3. Forest management strategies and aboveground dry biomass (AGDB) characteristics were in the range found throughout the Brazilian Amazon (Table 1).

Table 1. General information and variable features of the study areas. AGDB is above ground dry biomass.

Forest	Year of logging	Location	Site Elevation	Total area logged	AGDB	Harvesting intensity	Timber volume harvested	
			m	Ha	t ha^{-1}	m^3 ha^{-1}	m^3	% of AGDB
F1	2010	2º55´S 48°31' W	73	1,659	196	29	48,111	9.72
F2	2010	2°58' S 48°31' W	75	1,452	196	30	43,560	9.75
F3	2007	3° 6' S 51°33' W	119	1,734	226	26	45,084	7.10
F4	2008	3°31' S 51°31' W	117	2,474	226	29	71,746	8.42
F5	2006	3°52' S 48°37' W	105	1,071	196	25	26,775	8.75
F6	2006	3°43' S 48°38' W	122	4,274	226	30	128,220	8.71
F7	2002	3°16' S 47°39' W	104	600	226	15	9,000	4.42
F8	2003	3°37' S 49°19' W	83	200	226	27	5,400	7.61
F9	2016	3°23' S 48°30' W	85	2,426	226	30	72,780	8.97
F10	2007	2°52' S 51° 5' W	20	1,657	166	23	38,111	9.52
F11	2005	2°49' S 50° 1' W	41	3,267	166	29	94,749	11.49
F12	2007	2°55' S 50°12' W	68	3,724	167	27	100,548	10.49
F13	2007	2°39' S 50°12' W	52	5,674	167	30	170,220	11.65

Localization of the plots studied in Pará State:

2.2 Climate data and soil database

The managed sites were located in an equatorial tropical climate with a short dry season from June to November. For this study, the AgMERRA[32] climate database was used to provide daily, high-resolution, continuous data, designed for applications analyzing climate variability[33]. AgMERRA datasets consist of gridded rasters (NetCDF files) providing daily weather information.

Meteorological daily mean records of climate data between 1980 and 2010 (= 31 years) were extracted for each plot based on its coordinates, with a total of 11,315 days of data. We considered the following climate input parameters: minimum and maximum temperature, precipitation, solar radiation, vapor pressure deficit, and day length.

Table 2. Soil physical properties and permanent features in the study areas.

	Identification of soil	**Type of soil texture**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Effective soil depth (m)**
F1	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F2	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F3	S1	T3	17	16	67	1
	S2	T4	41.6	22	36.4	0.7
	S3	T5	55	26	19	0.3
F4	S1	T3	17	16	67	1
	S2	T4	41.6	22	36.4	0.7
	S3	T5	55	26	19	0.3
F5	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F6	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F7	S1	T1	72	3	25	1
	S2	T6	35.9	7	57.1	0.9
F8	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F9	S1	T1	72	3	25	1
	S2	T2	42.1	6.3	51.6	0.8
F10	S1	T7	28	11	61	1
	S2	T8	10	14	76	1
	S3	T9	87.1	3.4	9.5	1
	S4	T10	9	22	69	1
F11	S1	T7	28	11	61	1
	S2	T8	10	14	76	1
	S3	T9	87.1	3.4	9.5	1
	S4	T10	9	22	69	1
F12	S1	T7	28	11	61	1
	S2	T8	10	14	76	1
	S3	T9	87.1	3.4	9.5	1
	S4	T10	9	22	69	1
F13	S1	T7	28	11	61	1
	S2	T8	10	14	76	1
	S3	T9	87.1	3.4	9.5	1
	S4	T10	9	22	69	1

Physical soil properties like texture and soil depth needed for running the model for each forest site were taken from the Harmonized World Soil Database[34] (Table 2). Effective soil depth was adjusted based on the gravel content of different soil layers (topsoil and subsoil), while for soil texture we calculated the volume weighted mean of each soil layer.

2.3 Model

2.3.1 BGC-MAN

The BioGeoChemistry Management Model (BGC-MAN) is a process-based ecosystem model, designed to assess the transformation of energy and matter within ecosystems[35] by calculating the daily cycling of energy, water, carbon, and nitrogen within a given ecosystem. Model inputs include meteorological data, such as daily minimum and maximum temperature, incident solar radiation, vapor pressure deficit, precipitation, and day length. Aspect, elevation, nitrogen deposition and fixation, and physical soil properties are needed to calculate the following: daily canopy interception, evaporation, and transpiration; soil evaporation, outflow, water potential, and water content; leaf area index; stomatal conductance and assimilation of sunlit and shaded canopy fractions; growth and maintenance respiration; gross and net primary production; allocation; litterfall and decomposition; mineralization, denitrification, leaching and volatile nitrogen losses[35–38].

The model has been developed, tested, calibrated, validated, and applied in previous studies around the world[37–53]. For this study, BGC-MAN was applied to assess potential impacts of selective logging practices, focusing in particular on cumulative net primary productivity (NPP_{cum}) and cumulative net measure of ecosystem exchange (NEE_{cum}).

Daily climate data, plot/forest information, and management practices were provided as inputs to the BGC-MAN model. The dynamic biomass mortality rate was set to 3.6%[54]. The error assesment of predicted versus observed AGDB exhibited unbiased results[55] with confidence and prediction intervals of the error of -6.62% to 6.23% and -39.26% to 38.86%, respectively. For the self-initialization run, we assumed the following fixation rates based on the literature: nitrogen deposition as 5.3 kg ha^{-1}, fixed nitrogen as 2.5 kg ha^{-1} [56,57], and carbon dioxide concentration values from 338 to 712 ppm[58].

2.3.2 Scenarios

We simulated NPP$_{cum}$, NEE$_{cum}$, and biomass regrowth over a 120-year time horizon, which represents three cutting cycles, following the rotation time required by forest regulations. As in this experiment we were focusing on the regrowth and economic effects of harvesting the LR from the forest, we assumed that the climate condition scenario, based on our full available climate record for the simulation from 1980 to 2010, would not be influenced by either climate change or fire. Thus, we looped this data until 2100 to be able to estimate the whole period covering the three-timber rotation period. We developed five scenarios to evaluate selective logging (M) impacts: (i) no logging (reference), (ii–v) with either one or three cutting cycles (1cc, 3cc), each with either -charcoal or without harvesting logging residues greater than, or equal to, 10 cm in diameter for charcoal co-production (see Figure 1). In all scenario runs, atmospheric CO$_2$ concentration was gradual, in accordance with IPCC scenario[59].

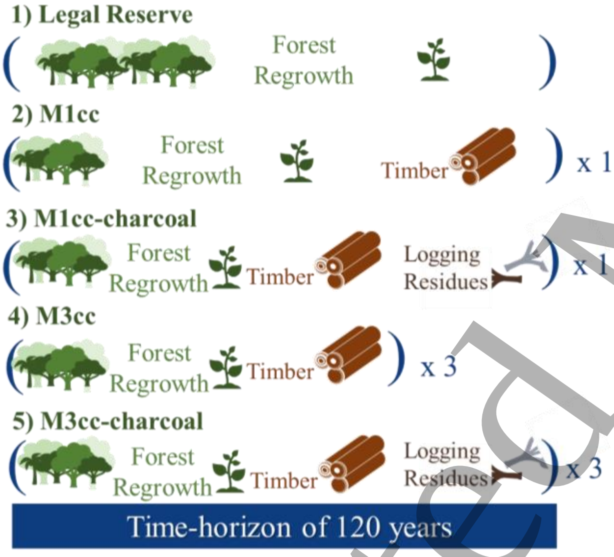

Figure 1. 1) Legal Reserve: the reference scenario without any intervention or management; 2) M1cc: 1 cycle of managed logging; 3) M1cc-charcoal: 1 cycle of managed logging + LR harvesting; 4) M3cc: 3 cycles of managed logging; 5) M3cc-charcoal: 3 cycles of managed logging + LR harvesting.

2.4 Logging Residues

All residues with a diameter equal to or greater than 10 cm (LR≥10cm) generated during the selective logging were quantified in a technical report as part of the authorization by Pará's Environmental and Sustainability Secretariat to explore the possibility of using residues to produce charcoal. A residual stem ratio for LR≥10cm in each plot for each 1m³ of timber logged was identified.

LR with a diameter of less than 10 cm (LR<10cm) needed to be estimated; these were not collected on site as they did not have economic value for the forest companies. Using an allometry equation[60] we estimated LR<10cm, under the consideration that 16.6% of an average tree's weight is made up of twigs, leaves, flowers, and fruits. As the biomass of the harvested trees is known, 16.6% of this biomass resulted in LR<10cm. With respect to the damage to surrounding trees, the LR≥10cm makes up 83.4% of the measured LR biomass. Therefore, the amount of LR<10cm is estimated as 16.6 ÷ 83.4 times the amount of LR≥10cm for the surrounding trees.

2.5 Charcoal production

All the companies used the hot-tail kiln to produce charcoal. Despite its lower efficiency in carbonization and its environmental drawbacks compared to other techniques, due to the low cost it is still the most widespread charcoal production technique beeing used in Brazil[61–63].

It is important to highlight that because of the heterogeneity of species, both the LR and the charcoal stemming from Amazon forest management are very different in density and size (Figure 2). It is thus not possible to use the standard biomass conversion efficiency from residues to charcoal to calculate the amount produced.

Figure 2. (a) LR for charcoal production in the kiln area; (b) (c) Different sizes of LR; (d) buttress root.

In Brazil, charcoal production is based on volume measured in cubic meters corrected for stacking[64] and it is usually sold by the "mdc" volume unit as volume of charcoal in bulk, representing the amount of the product that occupies one cubic meter[63,65]. This is done to discourage adulteration, for example, by wetting the charcoal or mixing it with earth, as the volume is not affected by stacking. At the same time it is an incentive for careful charcoal transportation to avoid volume reduction[64].

First, all the LR≥10cm were individually cut into ≈ 1-meter-long sections (Figure 3 (a)). Second, the residue was measured twice in each of the diameters (top and bottom) as well as in the length (Figure 3 (b)) to obtain the geometric volume (unbiased rounding logic – Smalian formula). Finally, LR were piled in ≈1-meter long per ≈1-meter high racks (Figure 3 (c)) to allow calculation of the stacked cubic meters (st) before they were placed inside the kilns.

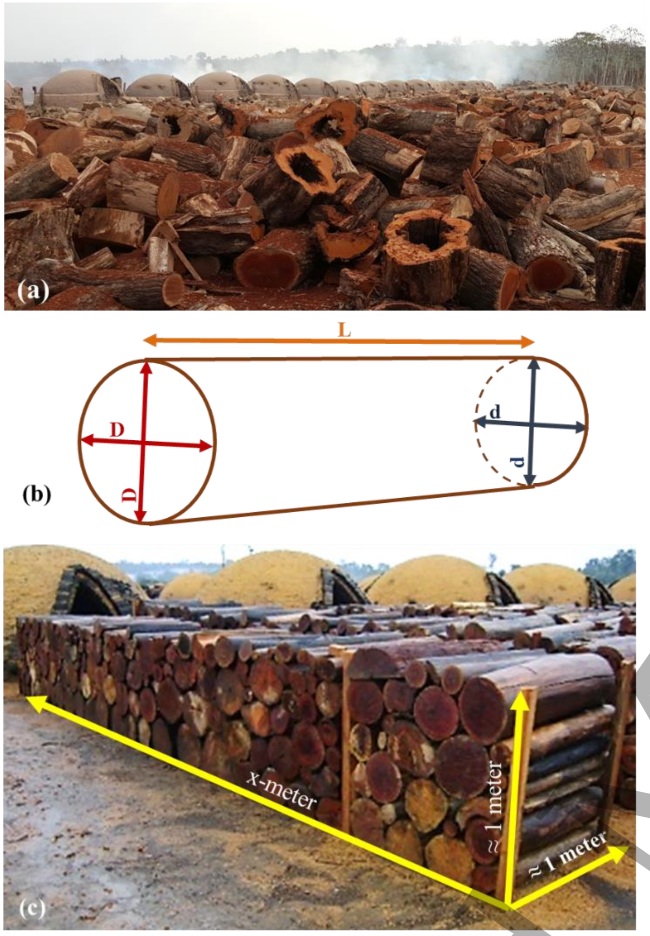

Figure 3. (a) LR≥10cm were individually cut ≈ 1-meter long; (b) measured LR dimensions; (c) placed in 1-meter long per 1-meter high piles

After the carbonization process, which lasted between 10 and 12 days, the charcoal volume was measured by placing it in the 1 cubic meter container and weighting it (mdc volume unit). The charcoal amount ratio is measured by the volumetric (of stacked residues) and weight (1 mdc or 1 metric ton) conversion coefficient factors from LR to charcoal[66,67].

Overall, the average density of charcoal in bulk represented 0.266 t mdc^{-1} with the lower and upper limit of confidence interval from 0.259 to 0.273 t mdc^{-1}. The coefficient of variation was 3.8%, and there was a relative sampling error of 2.7% (under a maximum absolute error of 10%, where $\alpha = 0.05$ and gl = 9).

The stacked results showed a factor of 1.47 (st) for each 1 m^3 of residues with lower and upper confidence interval limit of 1.398 to 1.545 st m^{-3}. The coefficient of variation was 7% and the relative sampling error was 4.99% (under a maximum absolute error of 10%, where $\alpha = 0.05$ and gl = 9).

The relation in volume between the residues (st) and the charcoal (mdc) was 1.473 st of LR for each 1 m^3 of charcoal, with the lower and upper limit of confidence interval ranging from 1.412 to 1.534 st 1 mdc.

The conversion coefficient factor to produce 1 metric tonne of charcoal was 5.549 st of LR, with a lower and upper confidence interval limit of 5.298 to 5.799 st. The coefficient of variation was 6.3% and relative sampling error was 4.52% (under a maximum absolute error of 10%, where $\alpha = 0.05$ and gl = 9).

2.6 Economic analysis

The use of biomass from residues for bioenergy is increasing[68–70]. Due to the relatively low cost of labor and LR transportation and the high residue-generation rate under forest management in the Brazilian Amazon, the activity is very attractive for forestry companies as an economic benefit.

The study analyzed the gross income, representing the economic gain of charcoal co-production relative to the timber value. The gross income was chosen to show the total economic value to the whole community, whereas the net profit shows only the value for the producer.

Based on the timber economic benefit percentage, this research quantified the potential economic gross profit gain with charcoal co-production by harvesting the LR≥10cm. The charcoal net income was calculated, including the cost of trimming the LR, transportation, and labor.

Furthermore, it is important to highlight that due to environmental concerns about charcoal production from native timber residues causing forest degradation[23,71,72], the Pará Environmental and Sustainability Secretariat allows the harvest of LR only after a technical report by a forest engineer providing information about the volume per hectare produced during the forest management.

3. Results

3.1 BGC-MAN

3.1.1 Biomass regrowth and carbon stock over the time horizon of 120 years

Figure 4 shows the carbon stock average in forest biomass regrowth (t C ha^{-1}) in the study areas over a 120-year horizon for each scenario. The results suggest that after the total simulation time, the managed forests have less carbon stock than the Legal Reserve. For each scenario, the loss of biomass was 2% in M1cc, 2.4% in M1cc-char, 10.6% in M3cc, and 9.9% in M3cc-char.

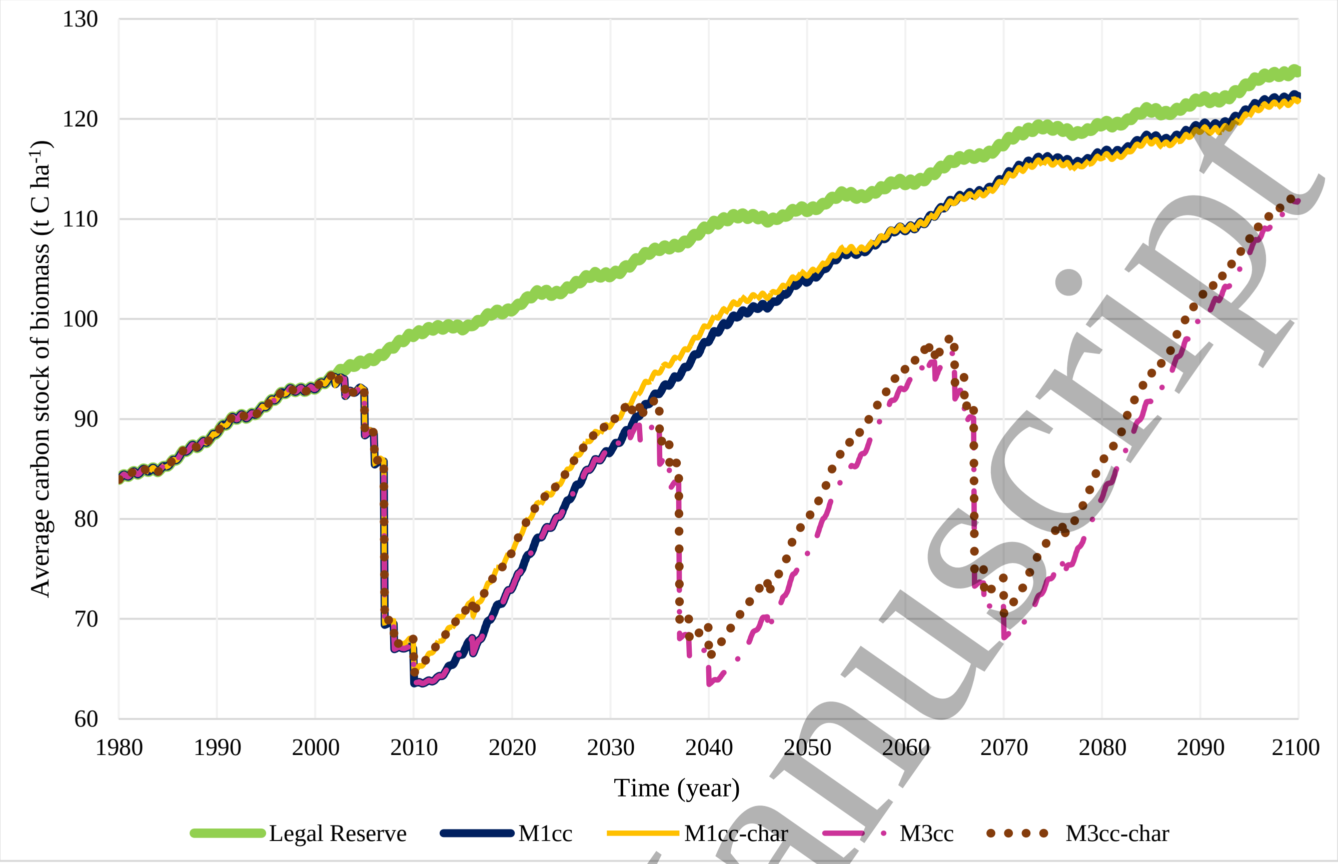

Figure 4. Average carbon stock of biomass over 120 years of all plots. Abbreviations as in Fig. 1.

However, in all scenarios, including the scenarios with three cutting cycles, biomass had increased in comparison with the initial stock at the start of the simulation, as shown in Table 3. In addition, the total average amount of biomass removed to produce wood products in M3cc-char was equal to the initial biomass stock (84 t C ha^{-1}), but the biomass stock still increased by 33% (112 t C ha^{-1}) over the simulation period, compared to the initial stock.

The highest relative increase in carbon stock at the end of the simulated time horizon for the harvesting scenarios compared to the Legal Reserve was considered to be the best scenario, and the lowest relative increase as the worst scenario. Table 4 shows that F7-S1 managed under reduced impact logging, represented the best scenario, with the biomass recovering almost to the level of the Legal Reserve. F13-S4 was the worst scenario, but still showed an increase in biomass over the simulated period.

Table 3. Average biomass production for the scenarios. . Abbreviations as in Fig. 1.

	Units	Legal Reserve	M1cc	M1cc-char	M3cc	M3cc-char
1980	t C ha^{-1}	84	84	84	84	84
2100	t C ha^{-1}	125	122	122	111	112
Increase from initial stock [%]	%	48	45.1	44.5	32.3	33.4
Biomass removed (logs and LR≥10cm)	t C ha^{-1}	-	9	28	27	84
Biomass left behind (LR<10cm)	t C ha^{-1}	-	25	06	74	17

Table 4. Best and worst scenario of average biomass production. Abbreviations as in Fig. 1.

Best Scenario: F7-S1						
	Units	**Legal Reserve**	**M1cc**	**M1cc-char**	**M3cc**	**M3cc-char**
1980	t C ha^{-1}	75	75	75	75	75
2100	t C ha^{-1}	111	111	111	108	108
Increase from initial stock [%]	%	49	48	48	45	44
Worst Scenario: F13-S4						
	Units	**Legal Reserve**	**M1cc**	**M1cc-char**	**M3cc**	**M3cc-char**
1980	t C ha^{-1}	92	92	92	92	92
2100	t C ha^{-1}	137	131	131	114	116
Increase from initial stock [%]	%	49	43	42	23	26

Figure 4 also shows that after the LR≥10cm are harvested for charcoal co-production (≈2010) the biomass for M1cc-char recovers faster than M1cc, and it takes about 50 years for the carbon stock value of M1cc to catch up with M1cc-char. The same behavior occurs for M3cc and M3cc-char but, as in this case management and LR harvesting occur every 30 years, the carbon stock in biomass for M3cc never reaches the value of M3cc-char after the first harvest.

3.1.2 Cumulative NPP over 120 years

Minimum, average, and maximum NPP$_{cum}$ for each scenario at the end of the simulation were compared to the reference (Figure 5). In most of the cases, the Legal Reserve has the highest NPP$_{cum}$ values, except for the minimum NPP$_{cum}$ values in the M1cc-char and M3cc-char, as well as the average for M3cc-char. M3cc-char had the best average NPP$_{cum}$ result of all the scenarios for which we simulated selective logging.

The results also show that M1cc-char and M3cc-char had better NPP$_{cum}$ values than the M1cc and M3cc scenarios where all LR are left behind. Notice that the NPP$_{cum}$ results for M1cc and M3cc were quite similar, with a higher minimum and average value for M1cc and the maximum for M3cc.

To compare the NPP$_{cum}$ from the Legal Reserve with the selective logging scenarios, we calculated the average NPP$_{cum}$ relative to the Legal Reserve (as 0% and as baseline) represented in Figure 6. After the first management operation (2002), all relative NPP$_{cum}$ declined. For M1cc-char and M3cc-char, the relative NPP$_{cum}$ started to increase in 2012 after it reached -4.7%, whereas for M1cc and M3cc the turnover point was in 2013 after reaching a minimum of -7.3%.

Figure 5. Minimum, average and maximum NPP$_{cum}$ after 120 years for each scenario. Abbreviations as in Fig. 1.

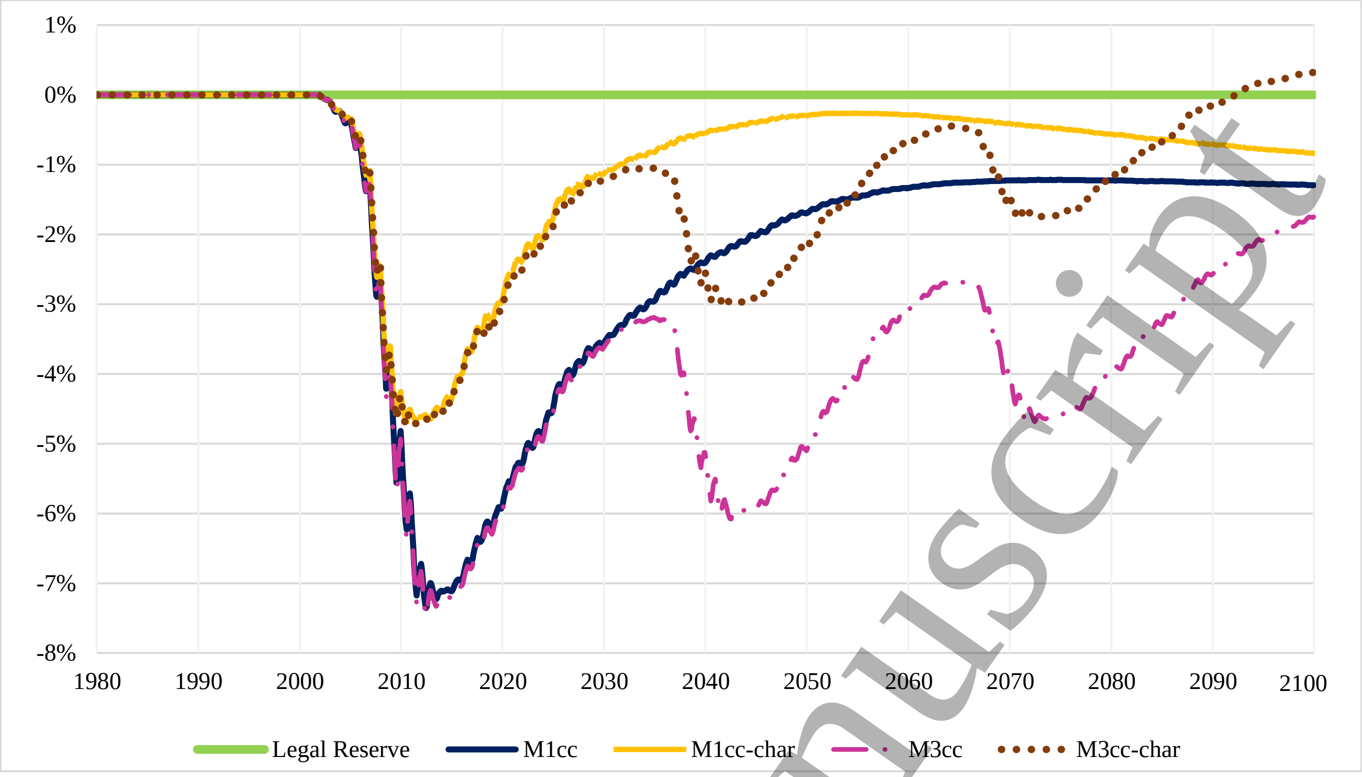

Figure 6. Average NPP_{cum} relative to Legal Reserve (0%). Abbreviations as in Fig. 1.

For M1cc-char, about 50 years after logging (2052) and 40 years after LR harvesting (2012), NPP_{cum} started to decline again, while for M1cc, it took about 76 years after logging (2078) until NPP_{cum} stabilized for 2 years and then started to decline once again (2088).

M3cc-char was the only scenario, in which average NPP_{cum} surpassed the Legal Reserve after the last cutting cycle rotation (2093), reaching a 0.3% higher NPP_{cum} than the Legal Reserve in 2100. The simulation suggests that the association of selective logging with LR harvesting during a 30-year timber rotation cycle helps to increase the NPP_{cum}.

3.1.3 Cumulative NEE over 120 years

We compared the minimum, average, and maximum cumulated NEE values in all scenarios (Figure 7), whereby the Legal Reserve had the lowest cumulated NEE values (minimum, average, and maximum) compared to the selective logging scenarios. The simulation results indicated that the harvest of LR≥10cm has a considerable positive impact on resulting NEE_{cum} values. The M3cc scenarios also had higher NEE_{cum} values than the M1cc scenarios. Figure 8 shows the positive trends for each scenario. The M1cc-char and M3cc-char scenarios have higher growth trends, while the M3cc scenario exhibited a less positive trend than the Legal Reserve.

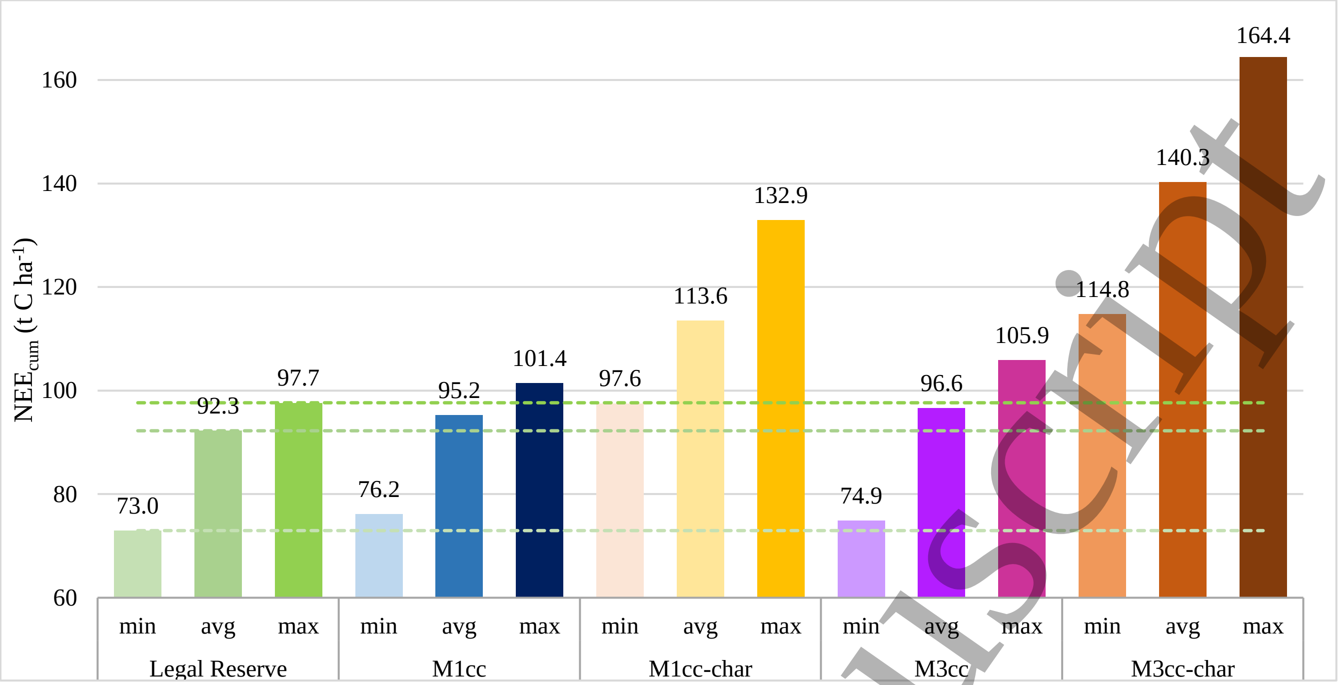

Figure 7: Minimum, average, and maximum NEE$_{cum}$ after 120 years for each scenario. Abbreviations as in Fig. 1.

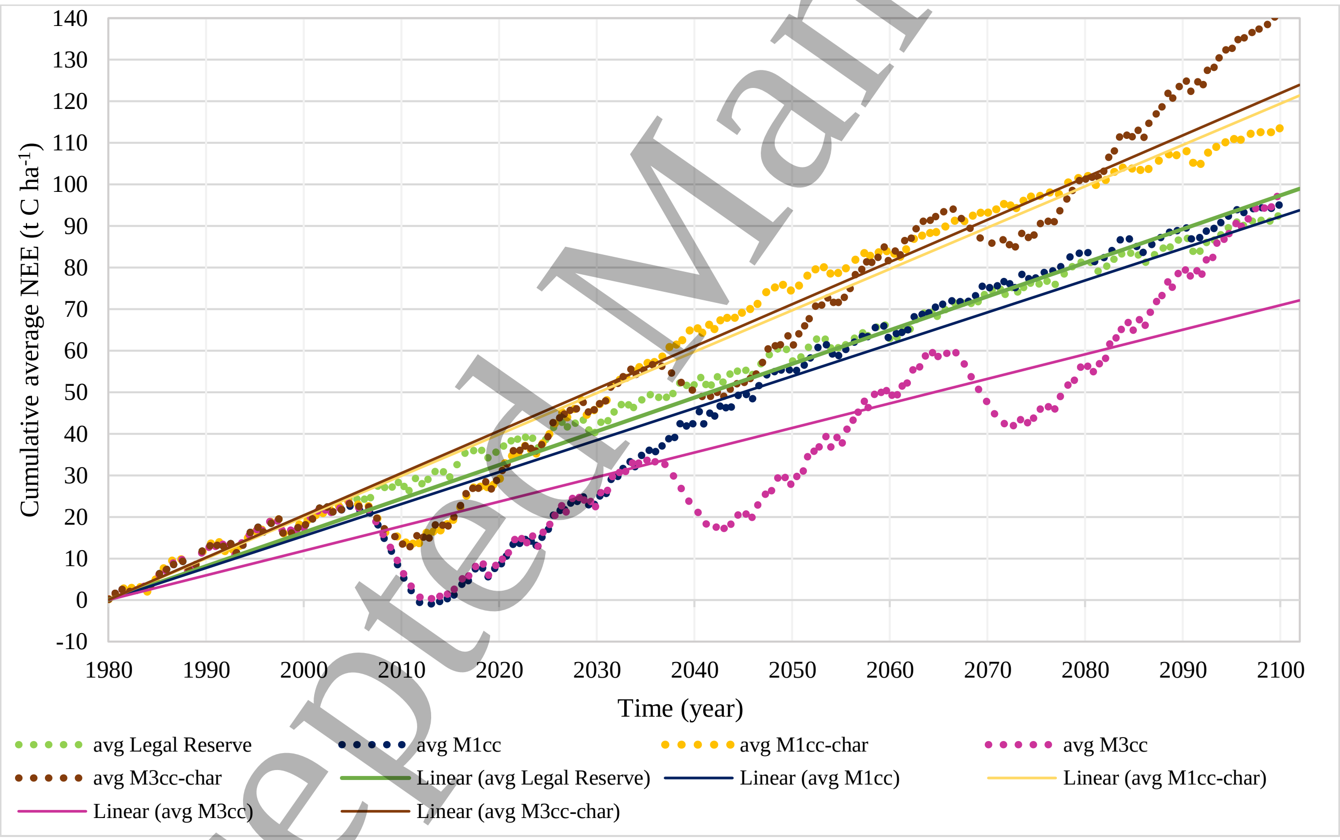

Figure 8. Average NEE$_{cum}$ for all scenarios with trendline. Abbreviations as in Fig. 1.

3.2 Economic benefit with charcoal co-production

The volume of LR produced during selective logging operations was estimated to range between 67% and 78% of the total harvested biomass withdrawn from the forest (timber + residues), with the volume of wood residues ranging from 2 m³ to 3.6 m³ per cubic meter of timber in the study samples (Figure 9). LR≥10cm amounted 75% to 79% of the total LR, and the residual stem ratio found for each 1 m³ of logged timber was between 1.5 m³ and 2.8 m³.

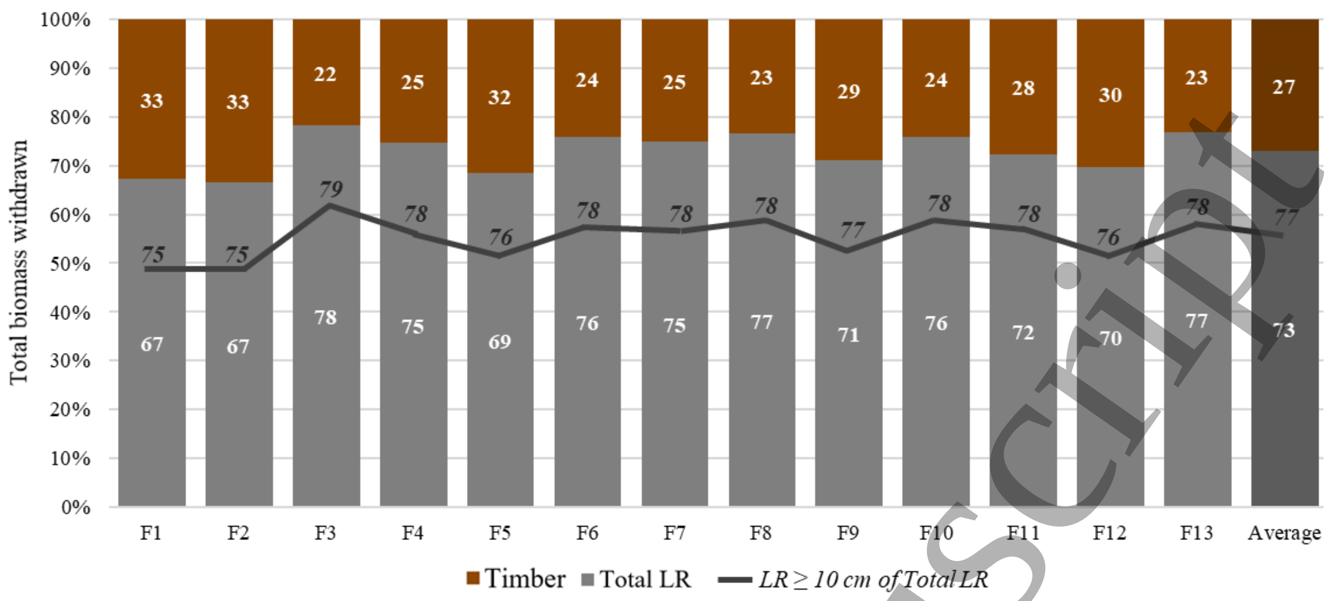

Figure 9. Timber logged and Total Logging Residues produced for each forest site based on the total biomass withdrawn in percentages. Logging Residues with a diameter equal to or greater than 10 cm (dark gray line) are presented as a percentage of the Total LR.

Although the charcoal co-production and sale was carried out in different years (from 2003–2018) and at different prices (from 40 US$ up to 150 US$ per kg m^{-3}), the results indicate that the economic gain through charcoal co-production by LR harvesting can reach an average of 32% of the timber price (Figure 10).

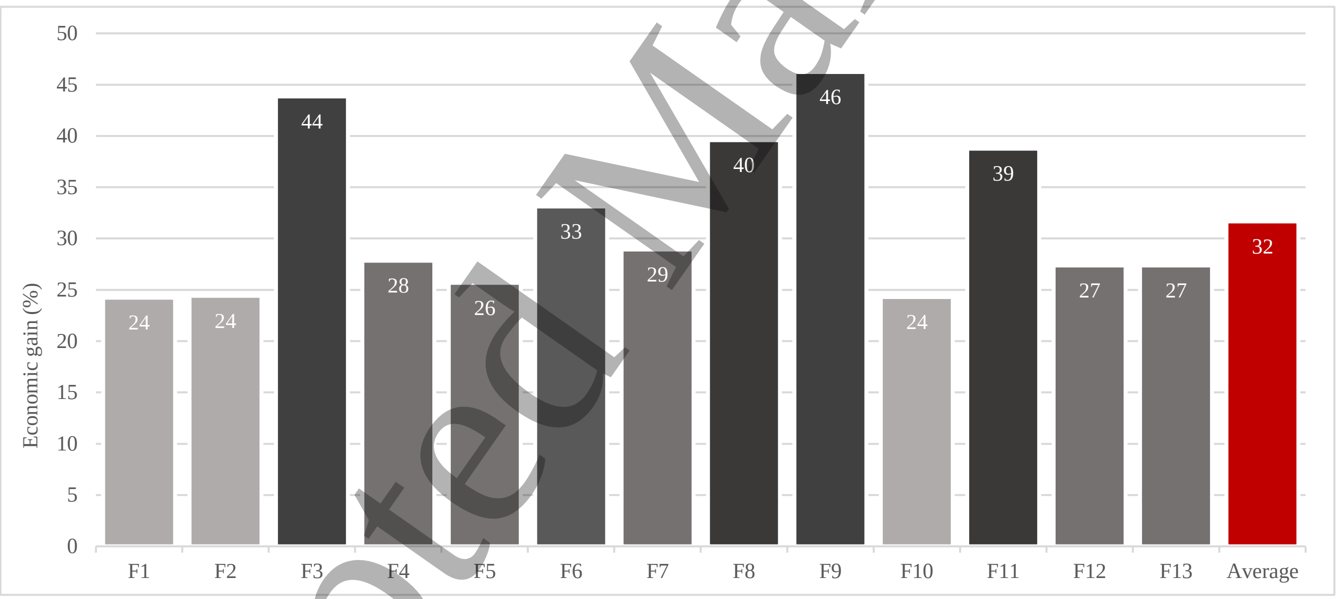

Figure 10. Economic gain (%) with charcoal production over timber price in each forest site.

4. Discussion

We applied a process-based ecosystem model (BGC-MAN) to assess the potential benefits of sustainable forest management (according to the Brazilian Forest Code) under different selective logging scenarios. We found an increase in forest biomass and timber production in all the scenarios run over the 120-year time horizon. Moreover, the results of the selective logging scenarios exhibited positive effects for NEE_{cum} and NPP_{cum} compared to the reference baseline scenario (Legal Reserve). Our findings revealed the advantages of applying sustainable forest management practices that foster removal of logging residues (LR≥10 cm) instead of leaving them behind in the forest, with associated CO_2 emissions being due to decomposition processes. We showed that harvesting of logging residues for charcoal production could have economic and environmental co-benefits for the Brazilian Amazon.

Interestingly, our modeling results indicated that the plant availability of major nutrients, such as nitrogen increased when logging residues (i.e., mostly stem wood) have been removed for charcoal production. This finding is related to the fact that timber takes much longer to decompose than leaf and twig litter. This alters (i) the rate of nitrogen release to the forest floor but also (ii) the demand for nitrogen immobilisation from the soil microbial community[73].

It is important to note that simulations presented here were based on historical daily weather data and current site information, without including climate change scenarios as input. While climate change impacts might be minor compared to forest management scenarios[43], it is important to consider those impacts on forest development and timber production in the Amazon, as well as the impacts of selective logging operations on climate change mitigation[74–76]. For that reason, the need for a better understanding of forest disturbances associated with changing climate and timber production should be implemented in future studies investigating sustainable forest management practices under future climatic conditions.

Having said that, our model analysis presented here was based on the assumption that intact Amazonian forests, like the Legal Reserve, achieve a steady state system with almost equal rates of growth and mortality, as long as there is no influence by human activites (i.e., forest management, fire) or irregular events (i.e., drought, and strong wind storms[77–79]). Therefore, results presented in this study (under the assumption of a steady state and without consideration of climate change) might overestimate the relative benefits of carbon sequestration given that biomass growth of an old-growth forest is mainly balanced by carbon emissions due to respiration[80–83].

Charcoal production, as proposed in this study, is key for economic development in the Amazon. Based on a report from the Brazilian Institute of Geography and Statistics[84], the gross revenue from Legal logging in the Amazon[85] in 2017 was R$2 billion (≈0.5 billion US$) for 12.2 million cubic meters of timber logs. Although this economic benefit may vary based on the market price for commercial tree species, and on administration, maintenance of operations, and transportation costs, the net profit on the timber sale was estimated at 40% on average. The net profit on the charcoal sale was estimated at 32% on average, thus showing a potential economic benefit of 160 million US$ for charcoal co-production[86–88].

In addition, charcoal is an important feedstock for the Brazilian steel industry[23,89,90], and a more sustainable production of this renewable energy source needs policies that effectively address its potential to contribute to poverty reduction and environmental sustainability[72]. So far, the most common goods provided by sustainable forest management include timber, charcoal, and non-timber products (i.e., Brazil nuts)[91]. Even though our study proposed charcoal production from logging residues, it should be highlighted that a high demand for charcoal has been linked to deforestation in previous studies[72,92–95] showing that charcoal production has led to resource depletion when not carried out under sustainable forest management practices.

One of the main findings of our study was that scenarios accounting for harvesting of logging residues (i.e., M1cc-char and M3cc-char) yielded increased environmental response indicators over scenarios without charcoal production (i.e., M1cc and M3cc). This result points to a sustained environmental recovery during forest regrowth and highlights the positive impact of harvesting LR after timber removal. Such positive effects resulting from sustainable forest management could gain further momentum if LR were to be substituted for coal in power generation. Alternatively, instead of logging residues being used for energy production, they could be utilized for production of biochar; this would improve the quality of Amazon forest soil via silvicultural intervention practices that promote tree recruitment and stem volume growth. Overall, we propose that the carbon stock in all wood products should be taken into account in future analysis, as charcoal plays a crucial role in biomass consumption in Brazil. To that end, future analysis should account for the potential economic benefits of charcoal, pellets/briquettes, or "terra preta" when accounting for renewable biomass for energy production in incentives, such as REDD+, that aim to protect climate forests and livelihoods via sustainable management of the Brazilian Amazon.

5. Conclusion

Based on the application of a process-based forestry growth model (BGC-MAN) we analyzed biomass regrowth and timber production in forest stands located in the Brazilian Amazon and quantified the potential economic benefits of selective logging practices (i.e., harvesting LR for charcoal production) according to the Brazilian Forest Code. We found that compared to a "no management" scenario, biomass regrowth and timber production increased under selective logging scenarios. Our results provide evidence for the benefit of regulated forest management practices that aim to maintain biodiversity and increase carbon sequestration, while simultaneously generating economic and social benefits. However, due to the increased economic benefits of charcoal co-production in native forests, there is a risk of deforestation as a consequence of illegal charcoal production[96,97]. This should be avoided by effective implementation of the charcoal policy and enhancement of its legitimacy. Consequently, for the charcoal industry to be sustainable, we would recommend regulations that guarantee the legal production charcoal of Brazilian origin. We conclude that policy proposals should focus on mandating foresting companies to invest in good post-harvest selective logging practices in order to ensure sustainable charcoal production, which should then provide economic, environmental, and social benefits under sustainable management scenarios.

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"The authors have confirmed that any identifiable participants in this study have given their consent for publication".