Economic efficiency of biochar as an amendment for *Acacia mangium* Willd. plantations

Eficiencia económica del biocarbón como enmienda en plantaciones de *Acacia mangium* Willd.

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ABSTRACT

Biochar is a product of pyrolysis obtained from any type of biomass and can be used as a soil amendment or conditioner, improving the physical, chemical, and biological properties of the soil. Additionally, it can serve as an alternative to the application of synthetic fertilization in forest species such as *Acacia mangium* Willd. This research was oriented towards the determination of the economic efficiency of the use of biochar in *A. mangium* compared to the use of synthetic fertilizers. Production costs of wood and by-products, income and profits from forestry, economic efficiency of capital (cost-benefit ratio), labor (wood production per worker), and land (wood production ha^{-1}) were considered. We found that the production of wood using biochar increased by 47% per unit area (ha), by 23% per unit of work (worker), and increased earnings by approximately one million Colombian pesos ha^{-1} compared to the use of only synthetic fertilizers.

Key words: costs, income, labor efficiency, land efficiency, profitability.

RESUMEN

El biocarbón es el producto de la pirólisis que se obtiene de cualquier tipo de biomasa y puede ser usado como enmienda o acondicionador para mejorar las propiedades físicas, químicas y biológicas del suelo. Además, se puede utilizar como una alternativa para reemplazar la aplicación de fertilizantes sintéticos en especies forestales como *Acacia mangium* Willd. Esta investigación se orientó hacia la determinación de la eficiencia económica del uso del biocarbón en *A. mangium* frente al uso de fertilizantes sintéticos. Se consideraron costos de producción de madera y subproductos, los ingresos y ganancias de la actividad forestal, la eficiencia económica del capital (relación costo-beneficio), del trabajo (producción de madera por trabajador) y de la tierra (producción de madera ha^{-1}). Se encontró que la producción de madera con biocarbón se incrementó en un 47% por unidad de superficie (ha), en un 23% por unidad de trabajo (trabajador) y las ganancias aumentaron en aproximadamente un millón de pesos colombianos ha^{-1} respecto al uso de sólo fertilizantes sintéticos.

Palabras clave: costos, ingresos, eficiencia del trabajo, eficiencia de la tierra, rentabilidad.

Introduction

Economic efficiency in agriculture, which includes forestry, is reflected in a better production with the same number of resources or the same production with a lower number of resources. Better production refers to a greater quantity, better quality, higher diversity, or a mixture of the above. For economic efficiency, the prices of resources and products at the time of their measurement are important. It is also important to consider the physical, social, environmental, and political context of the agricultural production being analyzed. Globally, from 1990 to 2020, the increase in planted forest area was 123 million ha, reaching 294 million ha (FAO & UNEP, 2020). In Colombia, the registered area of commercial forest plantations for 2016 was approximately 470,000 ha (Martínez *et al*., 2016).

The cultivation and use of forest species in Colombia are mainly aimed at obtaining wood. However, other additional uses are gaining value, such as the use of forest residues. Proper management of forest residues brings some benefits, such as avoiding contamination *in situ* and the nearby ecosystems. Additionally, these residues constitute a good source of improvement that, in turn, can reduce the use of synthetic fertilizers (Arvanitoyannis *et al*., 2006).

If organic waste, including that of forest species, is subjected to a thermal conversion of biomass in an oxygen-limited

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environment, a solid, fine-grained, and porous product with a high content of organic carbon called biochar is obtained from the pyrolyzed material (IBI, 2013; Ippolito, Donnelly, & Grob, 2015). Biochar stands out for absorbing nutrients and water and reducing the bulk density of the soil (Lehmann, 2007; Reddy *et al*., 2013). Given its stability in the environment (Ippolito, Spokas, *et al*., 2015), biochar generates environmental benefits associated with the reduction of CO_2 in the atmosphere through carbon sequestration in the soil increasing the organic matter content of the soil, and economic benefits by generating emission quantifiers for GHG or CERTS and carbon credits (Antle & McCarl, 2002; Lehmann *et al*., 2003; Post *et al*., 2004). These benefits have allowed biochar to be currently considered as an environmental alternative to the use of synthetic fertilizers in forestry production.

Forest crops such as *Acacia mangium* generate organic residues that are not yet being used properly. In the department of Meta, nine years after cultivation was established, 1 t of biomass was produced for every four usable trees (CONIF, 2013). Thus, in a plantation with a density of 400 plants ha^{-1}, an average of 100 t ha^{-1} of biomass is obtained, whereas in the studied plot this biomass is obtained after 12 years under the same conditions. Of the total biomass, 40% remains in the field as waste, 40% remains in the sawmill as waste, and only 20% is used as wood (SIOC, 2018). These 80 t ha^{-1} of unused residue could be converted into 24 t ha^{-1} of biochar at an efficiency of 30%. The use of this biochar in the same forest crop to replace synthetic fertilizers could have consequent favorable economic and environmental effects.

The economic efficiency of biochar as an amendment was analyzed in a commercial forest plantation of *A. mangium* located in Colombia. This research studied the costs, income, and efficiency of labor, land (yield) and capital (profitability) for the use of biochar vs. the use of synthetic fertilizers in *A. mangium* to determine whether the application of biochar in the soil of an *A. mangium* agroecosystem is viable in economic terms, compared to the conventional agronomic practices of the same plantation.

Materials and methods

Location and characteristics of the study area

The study was carried out in the Planas village, located in the municipality of Puerto Gaitán, department of Meta (Colombia), (between 3°05' and 4°08' N, and between 71°05' and 72°30' W). The area has an average annual temperature of 30°C and a total annual rainfall of around 2,300 mm with a bimodal pattern. The soils that dominate the region are Oxisols and Ultisols. In the Planas village, the soils are Typic Troporthents, shallow and low in bases (IDEAM, 2013). In Planas, there is a commercial *A. mangium* crop belonging to an associative forestry company. At the time of the study, the *A. mangium* crop had an area of 2,100 ha in different stages of development. The first plantations were established in 2008. Between 2017 and 2018, a field trial was carried out on this company's facilities, which served as the basis for the elaboration of a doctoral thesis from which the data for the present article were taken (Reyes Moreno, 2018). Under the same edaphoclimatic conditions of the forest farm, two comparative forms of timber production with different nutrition models were considered: a "standard" crop (ST), with the use of a synthetic fertilizer ("Triple 15" or 15-15-15: nitrogen (N) 15%, phosphorus (P_2O_5) 15%, potassium (K_2O) 15%, YARA, Colombia) and an "optimal" crop (OP) with biochar and synthetic fertilizer applications. The biochar was applied once at the beginning, while the synthetic fertilizer was applied every year in both scenarios. A "real" analysis was performed for ST, and a projection, with data that came from a statistical analysis of response surface (Reyes-Moreno *et al*., 2019), was performed for OP of management and harvesting activities (pruning, thinning, and cutting). The first pruning was carried out in the first year of establishment and then every 15 months. The first thinning was performed in the fifth year and the second in the ninth year. The thinnings provided saleable timber. After the two thinnings, the crop was left with a density of 400 trees ha^{-1} until the time of cutting, which was carried out in year 12. The projected cultural activities of the trial were those corresponding to commercial cultivation and consisted of pruning and thinning. The first pruning was carried out in the first year of establishment, then every 15 months. The thinning was carried out in the fifth and ninth years. Thinning also provided saleable timber material. After thinning, the crop was left with 400 trees ha^{-1} until the time of cutting.

The biochar was obtained from the same plantation according to the methodology of Jouiad *et al*. (2015). Thinning and pruning residues from the commercial *A. mangium* plantation were subjected to slow pyrolysis with a residence time of 14 h and temperatures between 350°C and 400°C in two pyrolytic furnaces (made with local technology) located in the same plantation.

The field information was obtained in two different phases: during the nursery phase, which lasted three months (April to June 2017), and during the initial growth phase in the field with a duration of one year (July 2017 to July 2018). The field trial consisted in a comparison of the effects of synthetic fertilization and the application of biochar on the growth and biomass gain of the *A. mangium* crop, allowing a projection of future production. The treatments with three replicates are shown in Table 1.

TABLE 1. Comparative trial with three replicates of synthetic fertilizer vs. biochar in the *Acacia mangium* plantation during the establishment and early growth.

Biochar (t ha^{-1})	Synthetic fertilizer 15-15-15 (g/plant per year)		
	0	50	100
0	T_1	T_2	T_3
40	T_4	T_5	T_6
80	T_7	T_8	T_9

Estimated volume of OP wood

Estimates of the wood volume in OP were made using the volume equation of a truncated cone, using the height and radii of the lower and upper bases of the trunk (Eq. 1). Measurements were carried out with a caliper for the radii and tape measure for the height. This approach was confirmed with a destructive pilot sampling to discard the use of the form factor and use the convenience of the truncated cone instead of the oblique one, since it is the most similar three-dimensional geometric shape in practice for the age of the plantation. For the process of optimizing the volume of *A. mangium* wood, two applications of fertilizer were carried out to the soil, each at two concentrations, adjusting a second order model design. In the model, two treatment levels were used, namely 40 and 80 t ha^{-1} of biochar and 50 and 100 g of synthetic fertilizer per plant. Finally, in this analysis, data were obtained for the application of 63.1 t ha^{-1} of biochar at transplanting (seeding) and 84.4 g/plant per year of synthetic "Triple 15" fertilizer. This was done once at crop establishment (Reyes-Moreno *et al*., 2019).

$$A = \pi r^2 \tag{1}$$

where A = area, π = 3,141592, and r = stem radius.

Estimated volume of wood in the standard system (ST)

Projected timber production in the ST was calculated through a non-linear regression developed from the information collected in the above-mentioned trial. To calculate the projection of wood volume (Tab. 2) in the ST, a non-linear regression was used (Eq. 2):

$$E(V|t) = (65{,}7753 + 206{,}741 * Ln(t))^2 \tag{2}$$

where V was the estimated volume (cm^3/plant), E(V|t) was the expected value of the volume given the explanatory variable associated with time (*Ln* is the natural logarithm), and *t* was time in years.

In the ST crop, 100 g/plant per year of synthetic fertilizer was applied as a crown at the base of each tree.

TABLE 2. Projection of the volume of wood produced (m^3 ha^{-1}) during a cycle under the standard production system in a 600-ha crop of *Acacia mangium*.

Year	Accumulation of biomass (m^3/plant)	Wood available per each plant (%)	Trees harvested ha^{-1}	Wood harvested (m^3 ha^{-1})	Wood harvested (m^3 600 ha^{-1})
1	0.004	0.20	0	0	0
2	0.044	0.20	0	0	0
3	0.086	0.20	0	0	0
4	0.124	0.20	0	0	0
5	0.159	0.20	300	9.53	5,718
6	0.190	0.20	0	0	0
7	0.219	0.20	0	0	0
8	0.246	0.20	0	0	0
9	0.270	0.20	300	16.23	9,738
10	0.294	0.20	0	0	0
11	0.315	0.20	0	0	0
12	0.336	0.20	400	26.88	16,128
Total			1,000	52.64	31,584

The plant density in the plantation in the first year was 1,000 plants ha^{-1}.

Apart from logging, the plantation provides indirect services associated with carbon fixation. The carbon credits corresponded to one metric ton of CO_2 verified by an entity governed by ICONTEC standards. Regarding the carbon reservoir, biomass above ground was considered (only living wood), where 240,000 t were quantified with a value per ton of 15,000 Colombian pesos (in 2018).

Studied variables

The variables used were production costs, income and, therefore, profits and profitability. Additionally, the efficiency of labor and land use for the crops under study were compared (Tab. 3).

TABLE 3. Differences in production costs (millions of Colombian pesos in 2018) between a standard system (ST) and an optimal system (OP) (600 ha).

	ST	OP
Production factors	**Quantity**	
Fixed assets		
Seeding machine	1	1
Chainsaw	3	3
Tractor	3	3
Vehicle	1	1
Sawmill	3	3
Finger machine	1	1
Power plant	2	2
Biochar furnaces	2	4
Facilities	1	1
Inputs		
Pellets (unit)	660,000	660,000
Pesticides (L)	1,220	1,220
Fertilizers (kg)	132,600	112,008
Gasoline (gal)	1,300	2,150
Labor		
Wages	1,557	1,350
Services		
Technical consultant	20	18
Accountant	1	1
Manager	1	1
Secretary	1	1
Soil analysis	10	10
Maintenance of machinery and equipment	31	29
Transportation (gasoline gallons)	2,200	2,200
Land (ha)	600	600

Table 4 shows the differences between the standard and optimal systems in terms of production.

TABLE 4. Differences in production between a standard system (ST) (600 ha) and an optimal system (OP) (600 ha).

Products and by-products	ST	OP
Charcoal (12 kg)	40,000	40,000
Wood (m^3)	31,578	47,052
Carbon credits (t)	38,921	73,710

Results

Production costs

Production costs by stages

Production in the entire cycle in OP is approximately 2% less expensive than in ST (Tab. 5). On average, 1 ha of the *A. mangium* crop costs approximately 30 million pesos per 12-year cycle (2.5 million pesos per year).

Production costs by factors

Direct costs, made up of inputs and labor, are 20% and 23% of total costs for OP and ST, respectively; indirect costs, made up of fixed assets, services and land, are 80% and 77% for OP and ST, respectively. Thus, this activity is high in demand for investment (capital), with a return in the medium (5 years) and long term (9-12 years). Fixed assets are the costs with the highest proportion (64-65%), followed by inputs (13-15%), services (10%), labor (7-8%) and land (4%) (Tab. 6).

Regarding production factors, OP and ST differ fundamentally in labor and the use of fertilizer and biochar. The OP uses more labor than the ST in harvesting and pyrolysis due to higher production, and the ST uses more labor than the OP in the annual application of fertilizer.

Income

Income from forestry is generated by producing charcoal, wood and by fixing CO_2 (carbon credits). The main business is the production of wood.

According to the projected yields, the OP obtains 47% more wood production (78 m^3 ha^{-1}) than the ST (53 m^3 ha^{-1}). The first harvest at year 5 generates 18% of the total wood production, the second at year 9 generates 31%, and the third at year 12 generates 51% (Tab. 7). The production of charcoal from year 5 generates income to cover part of the labor costs (Tab. 8).

TABLE 5. Costs (millions of Colombian pesos in 2018) of production by stages. Standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Nursery		Establishment of crop		Management of crop		Harvest		Wood produced		Pyrolysis		Total	
	ST	OP	ST	OP	ST	OP	ST	OP	ST	OP	ST	OP	ST	OP
1	172	171	2,189	2,157	0	0	524	521	1,375	1,367	150	298	4,411	4,516
2	0	0	0	0	1,155	1,121	0	0	0	0	0	0	1,155	1,121
3	0	0	0	0	1,155	1,121	0	0	0	0	0	0	1,155	1,121
4	0	0	0	0	1,155	1,121	0	0	0	0	0	0	1,155	1,121
5	0	0	0	0	811	711	194	236	253	254	72	126	1,329	1,327
6	0	0	0	0	1,009	999	0	0	0	0	200	159	1,209	1,158
7	0	0	0	0	1,009	999	0	0	0	0	200	159	1,209	1,158
8	0	0	0	0	996	983	22	25	0	0	198	156	1,215	1,164
9	0	0	0	0	757	695	235	287	236	248	150	111	1,378	1,342
10	0	0	0	0	996	983	22	25	0	0	198	156	1,215	1,164
11	0	0	0	0	1,009	999	0	0	0	0	200	159	1,209	1,158
12	0	0	0	0	691	629	412	466	216	225	137	100	1,456	1,420
Total	172	171	2,189	2,157	10,742	10,361	1,409	1,561	2,080	2,094	1,505	1,424	18,098	17,769

ST: 100 g/plant per year of 15-15-15 used for fertilization. OP: 63.1 t ha^{-1} of biochar plus 84.4 g/plant per year of 15-15-15 used for fertilization.

TABLE 6. Costs (millions in 2018) of production by factors. Standard system (ST) vs*.* optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Fixed assets		Inputs		Labor		Services		Land		Total	
	ST	OP	ST	OP	ST	OP	ST	OP	ST	OP	ST	OP
1	3,244	3,364	291	260	70	78	152	149	667	667	4,424	4,518
2	750	750	218	186	42	38	154	149	0	0	1,164	1,123
3	750	750	218	186	42	38	154	149	0	0	1,164	1,123
4	750	750	218	186	42	38	154	149	0	0	1,164	1,123
5	750	750	218	195	179	204	154	149	0	0	1,301	1,298
6	750	750	218	186	95	76	154	149	0	0	1,217	1,161
7	750	750	218	186	95	76	154	149	0	0	1,217	1,161
8	750	750	218	186	95	76	154	157	0	0	1,217	1,169
9	750	750	218	195	240	231	154	167	0	0	1,362	1,343
10	750	750	218	186	95	76	154	154	0	0	1,217	1,166
11	750	750	218	186	95	76	154	149	0	0	1,217	1,161
12	750	750	218	195	312	303	154	175	0	0	1,434	1,423
Total	11,494	11,614	2,689	2,333	1,402	1,310	1,846	1,845	667	667	18,098	17,769

Fixed assets (ST): seeder machine (1), chainsaws (3), tractors (3), vehicles (1), sawmills (1), finger machine (1), power plant (2), biochar furnaces (2) and facilities (3 houses, 4 cabins and a dining room).

Fixed assets (OP): seeder machine (1), chainsaws (3), tractors (3), vehicles (1), sawmills (1), finger machine (1), power plant (2), biochar furnaces (4) and facilities (3 houses, 4 cabins and a dining room).

Inputs (ST): pesticides 25 L ha^{-1}/12-year cycle, synthetic fertilizer 900 kg ha^{-1}/12 years, gasoline (18,500 gallons/12-year cycle).

Inputs (OP): pesticides 25 L ha^{-1}/12-year cycle, synthetic fertilizer 747 kg ha^{-1}/12 years, gasoline (2050 gallons/12-year cycle).

Workforce (ST): workers: 84 salaries/12 years.

Labor force (OP): workers: 102 salaries/12 years.

Services (ST): consulting (6), maintenance (5), secretary (1), manager (1) and accountant (1).

Services (OP): consulting (6), maintenance (5), secretary (1), manager (1) and accountant (1).

Land: purchase of land.

TABLE 7. Wood production for a standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	ST		OP	
	Harvested wood (m^3 ha^{-1})	Harvested wood (m^3 600 ha^{-1})	Harvested wood (m^3 ha^{-1})	Harvested wood (m^3 600 ha^{-1})
5	10	5,718	14	8,520
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	16	9,738	24	14,510
10	0	0	0	0
11	0	0	0	0
12	27	16,122	40	24,022
Total	53	31,572	78	47,042

TABLE 8. Income (Colombian pesos in 2018) by forest production for a standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Products	Unit	Production		Unit price		Income	
			ST	OP	ST	OP	ST	OP
5	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
	Wood	m^3	5,718	8,520	470,000	470,000	3,259,260,000	4,856,400,000
6	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
7	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
8	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
9	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
	Wood	m^3	9,738	14,510	470,000	470,000	5,550,660,000	8,270,700,000
	Carbon credits	t	38,921	73,710	15,000	15,000	583,815,000	1,105,650,000
10	Charcoal	Package	5,000	5,000	12,000	12,000	60,000.000	60,000,000
11	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
12	Charcoal	Package	5,000	5,000	12,000	12,000	60,000,000	60,000,000
	Wood	m^3	16,122	24,022	470,000	470,000	9,189,540,000	13,692,540,000
			Total				19,063,275,000	28,405,290,000

Economic efficiency

Economic efficiency of capital

The OP has higher income due to higher production and lower production costs due to less use of synthetic fertilizers. Its profitability is approximately 1.60 compared to 1.05 for the ST (Tab. 9).

Economic efficiency of work

The OP is also superior to the ST in terms of labor efficiency. Thus, a worker in the OP produces approximately 23% more wood than in the ST in a 12-year cycle (Tab. 10).

TABLE 9. Profit and profitability (cost-benefit ratio) (Colombian pesos in 2018) by forest production for a standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Income		Costs		Earnings	
	ST	OP	ST	OP	ST	OP
1	0	0	4,424,000,000	4,518,000,000	-4,424,000,000	-4,518,000,000
2	0	0	1,164,000,000	1,123,000,000	-1,164,000,000	-1,123,000,000
3	0	0	1,164,000,000	1,123,000,000	-1,164,000,000	-1,123,000,000
4	0	0	1,164,000,000	1,123,000,000	-1,164,000,000	-1,123,000,000
5	3,319,260,000	4,916,400,000	1,301,000,000	1,298,000,000	2,018,260,000	3,618,400,000
6	60,000,000	60,000,000	1,217,000,000	1,161,000,000	-1,157,000,000	-1,101,000,000
7	60,000,000	60,000,000	1,217,000,000	1,161,000,000	-1,157,000,000	-1,101,000,000
8	60,000,000	60,000,000	1,217,000,000	1,169,000,000	-1,157,000,000	-1,109,000,000
9	6,194,475,000	9,436,350,000	1,362,000,000	1,343,000,000	4,832,475,000	8,093,350,000
10	60,000,000	60,000,000	1,217,000,000	1,166,000,000	-1,157,000,000	-1,106,000,000
11	60,000,000	60,000,000	1,217,000,000	1,161,000,000	-1,157,000,000	-1,101,000,000
12	9,249,540,000	13,752,540,000	1,434,000,000	1,423,000,000	7,815,540,000	1,232,954,000
Total	19,063,275,00	28,405,290,000	18,098,000,000	17,769,000,000	9,652,750,000	10,636,290,000
Mean (Colombian pesos ha^{-1} per year)	2,647,677	3,945,179	2,513,611	2,467,917	134,067	147,7263
				Profitability	1.05	1.60

TABLE 10. Work performance (m³/worker) for a standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Production of wood (m³)		*Number of workers		Work performance (m³/worker)	
	ST	OP	ST	OP	ST	OP
1	0	0	22	28	0	0
2	0	0	12	11	0	0
3	0	0	12	11	0	0
4	0	0	12	11	0	0
5	5,718	8,520	42	33	136	258
6	0	0	22	31	0	0
7	0	0	22	31	0	0
8	0	0	22	31	0	0
9	9,738	14,510	44	56	221	259
10	0	0	22	31	0	0
11	0	0	22	31	0	0
12	16,122	24,022	48	60	336	400
Total/mean	31,572	47,042	302	365	105	129

A worker is active 44 h a week with a monthly salary of $900,000 Colombian pesos (in 2018). Year 1 is dedicated to the nursery and establishment. Years 2 to 8, 10 and 11 are dedicated to management. Year 5 is the first thinning and year 9 the second thinning (wood harvest). Year 12 is of wood harvest.

Economic efficiency of the land

The expected average production of wood ha^{-1} is 53 m³ and 78 m³ in the ST and OP respectively; that is, the OP is 47% more efficient in land use than ST. Additionally, OP earnings are approximately 10 times more than ST earnings (Tab. 11).

TABLE 11. Land yield (m^3 ha^{-1} and Colombian pesos in 2018 ha^{-1}) for standard system (ST) vs. optimal system (OP) of a 600-ha crop of *Acacia mangium.*

Year	Wood production (m^3)		Earnings	
	ST	OP	ST	OP
1	0	0	-4,424,000,000	-4,518,000,000
2	0	0	-1,164,000,000	-1,123,000,000
3	0	0	-1,164,000.000	-1,123,000,000
4	0	0	-1,164,000,000	-1,123,000,000
5	5,718	8,520	2,018,260,000	3,618,400,000
6	0	0	-1,157,000,000	-1,101,000,000
7	0	0	-1,157,000,000	-1,101,000,000
8	0	0	-1,157,000,000	-1,109,000,000
9	9,738	14,510	4,832.475,000	8,093,350,000
10	0	0	-1,157,000,000	-1,106,000,000
11	0	0	-1,157,000,000	-1,101,000,000
12	16,122	24,022	7,815,540,000	12,329,540,000
Total	31,572	47,042	965,275,000	10,636,290,000
Mean (ha per cycle)	53	78	1,608,804	17,727,156
Mean (ha per year)	4.4	6.5	134,067	1,477,263

Discussion

The cost difference between the ST and OP systems is relatively small. The OP costs are 2% lower than ST for 185 USD ha^{-1}. However, this small difference is part of the economic advantage of the OP system over the ST system. The application of biochar, like the application of fertilizers, has a cost. Although this study did not focus on this, Williams and Arnott (2010) give us an idea in this regard. Depending on the quantity (2.5 - 50 t ha^{-1}) and the application method (broadcast-and-disk and trench-and-fill), the costs found were between 29 and 300 USD ha^{-1}. The great advantage of using biochar is the increased yield; the OP system has 25 m^3 more production (47%) than the ST system. Higher production and a lower cost lead to an even higher profit, with 60% in the OP system and only 5% in the ST system. The economic advantages of using biochar are also reflected in the efficiency of the use of land and labor resources. The OP system needs more work, but by producing more, it obtains 23% more wood per worker and 47% more per ha of land than the ST system. The economic efficiency of capital is measured through profitability. In our case, the difference between both systems is remarkable. In other studies, such as those of Maraseni (2010), positive results were also found with the addition of biochar. The researchers found that the income per kilogram of wheat went from USD$1098.84 to USD$1741 t ha^{-1} when biochar was applied to the soil. However, in other trials such as those of Ringius (2002), the financial returns of different agricultural practices with the application of various biofuels oscillated between 4.1 and -1.3, values below those found in this research.

Conclusions

The cost of producing *A. mangium* wood under an optimal system (with the use of biochar) is slightly lower than that of a conventional system (with the use of a synthetic-based fertilizer). The production cost in the optimal system includes the purchase of equipment and machinery for the pyrolysis of the organic remains of the plantation as well as the production and use of biochar as a basic addition. Fixed assets make up a large part of the costs.

The higher production of wood (about 50% more) in the optimal system (with the use of biochar) compared to the conventional system increases income and, therefore, profit. Thus, the economic profitability (cost-benefit ratio) of the *A. mangium* crop is 1.60 under an OP whereas under the ST it reaches only 1.05.

The efficiency of labor in the OP is 23% higher than in the ST. OP land efficiency is also higher since the OP produces 47% more wood per ha than the ST.

Thus, from the economic point of view, the OP production of *A. mangium* is more favorable than the ST production; thus, the system becomes an economic and environmentally friendly alternative to produce wood of this species.

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Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions

GRM participated in the conceptualization of the initial project from which this article originates, as well as in the data curation, supervision, formal analysis, and research. JCBF wrote, reviewed, and edited the manuscript, and supervised the research activity. EDC participated in the formal analysis and supervision of the research.

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