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Biochar co-benefits are valued in the voluntary carbon market

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Climate mitigation pathways towards global net-zero emissions targets commonly include large-scale deployment of carbon dioxide removals. Investment in novel carbon dioxide removal technologies is currently driven by the self-steering voluntary carbon market. Here we assess whether the upscaling of biochar carbon dioxide removals via voluntary carbon market can deliver sustainable development co-benefits. We use hedonic pricing to estimate how Sustainable Development Goal claims are reflected in biochar carbon credit prices in transactions up to 2024. The results show that biochar carbon credit prices increase by 0.14% for each 1% increase in associated co-benefit claims. Grouping co-benefit claims into environmental, economic, and social pillars reveals that credits with more economic claims tend to be priced higher, while those with more environmental claims tend to be priced lower. Since the market values co-benefit claims, auditing them is critical to verify their genuine contributions and to maintain the integrity of novel carbon dioxide removals.

Achieving global net-zero emissions, as outlined in the Paris Agreement, is expected to require gigatonne-scale removal of CO_2 annually by 2050[1,2]. Novel carbon dioxide removal (CDR) is a group of removal methods that uses engineered technologies to capture and store atmospheric CO_2[1]. Biochar is one example of novel CDR which relies on plants' ability to capture CO_2 through photosynthesis and stores carbon through pyrolysis. While countries have been slow to integrate novel CDRs into their net-zero strategies and continue to rely heavily on nature-based methods[3], investments in novel CDRs are primarily driven by the voluntary carbon market[1,4,5]. In response to the global need to mitigate climate change, many private-sector actors commit to voluntary climate initiatives to maintain market competitiveness and signal company values[6,7]. While emissions reductions are critical to achieving net-zero targets, some emissions are expected to remain unavoidable or prohibitively expensive to eliminate, creating demand for carbon credits[8]. Some sustainability initiatives, such as the Science Based Targets initiative, only permit novel CDR credit offsets[9]. The novel CDR credit market is nascent; the first credits were issued in 2019[10]. Demand for novel CDR credits is anticipated to continue growing as companies approach net-zero target years[1,8]. This paper focuses on biochar-based CDR and biochar carbon credits, which are the most widely produced novel CDR credits as of 2024[11].

Climate mitigation and adaptation measures are typically expected to be pursued in conjunction with sustainable development[12–14]. In addition to emissions avoidance and reduction projects[15], CDR deployment also has the potential to deliver sustainable development benefits[16–18]. The co-benefits are highly dependent on the chosen CDR method and the scale of its implementation[8,19]. Earlier studies have shown that carbon removal activities based on soil or land, such as biochar, deliver higher co-benefits than other novel CDRs[19–21]. Although current biochar carbon credit standards allow multiple biochar storage options[22,23], biochar is most commonly applied to agricultural soils in practice[24]. Previous literature suggests that, under suitable conditions, biochar can enhance crop yields, support ecosystems both on land and in water, and contribute to various economic benefits[25–27]. In this paper, we assess the co-benefits of biochar using the United Nations' 2030 Agenda for Sustainable Development Goals (SDGs) framework, launched in 2015[19,28]. We further categorise the SDGs into the three sustainability pillars: environmental, economic, and social[29]. Following its launch, the SDG framework was widely adopted in corporate sustainability reporting[30,31] and is used by investors to assess the sustainability performance of companies[32].

While empirical research on the pricing of novel CDR credits in relation to SDG claims is currently lacking, similar studies have been conducted on emissions avoidance and nature-based carbon removal credits. The literature finds that buyers show increasing willingness to pay for emissions avoidance credits associated with more SDG claims[33]. Similarly, studies on nature-based forestry removal credits have shown that credits offering more co-benefits are in higher demand among buyers[34,35]. According to a novel CDR industry report[36], 38% of respondents rank co-benefits among the top three reasons for choosing a removal provider. Given the importance of novel CDR for limiting global warming and the influence of the voluntary carbon market on scaling up the capacity of novel CDRs, there is a need to explore how market-based

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Table 1 | Hedonic pricing results for biochar carbon credit prices on a transaction level

	(1)		(2)		(3)	
Number of SDG claims	0.101 (0.045)	**	0.098 (0.046)	**	0.143 (0.050)	***
Reference: Europe						
Africa					−0.265 (0.129)	**
Asia					−0.669 (0.138)	***
Australia					−0.066 (0.188)	
North America					−0.445 (0.114)	***
South America					−0.211 (0.108)	*
Technology (Industrial=1)					−0.134 (0.121)	
European Biochar Certificate (EBC = 1)					0.082 (0.093)	
Biochar project developer size			−0.062 (0.025)	**	−0.011 (0.024)	
Transaction size			−0.011 (0.024)		0.015 (0.019)	
FE Transaction date, year	Yes		Yes		Yes	
Within R^2	0.02		0.08		0.44	
Fstat	0.93		2.65		9.56	
N	171		171		171	

The dependent variable is the natural log-transformed biochar carbon credit prices across all models (prices given in USD). All the models are log-log. The independent variable of interest, Number of SDGs, represents the number of Sustainable Development Goal (SDG) claims associated with credits in a transaction. The SDG claims are uniform for credits within the same transaction. The dataset contains 171 transactions. Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

scaling of biochar capacity aligns with sustainable development objectives.

This paper aims to explore whether investments into biochar carbon credits by the voluntary carbon market can support both the upscaling of biochar production capacity and the delivery of sustainable development benefits. More specifically, we study to what extent biochar carbon credit buyers value the non-carbon attributes of biochar credits, with a focus on the SDG claims associated with the credits. We address this objective through two research questions. First, we study the effect of the number of advertised SDG claims on biochar carbon credit prices and whether a higher number of SDGs contributes to a higher credit price premium. Second, we evaluate whether buyers' willingness to pay varies across SDGs across the three sustainability pillars: environmental, social, and economic. We employ the well-established method of hedonic pricing and build on earlier studies exploring emissions avoidance credits. In addition to SDG claims, the other non-carbon attributes studied are biochar quality certification, European Biochar Certification, biochar production technology type, and the geographic origin of biochar production, assessed both by continent and by the development status of the originating country. The study relies on an original dataset that matches biochar carbon credit transactions to their associated SDG claims which were collected from biochar producers, marketplaces, and registries as texts describing co-benefits or SDG icons.

We show that buyers of biochar carbon credits are willing to pay a premium for credits linked with more SDGs ($p < 0.01$). Additionally, we show that buyers prefer economic ($p < 0.01$) and social ($p < 0.1$) SDG claims, while an increase in environmental SDG claims is associated with a negative impact on prices ($p < 0.05$). In addition, we find that European origin is valued higher than other regions while origin in developing countries is associated with lower prices. Industrial biochar projects that are certified with European Biochar Certification, show statistically significant positive price effects only in the sustainability pillar specification. Our results, alongside the existing literature on emissions avoidance and forestry-based carbon credits, suggest that SDG claims are indeed valued across all carbon credit types.

Results

Increasing the number of SDGs associated with biochar production increases biochar carbon credit price

We first analyse the relationship between biochar carbon credit prices and the number of SDG claims associated with each credit transaction (Table 1). Our results (see model 3 in Table 1) indicate that increasing the number of SDG claims by 1% increases the biochar carbon credit price by 0.143% ($\beta = 0.143, p < 0.01$) conditional on controls and year fixed effects. Based on the estimated price elasticity, our results imply that credits associated with, for example, three SDG claims, are 6% more expensive than those with two SDGs all else equal. In this example, the price premium associated with an additional SDG is 10.14 USD given the average credit price in our dataset, 170 USD/ton CO_2eq. The price elasticity implies that credits with the highest number of SDG claims are approximately 46% more expensive than those with the lowest, conditional to controls and year fixed effects. However, there is only a small number of observations with the highest SDG scores, and caution should be exercised when applying this result (Supplementary Methods 1 Fig. 5).

We find a significant association between credit prices and the location of the biochar project (Table 1). Credits backed by biochar produced in Europe (reference category) are the most expensive compared to those from other regions. The next most expensive credits are from Africa ($\beta = -0.265, p < 0.05$), North America ($\beta = -0.445, p < 0.01$), and the cheapest credits are of Asian origin ($\beta = -0.669, p < 0.01$).

No significant relationship is observed between biochar credit prices and the European Biochar Certification. The lack of a significant relationship suggests that either buyers do not perceive certification as a price determinant or that its recognition in the biochar carbon credit market remains limited. The type of biochar production technology (artisanal or industrial) does not significantly influence credit prices.

The coefficients for the SDG variable are positive and statistically significant across models 1 and 2 in Table 1. Further robustness checks confirm the positive estimated effect of the number of SDGs on credit prices (Supplementary Data 1 Robustness – total). Comparing log-log model specifications, we find that the SDG coefficient stays within the range from 0.126 to 0.230, close to our baseline estimate of 0.143, and the coefficient is always significant at $p < 0.05$. These log-log robustness checks include alternative model specifications: without the European Biochar Certification variable, with an interaction term between SDG and European Biochar Certification, without the technology variable, and different geographic controls (country or developing-country dummy and GDP, instead of continent). The SDG coefficient remains positive and significant at the 10% ($p < 0.1$) when log–linear and linear–linear functional forms are considered. We also test the assumptions underlying the SDG data collection approach: the data sources (supplier, registry or marketplace websites) of the SDG claims and whether the SDGs were interpreted from co-benefit description text or given

Table 2 | Hedonic pricing results for biochar carbon credit prices on a transaction level, sustainability pillars result

	(1)		(2)		(3)	
Environmental SDGs	−0.014 (0.032)		0.004 (0.031)		−0.062 (0.031)	**
Economic SDGs	0.157 (0.043)	***	0.254 (0.043)	***	0.239 (0.048)	***
Social SDGs	−0.083 (0.037)	**	0.003 (0.067)		0.093 (0.056)	*
Economic SDGs: Social SDGs			−0.049 (0.022)	**	−0.048 (0.019)	**
Developing country =1					−0.584 (0.128)	***
Technology (Industrial=1)					−0.048 (0.100)	
European Biochar Certificate (EBC = 1, otherwise=0)					0.274 (0.090)	***
Country GDP					−0.014 (0.004)	***
Biochar project developer size			0.000 (0.000)	***	0.000 (0.000)	
Transaction size			0.000 (0.000)		0.000 (0.000)	
Within R^2	0.10		0.17		0.47	
Fstat	3.13		3.74		10.67	
N	171		171		171	

The dependent variable is the natural log-transformed biochar carbon credit price across all models (prices given in USD). All models are log-linear. The social, economic, and environmental SDGs are the number of Sustainable Development Goal (SDG) claims associated with credits in a transaction per each sustainability pillar. The number of SDGs per each pillar is uniform for credits within the same transaction. The dataset contains 171 transactions. Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

icons in the description of the credit. Neither of these variables changes the SDG variable in a substantial way. Overall, these robustness checks suggest that the positive association between the number of SDG claims and biochar credit prices is robust across reasonable alternative model specifications.

The types of SDGs are valued differently by the biochar carbon credit buyers

Next, we analyse the relationship between biochar credit prices and the type of SDG claims across three sustainability pillars: social, economic, and environmental (Table 2). The economic SDG pillar shows a credit price premium. The economic pillar is related to economic growth, reducing inequalities, and responsible production and consumption. Our results indicate a positive and significant coefficient that corresponds to a 23.9% price increase per additional economic SDG ($\beta = 0.239, p < 0.01$). Increasing the number of environmental SDG claims is associated with a decrease in biochar credit prices. One additional environmental SDG results in a discount of 6.2% ($\beta = -0.062, p < 0.01$). Thus, a credit with a higher number of environmental SDG claims is associated with lower prices all else equal. The environmental pillar is centred on climate mitigation, water and life on land. Social SDGs command a price premium of 9.3% premium but only at the 10% confidence level ($\beta = 0.093, p < 0.10$). The social SDG pillar relates to improvements in human well-being, access to resources and food, and gender equality. Lastly, the negative interaction term between economic and social SDG pillars ($\beta = -0.048, p < 0.05$) shows that when social SDGs are claimed, the marginal price premium for adding an economic pillar SDG is reduced from 23.9% to 19.1%. The interaction term suggests that there is a trade-off between the two pillars.

In contrast to the results for the total number of SDG claims associated with biochar carbon credits, the European Biochar Certification affects prices when considered in the sustainability pillars model. The results suggest that biochar carbon credits produced by certified biochar project developers are priced higher ($\beta = 0.274$, $p < 0.01$). In our dataset this applies only to industrial biochar project developers. Next, we find that the biochar project origin in a developing country is associated with a discount ($\beta = -0.584, p < 0.01$) while the technology coefficient is consistently insignificant, as in the results for the total number of SDG claims. The estimated effect of economic sustainability pillar claims on biochar carbon credit prices is robust across Models 1 and 2 (Table 2), as well as across several alternative specifications, including models excluding the economic–social interaction term, GDP, and the developing country indicator (Supplementary Data 1 Robustness - type). The coefficient varies little across specifications and is consistently significant (between 0.152 and 0.279, $p < 0.01$). The environmental pillar coefficient is insignificant when the model includes only the control variables and when the origin variable, in this case a developing country dummy, is excluded. However, the sign of the coefficient remains stable across specifications, with changes primarily affecting statistical significance. The social SDG pillar is insignificant across robustness checks, and the result seems to rely on the economic-social SDG pillar interaction term. We also check the assumptions regarding the source of the SDG claims, including whether they were collected from different sources (supplier, registry, or marketplace websites) and whether the SDGs were interpreted from text or reported as icons in the credit descriptions. These variables affect the social SDG pillar coefficient: in the first case, the coefficient becomes insignificant, while in the second case, it is significant at the 5% level. Overall, the robustness checks suggest that the economic and environmental SDG pillar findings are robust, while the social sustainability pillar result relies more on model specification. However, while the strength of statistical significance varies across the social pillar, the results are consistently directional across reasonable specifications.

Discussion and conclusions

The central finding of our study is that the co-benefits of novel biochar carbon removal technologies are valued in the voluntary carbon market. We find that biochar carbon credit buyers are willing to pay a premium for credits associated with SDG claims, and that the biochar carbon credit price elasticity is 0.14% per 1% change in the number of SDGs ($p < 0.01$). The results suggest that SDG claims influence investment behaviour in biochar credits and, more broadly, shape the development of emerging novel carbon removal markets. A similar relationship has been previously established in the literature on emissions avoidance and forestry-based carbon removal credits. In the case of emissions avoidance credits, it has been shown that buyers are willing to pay 30% more for credits with the highest co-benefits[33]. This is comparable to the 48% price difference between credits with the highest and lowest number of SDGs that our model implies. Similarly, a study in Japan on nature-based forest removal credits found that the surveyed managers were willing to pay an additional 933 JPY (approximately 6.18 USD) per SDG when the credit prices presented to respondents ranged from 500 to 10,000 JPY/ton CO_2 (approximately between 33 and 66 USD/ton CO_2)[35]. Our results are very close to this valuation.

We find that biochar credit buyers have preferences for SDG types. The preference for some but not all SDGs means that while a higher number of SDG claims is preferred, buyers prioritize SDGs according to their type when purchasing biochar carbon credits. We find that economic SDG claims that are the most preferred ($\beta = 0.239, p < 0.01$), a positive effect at

10% confidence level is found with the social pillar SDGs ($\beta = 0.093$, $p < 0.1$), and a decrease in price is associated with additional environmental SDG claims ($\beta = -0.062$, $p < 0.05$).

The heterogeneous valuation of SDGs observed in our results is consistent with the priorities reflected in corporate sustainability reporting. It was previously shown that SDG 8, Decent Work and Economic Growth, and SDG 12, Responsible Consumption and Production, are among the most frequently reported economic SDGs by corporations in sustainability reports[31]. While the most important social sustainability pillar SDGs linked to biochar production are SDG 1, No Poverty, and SDG 2, Zero Hunger, in both our dataset and in the literature[19], these are the least reported SDGs in sustainability reports[31]. Overall, social pillar SDGs are reported in fewer than half of the sampled sustainability reports[30,31]. Environmental SDG 13, Climate Action, is the most adopted SDG in sustainability reporting; however, reporting drops sharply for all other environmental SDG claims[30,31]. Given that sustainability reporting leans towards economic SDGs, buyers may seek economic SDG claims in credit descriptions. The fact that social SDG claims are the second most frequently reported may explain the small positive effect that is significant at the 10% level. We suggest that environmental SDG claims appear to be a baseline expectation, rather than a distinguishing feature. Their presence alongside a credit does not appear to have additional value, as climate change mitigation measures, such as carbon removal, have strong synergies with environmental SDGs anyway[37]. Thus, environmental SDGs are potentially easy to communicate to stakeholders and linking them to climate mitigation actions adds little additional value.

The location of biochar project developer significantly affects credit prices, showing higher credit prices for projects of European origin, in line with previous research[38]. This result is robust across different robustness checks (Supplementary Data 1 Robustness total). In the SDG sustainability pillar specification, we find a consistent discount for carbon credits originating from developing countries. These credits are therefore sold at lower prices. This result is consistent with research on forestry credit pricing, but contrasts with findings related to emissions avoidance credits[38]. Forestry credits benefit from developed country origins, signalling a level of trust in the credits[38]. Conte and Kotchen[38] also hypothesise that European buyers are more informed about climate change and have a higher demand for locally produced carbon removal. While we do not have the data to determine whether there is a clear preference for locally produced biochar carbon credits, the appeal of European-origin credits could stem from factors such as perceived institutional quality, green reputation, and higher institutional trust. Previous literature has found that buyers in the voluntary carbon market often prefer credits from regions with strong regulatory frameworks and transparent monitoring, such as Europe, due to higher trust in verification standards and perceived quality[39]. These factors could help explain why buyers seem more inclined toward European projects and projects located in developed countries, even if that means less support for sustainable development efforts in the Global South. This may reflect buyer perceptions of delivery or permanence risks, or a preference for projects located in more highly regulated settings.

Our findings suggest that the biochar production technology type does not function as an important hedonic signal for buyers. Furthermore, the relationship between biochar quality certification and biochar credit prices is only significant when we disaggregate the SDGs into types. This finding contradicts previous studies that have shown consistently that certifications for emissions avoidance credits increase credit prices[33]. This indicates a reliance on the supply side, namely project developers and credit issuers, to uphold quality standards for novel carbon removal credits. However, the actors in the voluntary carbon market arguably do not have enough incentive to produce carbon removals that are durable and reliable[13]. While either of the biochar technologies, industrial and artisanal, deliver biochar credits, the industrial method is superior from a climate mitigation perspective. The technologies differ in their ability to control and avoid production emissions[23,40]. More complex industrial technologies allow higher temperatures for pyrolysis, which results in higher carbon content and permanence beyond the 100 years that credit issuance methodologies require[40,41]. In addition, higher feedstock efficiency in industrial production systems means that fewer resources need to be taken through pyrolysis to produce biochar carbon credits[40]. However, as of 2024, 47% of the biochar carbon credits on the market are low-technology artisanal biochar carbon credits[42]. Given that production type does not appear to act as an important hedonic signal for buyers, market preferences may favour lower-cost artisanal biochar credits, even when industrial biochar offers superior climate mitigation performance.

An important consideration is how genuine the SDG claims are. Our results suggest that the observed demand for SDG-related attributes could incentivize biochar project developers and marketplaces to exaggerate SDG claims in credit descriptions[34]. Biochar CDR has the potential to deliver co-effects that are likely positive (SDGs 2, 6, 8, 9, 10, 12, 15), negative (SDGs 5, 7) and conditional on the project setup (SDGs 1, 3, 13)[19]. On average, transactions in our dataset were advertised with 6.5 SDGs, with a maximum of 14 SDGs. From a sustainable development and the 2030 Agenda perspective, credit descriptions should accurately reflect validated co-benefits, as misleading claims will not contribute to achieving the targets. However, the real impacts of CDR projects are challenging to measure[33]. An initiative to increase transparency in advertised SDGs was introduced by Puro. It allows project developers to verify delivered co-benefits and have their SDGs certified[43]. However, at the time of writing, none of the biochar project developers were able to show certified SDGs other than SDG 13, Climate Action.

The novel carbon removal credit market remains nascent, offering many pathways for future research building on this paper. First, with greater data availability, future research could explore buyer characteristics and how they affect the valuation of SDG claims. Variables such as buyers' geographical location have shown a significant effect on emissions-avoidance credit prices, whereas buyers' profit vs. non-profit status and industry sector have not[33]. Second, future research could evaluate the valuation of individual SDGs. There appears to be a lack of empirical assessments on this topic within the context of carbon credits. It would also be valuable to investigate why certain types of SDGs are preferred over others in carbon credit pricing. Third, as more and more projects receive biochar quality certifications, the literature could benefit from new evidence when both types of technologies are certified, as it is not currently the case in the analysis dataset. This would determine whether certification is also recognised when applied to artisanal biochar carbon credits. Fourth, our dataset indicates that artisanal biochar project developers tend to report more SDG claims than industrial producers. This suggests that interactions between technology type and SDG claims warrant further study, which we were unable to examine due to limited data availability. It is likely that artisanal biochar credits are associated with more SDG claims in credit descriptions and can deliver more co-benefits in practice, but may also be perceived differently by buyers. Lastly, the results of this study may also be applicable to other durable carbon removal credits (for example, enhanced weathering, bioenergy, and carbon capture and storage), although further investigation is needed, especially because the ability to deliver co-benefits varies across novel CDRs[16–19]. The biggest limitation of our study is the limited number of observations in our dataset, and this should be taken into account when interpreting our results. A low number of observations is typical for data samples in early empirical research[38], which tend to grow together with data availability[33].

Our results indicate that biochar carbon credits are not perfectly substitutable but are differentiated in the voluntary carbon market by their underlying non-carbon attributes. Thus, even if the carbon removal method and the promised carbon storage timeframe are the same, credits associated with more SDG claims tend to be perceived more positively, and the type of SDG claims matters. The findings are supported by previous literature on emissions avoidance and forestry credits, which also shows that co-benefits are valued by voluntary carbon market actors. Our results indicate risks for the current market-based upscaling of novel CDR. First, the results highlight a risk of inflation of SDG claims by biochar project developers and marketplaces, since biochar credits associated with more co-benefits have a market advantage. Second, if preferences for particular SDGs drive demand toward specific biochar credits, future research should determine whether this is also observed across all novel CDR technologies. Preferences for SDGs could shape the future composition of the novel CDR portfolio, limit aggregate climate mitigation potential, and lead to unbalanced sustainable development outcomes. Given that a large share of investments in scaling up novel CDR comes from private actors in the voluntary carbon market, our results suggest the potential for simultaneous investment in scaling climate change mitigation measures and sustainable development.

Methods

We used hedonic pricing to identify the value of SDGs in biochar carbon credit price, alongside other non-carbon attributes. Hedonic pricing treats goods as a bundle of attributes and estimates the value of each of these attributes separately to find the value of the whole good[44]. It is a revealed pricing method used to evaluate market values of attributes that otherwise do not have market prices. The method is commonly used in real estate and food markets[45], but has also been applied to emissions avoidance credit pricing[33,38] and the valuation of renewable energy projects[46]. In this study, hedonic pricing was applied to an original dataset linking biochar carbon credit prices and their associated SDG claims.

Data

The biochar carbon credit prices were sourced from the CDR.fyi database, which records novel CDR credit transactions reported by voluntary carbon market actors (e.g. marketplaces, buyers, and biochar project developers)[11]. Our analysis focused on biochar carbon credits, representing nearly half of the dataset. Biochar-backed carbon credits are the most widely produced and delivered type of novel carbon removal credits currently available on the market[11]. Out of 1716 biochar carbon credit transactions, 173 had recorded credit prices and could be used for analysis. The data was downloaded in August 2024. Our dataset accounts for 10% of the total number of biochar transactions, which represent 3% of the original dataset's biochar carbon credit transaction volume. However, it represents 40% ($N = 31$) of the biochar project developers in the overall database ($N = 78$), which reflected the biochar market at that time. The subset reflects the global distribution of biochar project developers[47] and provides a market-representative biochar credit price distribution (Supplementary Methods 1, Figures 8 and 9). Lastly, the dataset shows substantial variation in the number of SDG claims and sustainability pillars (Supplementary Methods 1, Figures 4 to 7).

The SDG claims associated with biochar carbon credits were collected from biochar carbon credit descriptions on marketplace websites, biochar project developers' websites, or credit registries (Supplementary Data 1). Currently, the promotion of SDGs is left to the discretion of biochar project developers, registries, and marketplaces. Most of the transactions on the CDR.fyi database indicate whether the credits were acquired through a marketplace or directly from biochar project developers. When information on the point of sale was not available, we first checked the SDG descriptions on biochar project developers' websites and, if those were not available, the registry from which the credit was issued. If the same biochar project developer sold credits on different marketplaces, the SDG descriptions might differ, and thus, the SDGs were recorded per transaction accordingly. Most of the credits' co-benefits were advertised as SDG icons. Close to a third of transactions had co-benefit descriptions in text format. The textually described co-benefits were mapped onto the SDGs by matching keywords to the SDG descriptions, with two authors performing the mapping independently (full procedure description in Supplementary Methods 2). We could not locate SDGs or co-benefit descriptions for two transactions. Therefore, the dataset used for analysis consisted of 171 transactions that had matched credit prices and SDG descriptions[48]. The overall relationship between credit prices and SDG claims is shown in Supplementary Methods 1 Fig. 1–3.

The SDG claims associated with each credit constitute the independent variables of interest. In the first research question, the independent variable of interest was the number of SDG claims advertised with a biochar credit. In the second research question, the independent variable of interest was the number of SDG claims per sustainability pillar: environmental, social, and economic. The sustainability pillar framework used in this study was developed by the Stockholm Resilience Centre[29]. While the framework was initially built to describe SDG interconnections in the food sector, it was later adopted by researchers in a range of social science fields, including corporate social responsibility management[49] and sustainable governance[50]. The social pillar in this framework covers SDG 1, No Poverty; SDG 2, Zero Hunger; SDG 3, Good Health and Well-being; SDG 4, Quality Education; SDG 5, Gender Equality; SDG 7, Affordable and Clean Energy; SDG 11, Sustainable Cities and Communities; and SDG 16, Peace, Justice and Strong Institutions. The environmental pillar is centred on SDG 6, Clean Water and Sanitation; SDG 13, Climate Action; SDG 14, Life Below Water; and SDG 15, Life on Land. Lastly, the economic pillar relates to SDG 8, Economic Growth; SDG 9, Industry, Innovation, and Infrastructure; SDG 10, Reduced Inequalities; and SDG 12, Responsible Consumption and Production.

In addition, we considered other non-carbon biochar carbon credit attributes in the analysis. We included a dummy variable for the European Biochar Certification. While it is not a co-benefit certification, it is a globally recognised biochar quality standard and currently the most prominent certification available for biochar and biochar credits[51,52]. As the biochar market expands, the expectation for certification as a baseline is growing[52]. Labelling is a common hedonic attribute discussed in the literature, including in studies on carbon credits. It has been shown that certified co-benefits associated with emissions avoidance credits increase credit prices[33]. We follow previous studies that include a dummy variable for developing country project location and interpret a positive coefficient as an indication of willingness to pay for sustainable development in such contexts[38]. We examined biochar project location at a continental level[38]. Lastly, we investigated the price effect of biochar production technologies. There are two broad types of technologies currently in use. The first, industrial technology, uses a closed system with emissions control[23]. The second, called artisanal, includes pyrolysis methods with kilns that are fired from the top; burning biomass on the top forms a flame curtain or flame cap, protecting the bottom biomass layer from oxygen and turning into ash[53]. We hypothesized that closed system methods command a price premium over low-technology production approaches because of their standardised process, easier quantification, and the perception of higher-grade biochar[54]. Control variables include the volume of biochar credits that a biochar project developer has delivered since the beginning of operation, the GDP of the project country, and the volume of the transaction.

The biochar carbon credit prices have a right-skewed distribution with a mean of 171 USD/ton of CO_2eq (Supplementary Methods 1 Figure 9; Table 3). On average, each biochar carbon credit is advertised with nearly seven SDG claims, while the range is from one to fourteen SDGs (there are seventeen possible SDGs in total). The social pillar consists of eight SDGs, while the environmental and economic pillars have four SDGs each. SDG 17, Partnerships for the Goals, was included in calculating the total SDG score and excluded from the sustainability pillars analysis, as the chosen SDG framework does not include it in the three sustainability pillars. The environmental pillar has the highest number of SDGs per credit on average (2.42 SDGs per credit). The biochar-producing companies vary by size; the largest project developer produces nearly 1000 times more removal credits than the smallest project developer (Table 3). Most biochar producers employ industrial pyrolysis plants.

The most advertised SDGs are environmental: SDG 13, Climate Action, and SDG 15, Life on Land. Next are the social: SDG 2, Zero Hunger, and SDG 1, No Poverty, along with the economic SDGs: SDG 12, Responsible Consumption and Production, and SDG 8, Decent Work and Economic Growth (Fig. 1). The pattern of SDGs advertised

Table 3 | Descriptives of the variables used in the hedonic pricing model

Variable		Type	Mean	St. dev.	Min	Max	Source
Dependent variable:							
Biochar carbon credit price (USD/ton of CO_2eq)		Continuous	170.84	79.28	89.29	600	11
Independent variables:							
Total number of SDG claims		Categorical	6.47	3.04	1	14	Marketplaces, registries, biochar project developers' websites.
Environmental SDG claims		Categorical	2.42	0.96	0	4	
Economic SDG claims		Categorical	1.69	1.20	0	4	
Social SDG claims		Categorical	2.18	1.48	0	6	
European Biochar Certificate (EBC = 1, otherwise=0)		Dummy	0.30				51
Project located in a developing country (Developing=1, Developed=0)		Dummy	0.35				57
Project location:							
37.4%*	Europe	Dummy					11
24%	Asia	Dummy					
7.6%	Africa	Dummy					
24%	North America	Dummy					
2.3%	South America	Dummy					
4.7%	Australia	Dummy					
Biochar project developer (tons of CO_2eq over lifetime)		Continuous	15,741	26,263	124	111,955	11
Biochar production method (Industrial=1, Artisanal=0)		Dummy	0.76				Determined according to the standard the credits were issued

* These values represent the relative distribution of project locations within the analysis dataset.

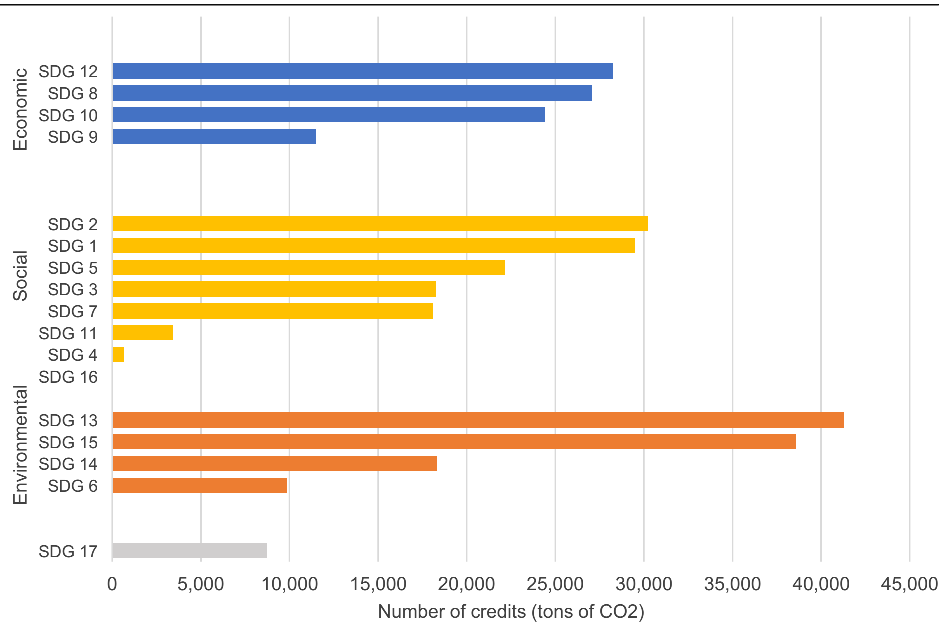

Fig. 1 | The number of biochar carbon credits associated with each of the Sustainable Development Goals (SDGs) in the analysis dataset (N=171 credit transactions). The sustainability pillar grouping follows Stockholm Resilience Centre developed SDG framework[29]. Blue bars refer to economic pillar SDG claims, yellow bars show social pillar SDGs, and orange bars refer to environmental pillar SDGs. SDG 1 No Poverty, SDG 2 Zero Hunger, SDG 3 Good Health and Well-being, SDG 4 Quality Education, SDG 5 Gender Equality, SDG 6 Clean Water and Sanitation, SDG 7 Affordable and Clean Energy, SDG 8 Decent Work and Economic Growth, SDG 9 Industry, Innovation and Infrastructure, SDG 10 Reduced Inequalities, SDG 11 Sustainable Cities and Communities, SDG 12 Responsible Consumption and Production, SDG 13 Climate Action, SDG 14 Life Below Water, SDG 15 Life on Land, SDG 16 Peace, Justice and Strong Institutions, and SDG 17 Partnerships for the Goals.

by biochar carbon credits corresponds closely to the sustainability impacts typically associated with biochar production. Carbon removal is primarily a climate action measure. Furthermore, since biochar is mainly applied to soil, it contributes to soil improvement and food production. In addition, biochar is primarily produced from plant waste, promoting responsible production and resource use. Lastly, biochar production is an economic action that creates employment and economic growth.

We assume that the credit descriptions were made available to the buyer at the time of the credit transaction. The SDG claims were collected in August 2024, while the transactions have been made since 2021. The largest volume of credits was sold in 2024.

Empirical Specification

The empirical specification for the first research question is as follows (Eq. 1):

$$log(p_{it}) = log(\beta_1 SDG_{it}) + \sum_{k=1}^{6} \vartheta_k LOC_{kit} + \beta_2 EBC_{it} + \beta_3 TECH_{it} + log(\beta_4 SIZE_{it}^{dev}) + log(\beta_5 SIZE_{it}^{tran}) + \theta_t + \varepsilon_{it} \quad (1)$$

where p_i is the biochar carbon credit price and index i refers to separate credit transactions, $i = 1, 2, \ldots, 171$ occurring at time t. SDG_{it} is the number of SDGs associated with credits in a transaction. Credits in one transaction are all sold at one price and have the same number of SDG claims. The remaining non-carbon attributes include LOC_{kit} is the project location (continent) per each transaction where the index k refers to the continents, $k = Europe, North\ America, \ldots$, European Biochar Certification dummy, EBC_{it}, and biochar production technology dummy, $TECH_{it}$, either industrial ($TECH = 1$) or artisanal ($TECH = 0$). The control variables include the size of the biochar project developer, $SIZE_{it}^{dev}$ and the volume of the transaction, $SIZE_{it}^{tran}$. We include fixed effects for a biochar carbon credit transaction announcement date (year), θ_t. Lastly, ε_{it} is an error term assumed to be normally distributed.

The empirical specification for the second research question is as follows (Eq. 2):

$$log(p_{it}) = \beta_1 SDG_{it}^{En} + \beta_2 SDG_{it}^{Ec} + \beta_3 SDG_{it}^{Soc} + \beta_4 SDG_{it}^{Ec} \times SDG_{it}^{Soc} + \beta_5 EBC_{it} + \beta_6 TECH_{it} + \beta_7 DEV_{it} + \beta_8 GDP_{it} + \beta_9 SIZE_{it}^{dev} + \beta_{10} SIZE_{it}^{tran} + \theta_t + \varepsilon_{it} \quad (2)$$

where the independent variables of interest are the number of SDG claims per sustainability pillar: environmental, SDG_{it}^{En}, economic, SDG_{it}^{Ec}, and social, SDG_{it}^{Soc}. In the sustainability pillar specification, instead of the continent variable, we include whether the project country is classified as a developing country, DEV_{it}, and the country-level GDP, GDP_{it}. This change was necessary because of multicollinearity between the continent variable and other covariates, as indicated by pooled OLS regressions using year-demeaned variables. It is known that individual SDGs have synergies and trade-offs[55,56], thus we include an interaction term between economic and social sustainability pillars to identify any potential overlap that the sustainability pillar framework might introduce. The other variables are the same as in Eq. 1.

We estimate a fixed-effects panel regression model on an unbalanced panel dataset in R using the within estimator (Product Version 2024. 12.0 + 467). In our model, the within estimator exploits variation over time. We treat SDG independent variables as numerical variables and use a log-log functional form for the first empirical specification (Eq. 1) to estimate the price elasticity with respect to the hedonic variables. The second empirical specification (Eq. 2) is log-linear, as there are multiple credits across the different sustainability pillars that do not have any SDGs in the pillar and natural log of zero is undefined. We use robust standard errors that account for both heteroskedasticity and autocorrelation (HAC), specifically HAC Newey–West standard errors.

Data availability

The biochar credit transaction price data used in this study were obtained under a restricted license and are not publicly available. Researchers interested in accessing the transaction prices should contact the data provider, CDR.fyi, directly. Anonymised transactions with limited descriptors and SDG data collected by the authors are provided in the Supplementary material and can also be found in a repository https://doi.org/10.6084/m9.figshare.32201031.

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Author contributions
Medilė Jokubė contributed to the conception and design of the model, obtaining data, coding, obtaining the results and their interpretation, visualisation, writing of the original draft, revising and editing. Matti Hyyrynen contributed to the modelling, interpretation of the results, revising and editing. Sampo Pihlainen contributed to the obtaining of data, the interpretation of the results, revising and editing. Kari Hyytiäinen contributed to the interpretation of the results, revising and editing. All authors agree to be accountable for all aspects of the work and approve the final version.

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