

Advances in biochar production in traditional Amazonian shifting cultivation fields as a technique for carbon removal

Avances en la producción de biocarbón en chacras tradicionales amazónicas como técnica de eliminación de carbono

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Abstract

The production of biochar - using woody biomass from fallow trees in shifting cultivation as feedstock - and its subsequent application as a soil amendment has previously been identified as a promising technique for removing carbon [C] from the atmosphere. Field trials were conducted on traditional shifting cultivation plots of the Kichwa indigenous people in the Ecuadorian Amazon to evaluate the practical feasibility of this technique. Based on the results, previous concerns that, in the highly humid environment of the western Amazon, it would be difficult to sufficiently dry the feedstock to prevent excessive emissions of the potent greenhouse gas methane [CH₄] were ruled out. The dry matter content of the raw material ranged from 78 to 81%, well above the recommended threshold of 75%. On average, 391 labor-hours were required per metric ton of carbon sequestered in biochar. Given Ecuador's official minimum wage, this cost is relatively high compared to other methods for carbon removal. In many other countries where shifting cultivation is practiced, however, minimum wage levels are lower, which means that this technique could be not only technically but also economically feasible there. It was also found that the thickness of the feedstock had little effect on its dry matter content after drying, suggesting that the number of hours spent splitting the firewood could be reduced, thereby lowering production costs.

Keywords: Amazon, carbon removal, climate change, CO₂, fallows, shifting cultivation.

Resumen

La elaboración de biocarbón - utilizando como materia prima la biomasa leñosa de los árboles de barbecho en la agricultura itinerante - y su posterior aplicación como enmienda al suelo, ha sido identificada anteriormente como una técnica prometedora para la eliminación de carbono [C] de la atmósfera. Se realizaron ensayos en campos de agricultura itinerante tradicional de la nacionalidad indígena kichwa en la Amazonía ecuatoriana con el objetivo de evaluar la viabilidad práctica de esta técnica. Con base en los resultados, se pudo descartar la preocupación previa de que, en el ambiente muy húmedo de la Amazonía occidental, fuera difícil secar suficientemente la materia prima para evitar emisiones excesivas del potente gas de invernadero metano [CH₄]. La proporción de materia seca en la materia prima fue de entre 78 y 81%, muy por encima del límite recomendado de 75%. En promedio, se necesitaron 391 horas de trabajo por tonelada de carbono capturada en biocarbón. Teniendo en cuenta el salario mínimo oficial de Ecuador, este coste es relativamente

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alto en comparación con otros métodos de eliminación de carbono. En muchos otros países donde se practica la agricultura itinerante, sin embargo, los niveles del salario mínimo son más bajos, lo que implica que allí esta técnica podría ser ya no solo técnicamente sino también económicamente factible. También se estableció que el grosor de los trozos de leña afectaba poco a su proporción de materia seca luego del secado, lo que sugiere que podrían reducirse las horas de trabajo dedicadas a la fragmentación de la materia prima, disminuyendo así el costo de producción.

Palabras clave: agricultura itinerante, Amazonía, barbechos, cambio climático, CO₂, eliminación de carbono.

1. Introduction

Biochar is the solid material with a high content of elemental carbon [C] obtained from the thermochemical conversion of biomass under conditions of limited oxygen (International Biochar Initiative, 2015). When incorporated into the soil, it can remain there for hundreds or even thousands of years without decomposing. In this way, it prevents carbon from returning to the atmosphere in the form of CO₂ through the natural process of biological decomposition, thereby counteracting global climate change caused mainly by the burning of fossil fuels (Figure 1). For this reason, it is considered a promising approach for removing carbon from the atmosphere (Jia et al., 2019; Liu et al., 2023; Weng & Cowie, 2025). Other advantages are that biochar amendments tend to improve soil quality, which increases tree growth (Ríos Guayasamín et al., 2024) and crop yield (Coomes & Miltner, 2017; Islami et al., 2011; Jeffery et al., 2017). In addition, they can reduce the uptake of heavy metals in crops (Bravo Medina et al., 2019; Virú-Vasquez et al., 2025). The increase in plant growth in soils amended with biochar is not, however, universal; for example, Valarezo et al. (2016) show a case from the Ecuadorian Amazon in which the biochar amendment had no consistent impact on the growth of the planted trees.

To avoid negative environmental consequences, feedstock originating from pristine ecosystems must not be used, nor should biomass be cultivated for the sole purpose of producing biochar; feedstock for biochar production must consist exclusively of surplus or waste biomass, whose C content would in any case have soon returned to the atmosphere through biological decomposition or combustion. Two decades ago already, shifting cultivation was identified as one of the largest potential sources of biochar feedstock worldwide (Lehmann et al., 2006). Shifting cultivation is a farming system widely practiced in tropical areas. In this system, a relatively short cropping period—normally 1 to 3 years—is followed by a longer fallow period, after which the fallow forest is cleared again and crops are replanted (see Mertz et al. (2009) for an analysis of the different variants of this basic pattern). The traditional chacras of the indigenous

peoples of the Ecuadorian Amazon are an example of this type of agriculture.

Although there has been an increase in research on biochar produced from feedstocks derived from industrial agriculture, forestry operations, wastewater, manure and industrial waste (Fawzy et al., 2021; Lehmann et al., 2021), research on biochar in shifting cultivation has so far been largely limited to desk studies quantifying its global potential for removing carbon from the atmosphere (Lenton, 2010; Lehmann et al., 2006). The most recent estimate of this potential is 0.42 Gt C year⁻¹ (Sirén, 2024), which corresponds to 4% of current annual emissions. Sirén (2024), moreover, incorporated practical experiments, producing biochar by hand using a chainsaw, axes and machetes to break down the feedstock and carrying out pyrolysis in flame curtain kilns consisting of simple earthen pits (cf. Pandit et al., 2017). Based on these experiments, the cost was calculated at 355 USD t⁻¹ CO₂, given the level of labor costs in Ecuador. It also identified the main remaining practical challenges as ensuring sufficient drying and optimizing feedstock fractioning, to reduce the labor hours per ton of biochar produced and thus reduce the corresponding cost.

Drying is important because, if wet feedstock is used, pyrolysis can cause methane emissions, which is a potent greenhouse gas, thereby worsening global warming instead of mitigating it (Cornelissen et al., 2023). Therefore, it is recommended that the feedstock have a dry matter content of no less than 75% (Ithaka Institute, 2024). Fractioning the feedstock is necessary not only to speed up drying, but also to achieve efficient pyrolysis, regardless of its moisture content.

The present work is part of a research project whose general objectives are: 1) to develop an appropriate field measurement methodology that makes it possible to assess the efficiency of different biochar production strategies in shifting cultivation, and 2) to establish permanent plots to compare different biochar production strategies and collect baseline data. Specifically, results related to feedstock preparation and to biochar yield in relation to the amounts of biomass and labor used will be presented here.

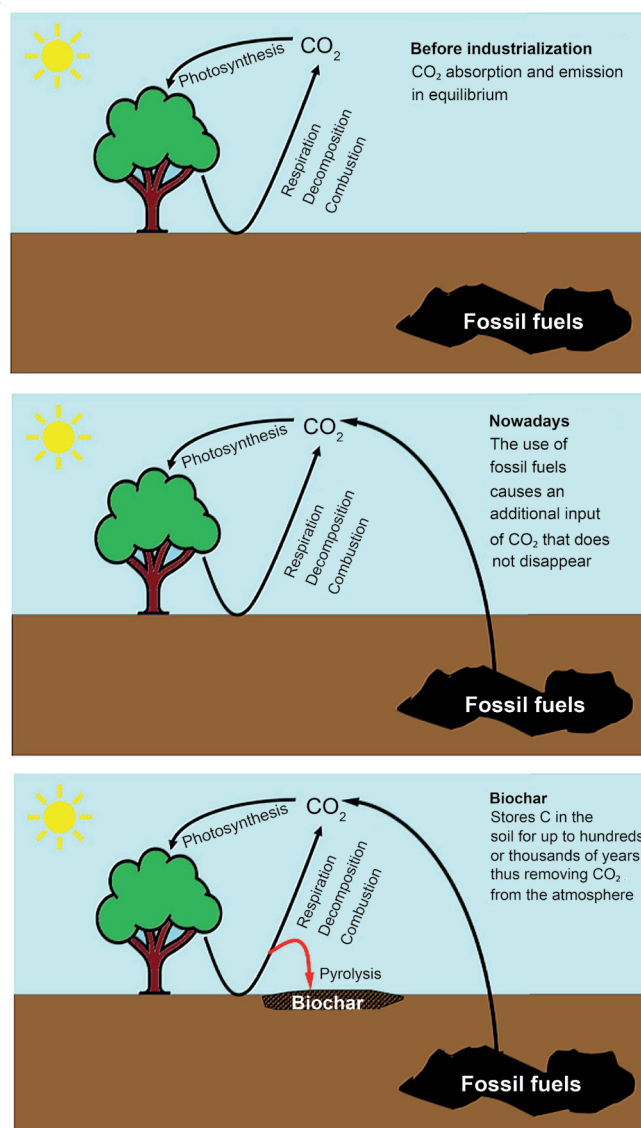


Figure 1. The principle of removing CO₂ from the atmosphere through the production of biochar.

2. Materials and Methods

Field work was carried out in the Kichwa indigenous community of Sarayaku (1°44' S, 77°29' W), in the province of Pastaza, in the Ecuadorian Amazon. Between August and October 2025, taking advantage of the dry season, biochar was produced on three traditional Amazonian shifting cultivation fields, locally known as *chacras*. The work was carried out with the permission of the respective owners, who also took part in the fieldwork. After the owners felled the fallow forest, four adjacent 12 × 12-meter trial plots were established in each field. In these plots, the volume of woody biomass was measured using the planar intersect method (Van Wagner, 1982), laying out transects with a density of 0.49 m⁻¹ for material with a diameter greater than 8 cm, 0.17

m⁻¹ for a diameter between 4 and 8 cm, and 0.06 m⁻¹ for a diameter between 1 and 4 cm. For material with a diameter greater than 8 cm, the circumference was measured with a measuring tape. In addition, the ten largest trunks in each plot were selected based on a visual assessment; these were identified according to local taxonomy, and wood samples were collected from them for subsequent laboratory analysis to determine the density of each species. All the wood was cut into pieces approximately 40 cm long and then split into pieces of feedstock wood about 4 cm thick using mechanical log splitters, which made it possible to work faster than with a regular axe (Figure 2). Pieces with a diameter of less than about 8 cm were left unsplit. The feedstock wood was then stacked and left to dry on site for several weeks (Figure 3). Following weather forecasts, pyrolysis was always carried out after there



Figure 2. Splitting the feedstock wood with a mechanical log splitter.



Figure 3. Feedstock wood stacked for drying.

had been several days of sunshine.

Pyrolysis was carried out on the same fields in flame curtain kilns, consisting of a pit dug into the ground (Figure 4). The principle of these kilns is that the flames at the surface consume all the oxygen, in addition to producing heat, thus providing the lower layers with the high-temperature, oxygen-free conditions necessary for pyrolysis to occur and biochar to accumulate. Once the pit was full, the fire was put out, first with water carried on shoulders from the nearest source, and then by covering the pit with soil. Several days later, the team returned to open the pit, remo-

ve the biochar and add it to the soil in the trial plots, where the effects of the biochar on the soil and crops will subsequently be assessed (Figure 5). In one of the fields, the fire in the pit could not be fully extinguished, so that, upon returning, approximately half of the biochar had already burned, leaving only ash. Therefore, complete field data could not be collected for this field.

While feedstock wood was being added to the kiln, wood samples were taken from the third layer from the bottom and the third layer from the top of the piles corresponding to the previously numbered trees.



Figure 4. Pyrolysis in a flame curtain kiln.



Figure 5. Experimental plot with added biochar (right) and control plot without biochar (left).

Their thickness was measured, and they were stored in Ziploc-type plastic bags for subsequent analysis of their dry matter content. When emptying the kiln to add the biochar to the soil in the trial plots, each bucket was counted in order to calculate the volume of biochar produced. Biochar samples were also taken to subsequently measure their dry density in the laboratory and thereby calculate the total weight of biochar produced. In the laboratory, the samples were first weighed and pre-dried at 87 °C for several hours and then dried at 105 °C until their weight changed by less than 0.1% per hour, at which point their dry weight was recorded. From these data, their dry matter content and carbon content were calculated. Estimated values for the C fractions in the feedstock and in the biochar were obtained from the literature. Based on these input data, several calculations were carried out in order to estimate, in particular, the fraction of C in the feedstock converted to C in the biochar, the labor hours used per volume of feedstock and per mass of C in the biochar, and, finally, the cost per mass of C or CO₂e in the biochar. The latter is particularly important in that it corresponds to the cost of providing the climate benefit of removing greenhouse gases from the atmosphere. The input data and the formulas applied are detailed in Table 1. Note that, due to the lack of some field data for Field 3, it was not possible to carry out for it all the calculations that were carried out for the other fields.

3. Results and Discussion

The main results are presented in Table 1. An important result was that the feedstock wood turned out to be sufficiently dry, with a dry matter content of 78 to 81% across the three fields, above the proposed minimum level of 75% (cf. Ithaka Institute, 2024), although still short of the ideal level of 85%. It should be noted, however, that there were some outliers, in which some pieces of feedstock wood showed a much lower dry matter content, reaching as low as barely 36%. The cause of these outliers, which represent pieces of feedstock wood much wetter than permissible, is not entirely clear, but there is evidently room for improving the drying procedures. The average wood density varied moderately across the three fields due to the variability in the species composition of the different trees, although the *pigüe* species (*Piptocoma discolor*) dominated in all of them, accounting for approximately 51% of the total woody biomass. Variability in the density of the biochar produced was quite marked, ranging from 0.084 to 0.129 tonnes m⁻³. Even the highest of these values, moreover, was lower

than the value of 0.140 tonnes m⁻³ that Sirén (2024) had previously used as a standard value for his calculations, based on Werdin et al. (2020).

The proportion of carbon from the feedstock that remained sequestered in the biochar was 43% and 40%, respectively, which are fairly normal values for pyrolysis in flame curtain kilns (cf. Cornelissen et al., 2016). The labor time required to process each cubic meter of feedstock was considerably reduced, dropping from the 48 hours previously recorded (Sirén, 2024) to just 24 and 32 hours, respectively, in the two fields. This is attributed, on the one hand, to the use of mechanical log splitters, which saved a great deal of time, and also to accumulated experience, which has increasingly allowed the procedures to be better optimized.

The amount of labor required per ton of C in the resulting biochar ranged from 308 to 476 hours, that is, from 38 to 60 days. Calculated using Ecuador's current officially established minimum wage, this implies a cost of 246 and 381 USD t⁻¹ CO₂e, respectively, in the two fields. This amount can be compared with the prices of biochar-based carbon credits in the voluntary market, which have recently ranged between 130 and 150 USD t⁻¹ CO₂e (Puro Earth, 2025), as well as with carbon taxes, which currently reach a maximum of 135 USD t⁻¹ CO₂e in Uruguay (Richie & Rosado, 2022). In other words, the cost remains relatively high. However, it should be borne in mind that Ecuador, where these trials were carried out, is an upper-middle-income country with a dollarized economy, which means that labor costs are much higher there than in most countries where shifting cultivation is practiced. In many countries in tropical Africa and South Asia, the minimum wage is 4 to 15 times lower than in Ecuador (World Population Review, 2026), so there, biochar production in shifting cultivation could be a carbon removal method that is not only technically but also economically feasible. On the other hand, it was observed that the dry matter content increased slightly with smaller thickness and later hours of the day. However, when three outliers were removed from the analysis, these effects practically disappeared (Figure 6). That is, at least up to 50 mm, the thickness of the feedstock wood had very little effect on drying, and future research should explore whether the thickness can be increased even further in order to reduce the labor hours devoted to fractioning the feedstock.

4. Conclusions

The concern that it might be difficult to dry the feedstock sufficiently to avoid excessive CH₄ emissions

Table 1. Test results.

Data type	Variable and calculation	Definition	Field 1	Field 2	Field 3
Field data	V_m	Feedstock volume (m ³)	2.15	2.06	9.19
	V_b	Biochar volume (m ³)	2.22	2.17	
	H_t	Total labor time used (h)	51.6	65.5	
Laboratory data	D_m	Feedstock density (t m ⁻³)	0.365	0.331	0.393
	F_s	Dry matter fraction in the feedstock	81%	78%	78%
	D_b	Biochar density (t m ⁻³)	0.100	0.084	0.129
Literature data*	F_m	Fraction of C in the feedstock		50% ¹	
	F_b	Fraction of C in the biochar		75.5% ²	
	S	Minimum wage in Ecuador (USD h ⁻¹)		\$2.94 ³	
Calculated results	$C_m = V_m \times D_m \times F_m$	Mass of C in the feedstock (t)	0.39	0.34	1.81
	$C_b = V_b \times D_b \times F_b$	Mass of C in the biochar (t)	0.168	0.138	
	$F_c = C_b / C_m = (V_b \times D_b \times F_b) / (V_m \times D_m \times F_m)$	Fraction of C in the feedstock converted to C in the biochar	43%	40%	
	$M_v = H_t / V_m$	Labor used per volume of feedstock (h m ⁻³)	24	32	
	$P_t = H_t \times S$	Total labor cost (USD)	\$152	\$193	
	$H_b = H_t / C_b = H_t / (V_b \times D_b \times F_b)$	Labor used per mass of C in the biochar (h t ⁻¹)	308	476	
	$P_c = P_t / C_b = (H_t \times S) / (V_b \times D_b \times F_b)$	Cost per mass of C in the biochar (USD t ⁻¹)	\$904	\$1,398	
	$P_e = P_c / 3.67 = (H_t \times S) / (V_b \times D_b \times F_b \times 3.67)$	Cost per mass of CO ₂ e in the biochar (USD t ⁻¹)	\$246	\$381	

* Values in italics indicate literature values used for the calculations. See the main text for explanations.

Source: ¹ Saatchi et al. (2011), ² Cornelissen et al. (2016), and ³ Acuerdo Ministerial No. MDT-2024-300, and assuming 160 working hours per month.

has been dispelled. In fact, it has been found that the feedstock could probably be fractioned much less without risking insufficient drying, which would also imply a considerable reduction in labor hours and, therefore, in the cost per ton of carbon captured in the biochar. The results confirm that biochar production on shifting cultivation fields has great potential as a technique for removing carbon from the atmosphere. Further planned research will clarify how the biochar

amendment affects soils and crops in shifting cultivation. Finally, it is important to point out that the possibility of removing a certain amount of CO₂ from the atmosphere through biochar production should never be used as a pretext for continuing to emit CO₂. Quite the contrary, rapidly eliminating the use of fossil fuels remains essential to stop global climate change. Biochar, however, may serve to partially remedy the climate damage caused by cumulative emissions.

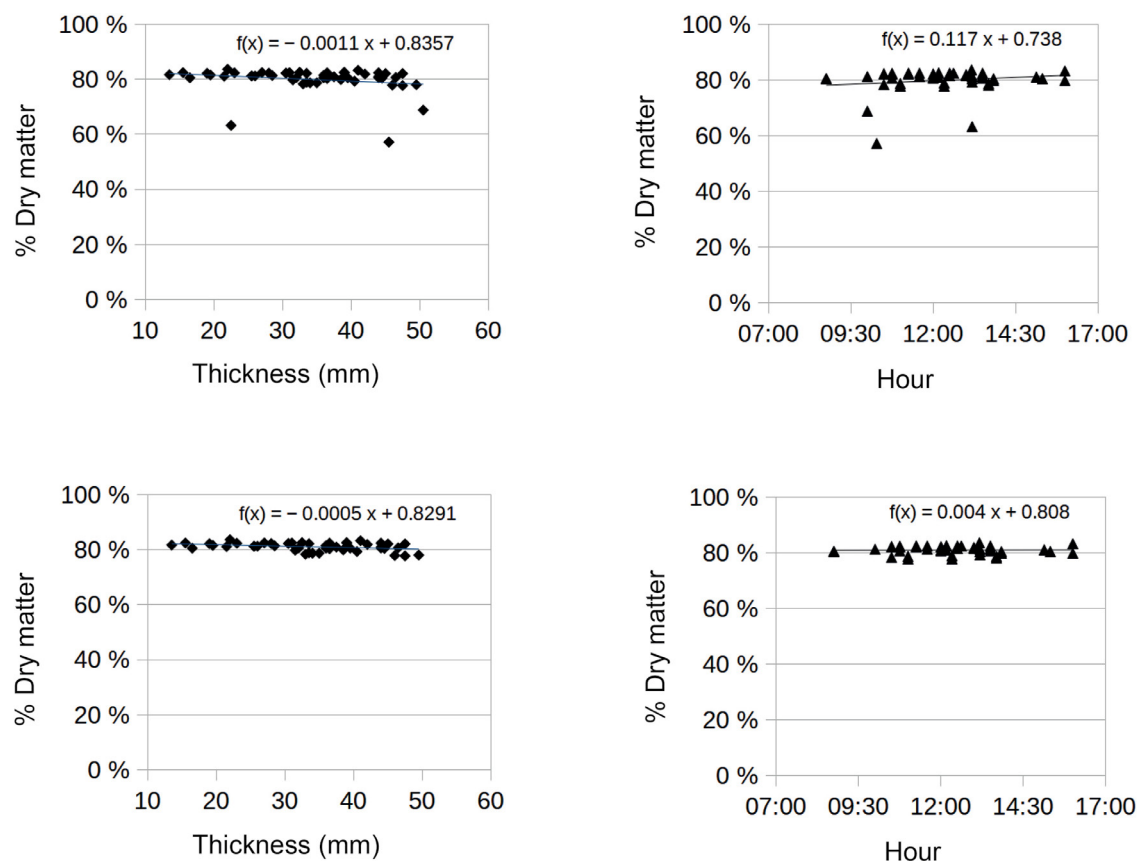


Figure 6. Effects on the dry matter content of the feedstock as a function of thickness (left) and hour (right), for the complete dataset (top) and after removing three outliers (bottom). Data are exclusively for feedstock wood of *Piptocoma discolor*.

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Contributor roles

- Anders Henrik Sirén: conceptualization, investigation, methodology, writing - review and editing.

Data Availability

The data will be available on request.

Preprint statement

A previous version of this manuscript has been deposited as a preprint in EcoEvoRxiv repository and can be accessed at <https://ecoevorxiv.org/repository/view/12172/>.

Use of Artificial Intelligence

The author declares that no artificial intelligence has been used in the preparation of the manuscript.

Ethical Implications

The author declares that there are no ethical implications.

Conflict of Interest

The author declares that he has no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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