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BREAK-EVEN PRICES FOR THE CONSERVATION AND RESTORATION OF MANGROVE ECOSYSTEMS: AN ASSESSMENT ON THE CEARÁ COASTLINE

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Resumo
Mangroves play a crucial role in the blue economy, providing a range of services that contribute significantly to human well-being. These ecosystems offer provisioning services (such as fishing, gathering, and extracting natural products), regulatory services (such as carbon sequestration, nutrient cycling, and climate regulation), supporting services (such as nutrient cycling and photosynthesis), and cultural services (including tourism, recreation, education, and research). These services are fundamental and hold substantial value for life on Earth. Regarding regulatory services, the mangrove forests have a higher carbon capture and storage capacity per unit area than that observed in tropical rainforests. The conservation and restoration of mangroves can yield greater benefits than their degradation, especially when considering sustainability issues. From this perspective, this research aims to estimate the carbon (CO2) prices that economically justify the conservation and restoration of mangrove areas. These prices serve as a baseline for supporting mechanisms like payments for ecosystem services, such as in the carbon market. The research was conducted in mangroves located in the state of Ceará, in Northeast Brazil, specifically in the municipalities of Acaraú and Itarema, situated on the western coast of the state. The degraded mangrove areas in these municipalities were the focus of a restoration project that sought funding for implementation. The total area of direct and indirect impact of the project, in terms of socioeconomic and environmental effects, encompasses the entirety of both municipalities, covering 1,563 km² and home to a population of 101,445 inhabitants. The total area of mangroves to be restored amounts to 805 ha, distributed across the estuaries of the Acaraú and Aracatimirim rivers, while the conserved mangrove area covers approximately 5,000 ha. Break-even prices necessary for the conservation of remaining mangroves and the restoration of degraded mangroves were estimated. To establish the break-even CO2 price for both conservation (which avoids CO2 emissions) and restoration (which removes CO2 emissions), the economic value that one ton of CO2 (US$/tCO2) would need to reach to compensate for the potential value of alternative economic use or the opportunity cost of exploiting the area (US$/ha) was estimated. The opportunity cost (US$/ha), divided by the avoided emissions (tCO2/ha), derived from the amount of carbon stored in the biomass and soil (CO2/ha), provided the break-even price for conservation. For the break-even price of restoration, both opportunity and restoration costs were considered, divided by the removed emissions (tCO2/ha). Different scenarios with levels of 25%, 50%, and 100% were analyzed for both the carbon stock lost due to deforestation and the carbon recovered through restoration, as well as the carbon emissions avoided through conservation. The value of US$ 2.30 per tCO2 represents the price necessary to ensure the conservation of the entire mangrove area, compared to the opportunity cost of alternative uses. If 50% of the CO2 stocks were lost, the price required to conserve half of the area would need to be adjusted to US$ 4.60 per tCO2. In the scenario where 25% of the area is lost due to deforestation, the necessary price would be US$ 9.20 per tCO2. A larger deforested area or a smaller conserved area would demand a higher return in terms of CO2

price. These values suggest that the conservation of the remaining mangroves could prevent the release of 2.77 to 11.09 $TgCO_2$ into the atmosphere. For the case of restoration, Table 2 presents the estimated break-even prices for mangrove restoration. The value of US$ 2.85 per tCO_2 represents the amount necessary to facilitate the restoration of degraded mangrove areas, taking into account both the opportunity cost of alternative land uses and the cost of restoration. If 50% of the CO_2 stocks are recovered, the price required to restore half of the area would need to be US$ 5.71 per tCO_2. For the restoration of 25% of the area, as outlined in the restoration project, the required price would be US$ 11.41 per tCO_2. Restoring a smaller area or leaving a larger portion degraded would demand a higher return in terms of CO_2 pricing. These figures suggest that restoring the degraded mangroves could result in the sequestration of 0.45 to 1.79 $TgCO_2$ in the study area.). The break-even price estimates indicate that relatively low carbon prices would be sufficient to offset the opportunity cost of using mangrove areas, even when accounting for the added cost of restoring already degraded areas. As expected, the carbon price required for restoration is higher than that for conservation, indicating that remediation efforts are more costly than preventing environmental damage. The present study aimed to assess the break-even price of CO_2 that would economically justify the conservation and restoration of mangrove ecosystem areas. The estimated prices convincingly indicate the feasibility of conservation and restoration practices for these areas, highlighting the potential for resource mobilization through the carbon credit market. This suggests a significant potential for socio-environmental improvement, not only for the specific context of the Ceará coastline but also for the entire mangrove coastal zone of the North and Northeast regions of Brazil. However, the study presents certain limitations, as it relies on average parameters associated with carbon stocks and uses an average opportunity cost without detailed consideration of activity type. For future research, it is recommended to conduct a more detailed cost-benefit analysis focusing on the conservation and restoration of mangroves.

Palavras Chave
Mangrove ecosystem, Carbon prices, Sustainability

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BREAK-EVEN PRICES FOR THE CONSERVATION AND RESTORATION OF MANGROVE ECOSYSTEMS: AN ASSESSMENT ON THE CEARÁ COASTLINE

1 INTRODUCTION

Mangroves play a crucial role in the blue economy, providing a range of services that contribute significantly to human well-being (Constanza et al., 2014; Estrada et al., 2015). These ecosystems offer provisioning services (such as fishing, gathering, and extracting natural products), regulatory services (such as carbon sequestration, nutrient cycling, and climate regulation), supporting services (such as nutrient cycling and photosynthesis), and cultural services (including tourism, recreation, education, and research) (Constanza et al., 2014; UNEP-WCMC, 2011). These services are fundamental and hold substantial value for life on Earth.

Regarding regulatory services, Alongi (2014) and Soares et al. (2022) emphasize that mangrove forests have a higher carbon capture and storage capacity per unit area than that observed in tropical rainforests. Globally, mangroves account for 10-15% of the total carbon stock in coastal areas (Alongi, 2014). In a more recent study, Alongi (2020) states that mangroves contribute to 17% of the global carbon stock in tropical marine areas.

The conservation and restoration of mangroves can yield greater benefits than their degradation, especially when considering sustainability issues. From this perspective, this research aims to estimate the carbon (CO_2) prices that economically justify the conservation and restoration of mangrove areas. These prices serve as a baseline for supporting mechanisms like Payments for Ecosystem Services (PES), such as in the carbon market. The empirical context used was the state of Ceará, located in the Northeast of Brazil, which has approximately 20,000 hectares of this ecosystem. The study focuses specifically on remaining and degraded mangrove areas in the coastal municipalities of Acaraú and Itarema.

Mangroves have been the subject of many environmental science studies that focus on ecological and biodiversity issues. However, studies in the field of economic analysis are relatively scarce (Rahman & Mahmud, 2018). Additionally, as Soares et al. (2022) point out, studies on blue carbon ecosystems in Brazil, such as mangroves, are still very limited, despite the urgency and relevance of adopting conservation and restoration practices for these ecosystems. This research intends to contribute to the body of literature on mangroves, particularly with an economic approach to potential prices that could support actions aimed at the sustainability of these ecosystems.

2 THEORETICAL BACKGROUND

Mangroves are under increasing pressure due to anthropogenic degradation. Deforestation, shrimp farming, real estate expansion, and solid waste disposal are destroying these ecosystems. Sustainable management is essential to ensure the sustainability of mangroves, promote coastal ecosystem resilience, and enable sustainable development. Thus, the conservation and restoration of mangroves are crucial for sustainability within the blue economy. Mangroves are particularly significant in coastal areas, especially in tropical zones, due to the various ecosystem services they provide (UNEP-WCMC, 2011). In many of these areas, traditional communities develop a way of life based on the ecosystem services associated with various uses and activities within mangroves. Additionally, mangroves are of great importance for carbon sequestration and, particularly, carbon storage.

Given the significant relevance of mangroves as carbon sinks, the quantification and valuation of this carbon are strategic for new forms of sustainability financing worldwide. Since 2015, the carbon market has grown more prominently, with an increase of over US$ 100 million in the global evolution of carbon credits generated in the voluntary market from 2020 to 2021 (Vargas et al., 2022). One of the most relevant ecosystem services today is climate regulation through carbon sequestration and storage, which has great potential and remains underexplored. In light of climate-related goals, carbon markets have great potential to reduce emissions and increase climate financing in the Global South (Trouwloon et al., 2023).

Environmentally, Brazil is highly competitive regarding the potential to attract resources for the financing of natural environments, with mangroves playing a prominent role. The country has a significant capacity to contribute as a carbon sink, largely due to its extensive coastline and ecological characteristics, with mangroves playing a critical role. Brazil has one of the largest areas of mangroves globally, covering approximately 9% of the world's mangrove area, accounting for 85% of the total carbon stock, and being responsible for 135% of the carbon sequestration in the soil, with sequestration rates 15-30% higher than global estimates (Rovai et al., 2022).

Carbon stock parameters in mangroves vary widely. Global estimates point to an average value of 956 Mg/ha (Alongi, 2014). Rovai et al. (2022) estimated an average carbon stock value of 281 Mg/ha for Brazilian mangrove soils. Brazilian mangroves store up to four times more carbon than other biomes in the country (Rovai et al., 2022). In Northeast Brazil, mangroves are highly competitive in terms of carbon storage strategies. In the semi-arid region, mangroves are the primary carbon sinks, storing twice as much as other ecosystems in the biome (Nóbrega et al., 2019).

In Ceará, Jimenez et al. (2022) estimated that average soil carbon stocks reach up to 202 Mg/ha in mature mangroves and up to 115 Mg/ha in restored mangroves. Rovai et al. (2022) identified a soil carbon storage capacity of 253 Mg/ha, while Kauffman et al. (2018) estimated soil carbon stocks ranging from 215 to 438 Mg/ha in the mangroves of the Acaraú estuary, Ceará. Carbon sequestration rates in mangroves also show variation. Alongi (2014) proposed a global estimated rate of 1.74 Mg/ha per year. Rovai et al. (2022) estimated global aboveground biomass carbon sequestration rates at 3.89 Mg/ha per year, while in Brazilian mangroves, these estimates were 3.18 Mg/ha per year aboveground and 2.81 Mg/ha per year in the soil.

The extensive capacity of mangroves to contribute to sustainability through climate change mitigation, via carbon storage and sequestration, necessitates break-even price estimates for the conservation of remaining mangrove areas and the restoration of degraded regions. These estimates can, in turn, support Payments for Ecosystem Services (PES) programs through carbon credits. PES in mangrove ecosystems remains underexplored in carbon policies, with only a few experiences documented globally (Thompson et al., 2017). The lack of recognition of the value of mangroves contributes to the degradation of these ecosystems and the replacement of landscapes following their removal, resulting in a decline in well-being (Rahman & Mahmud, 2018).

3. METHODOLOGY

3.1 STUDY AREA

The study was conducted in mangroves located in the state of Ceará, in Northeast Brazil, specifically in the municipalities of Acaraú and Itarema, situated on the western coast of the state. The degraded mangrove areas in these municipalities were the focus of a restoration project that sought funding for implementation. The following protected indigenous areas were directly involved: Tremembé de Almofala (Itarema, area = 4,900 ha), Tremembé do Córrego de Telhas (Acaraú, area = 3,177 ha), and Tremembé de Queimadas (Acaraú, area = 767 ha).

The total area of direct and indirect impact of the project, in terms of socioeconomic and environmental effects, encompasses the entirety of both municipalities, covering 1,563 km² and home to a population of 101,445 inhabitants. The total area of mangroves to be restored amounts to 805 ha, distributed across the estuaries of the Acaraú and Aracatimirim rivers, while the conserved mangrove area covers approximately 5,000 ha, located within the municipalities of Acaraú and Itarema.

The state of Ceará contains approximately 19,518 hectares of mangroves, distributed across 22 municipalities, representing about 1.4% of the country's total mangrove area (Leão et al., 2018). The municipalities of Acaraú and Itarema, along with the mangroves in the Metropolitan Region of Fortaleza, possess significant mangrove areas. Nationally, only the states of Maranhão, Pará, and Amapá hold approximately 80% of Brazil's mangrove area. The mangroves in the Acaraú River estuary exhibit a total carbon storage capacity of 605 MgC/ha, which is higher than that observed in other estuaries in the state of Ceará, such as the Jaguaribe River (224 MgC/ha) (Kauffman et al., 2018).

3.2 METHODOLOGICAL PROCEDURE

Based on the methodology employed by Jakovac et al. (2020), break-even prices necessary for the conservation of remaining mangroves and the restoration of degraded mangroves were estimated. Initially, an opportunity cost for the alternative use of mangrove areas was assumed, as proposed by Jakovac et al. (2020), serving as a measure of the potential economic production value (US$/ha). Additionally, the potential value of carbon stock (US$/ha) was calculated, taking into account the area (ha) and an average carbon stock parameter (CO_2/ha), the latter being calculated by Kauffman et al. (2018) for the study region. These data were used to determine the total amount of CO_2 stored in the mangrove areas designated for conservation and restoration.

To establish the break-even CO_2 price for both conservation (which avoids CO_2 emissions) and restoration (which removes CO_2 emissions), the economic value that one ton of CO_2 (US$/t$CO_2$) would need to reach to compensate for the potential value of alternative economic use or the opportunity cost of exploiting the area (US$/ha) was estimated. The opportunity cost (US$/ha), divided by the avoided emissions (tCO_2/ha), derived from the amount of carbon stored in the biomass and soil (CO_2/ha), provided the break-even price for conservation. For the break-even price of restoration, both opportunity and restoration costs were considered, divided by the removed emissions (tCO_2/ha). Different scenarios with levels of 25%, 50%, and 100% were analyzed for both the carbon stock lost due to deforestation and the carbon recovered through restoration, as well as the carbon emissions avoided through conservation.

4 RESULTS AND DISCUSSION

The results obtained present the break-even prices necessary for the conservation of mangrove areas and the restoration of degraded mangroves. The CO_2 stock was considered to be 605 MgC/ha or 2,218 tCO_2/ha, as estimated by Kauffman et al. (2018) for the Acaraú region in Ceará. The opportunity cost was defined as US$ 5,100/ha, based on the study conducted by Jakovac et al. (2020) for Brazil. The estimated value for restoration was derived from an independent estimate, based on the development of a project to restore 805 hectares of degraded mangroves in the study area. The restoration cost was estimated at US$ 1,230/ha, a value comparable to the estimate presented for developing regions, according to Bayraktarov et al. (2016). Table 1 presents the break-even prices for mangrove conservation.

Table 1 - Break-even Prices for Mangrove Conservation in Acaraú and Itarema, Ceará

Parameters	Units of Measure	Conservation Scenarios	Values
Remaining Area	(ha)		5,000
CO_2 Stock	(tCO_2/ha)		2,218
Total Stock	(tCO_2)		11,091,667
Avoid Emissions	(tCO_2)	25%	2,772,917
		50%	5,545,833
		100%	11,091,667
Opportunity Cost	(US$/ha)		5,100.00
Break-even Price	(US$/$tCO_2$)	25%	9.20
		50%	4.60
		100%	2.30
	(US$/ha)	25%	20,400.00
		50%	10,200.00
		100%	5,100.00

Source: authors

The value of US$ 2.30 per tCO_2 represents the price necessary to ensure the conservation of the entire mangrove area, compared to the opportunity cost of alternative uses. If 50% of the CO_2 stocks were lost, the price required to conserve half of the area would need to be adjusted to US$ 4.60 per tCO_2. In the scenario where 25% of the area is lost due to deforestation, the necessary price would be US$ 9.20 per tCO_2. A larger deforested area or a smaller conserved area would demand a higher return in terms of CO_2 price. These values suggest that the conservation of the remaining mangroves could prevent the release of 2.77 to 11.09 $TgCO_2$ into the atmosphere. For the case of restoration, Table 2 presents the estimated break-even prices for mangrove restoration.

Table 2 - Break-even Prices for Mangrove Restoration in Acaraú and Itarema, Ceará

Parameters	Units of Measure	Conservation Scenarios	Values
Area to be Restored	(ha)		805
CO_2 Stock	(tCO_2/ha)		2,218
Total Stock	(tCO_2)		1,785,758
Removed Emissions	(tCO_2)	25%	446,440
		50%	892,879
		100%	1,785,758
Opportunity Cost	(US$/ha)		5,100.00
Restoration Cost	(US$/ha)		1,230.31
Equlibrium Price	(US$/$tCO_2$)	25%	11.41
		50%	5.71
		100%	2.85
	(US$/ha)	25%	25,321.23
		50%	12,660.61
		100%	6,330.31

Source: authors

The value of US$ 2.85 per tCO_2 represents the amount necessary to facilitate the restoration of degraded mangrove areas, taking into account both the opportunity cost of alternative land uses and the cost of restoration. If 50% of the CO_2 stocks are recovered, the price required to restore half of the area would need to be US$ 5.71 per tCO_2. For the restoration of 25% of the area, as outlined in the restoration project, the required price would be US$ 11.41

per tCO_2. Restoring a smaller area or leaving a larger portion degraded would demand a higher return in terms of CO_2 pricing. These figures suggest that restoring the degraded mangroves could result in the sequestration of 0.45 to 1.79 $TgCO_2$ in the study area.

The estimated prices for conservation and restoration are consistent with those found in other studies, such as Jakovac et al. (2020). Moreover, the range of prices across the different scenarios was significantly narrower than those observed by other authors, such as Li and Martino (2024). The break-even price estimates indicate that relatively low carbon prices would be sufficient to offset the opportunity cost of using mangrove areas, even when accounting for the added cost of restoring already degraded areas. As expected, the carbon price required for restoration is higher than that for conservation, indicating that remediation efforts are more costly than preventing environmental damage.

In recent decades, the municipalities of Acaraú and Itarema in Ceará have experienced a high rate of mangrove ecosystem degradation, driven by anthropogenic activities such as shrimp farming, with its associated waste, and deforestation, spurred by real estate and tourism expansion. In this context, determining price values for different scenarios of avoided CO_2 emissions (conservation) and removed emissions (restoration) aligns with current carbon market standards (World Bank, 2023).

5 CONCLUSION

The present study aimed to assess the break-even price of CO_2 that would economically justify the conservation and restoration of mangrove ecosystem areas. The estimated prices convincingly indicate the feasibility of conservation and restoration practices for these areas, highlighting the potential for resource mobilization through the carbon credit market. This suggests a significant potential for socio-environmental improvement, not only for the specific context of the Ceará coastline but also for the entire mangrove coastal zone of the North and Northeast regions of Brazil. However, the study presents certain limitations, as it relies on average parameters associated with carbon stocks and uses an average opportunity cost without detailed consideration of activity type. For future research, it is recommended to conduct a more detailed cost-benefit analysis (CBA) focusing on the conservation and restoration of mangroves.

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