

Economic valuation of ecosystem services from biochar-mediated soil erosion control for carbon-neutral land management

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Keywords: Biochar, Soil erosion, Ecosystem services, Economic valuation, Carbon neutrality By translating reductions in soil erosion into ecosystem service values, this study provides a system-level perspective on the role of biochar in supporting sustainable and carbon-neutral land management under global environmental change., Soil organic carbon

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Abstract

This study develops a framework to quantify the ecosystem service value of biochar-mediated soil erosion control, linking reductions in soil loss and runoff to climate regulation, agricultural productivity, and water system benefits. Soil erosion is a major driver of land degradation, with global losses exceeding billions of tonnes annually and affecting approximately 24% of European land. Meta-analytical evidence indicates that biochar application reduces soil erosion by 16% and surface runoff by 25% on average, with stronger effects observed in erosion-prone environments.

Building on this evidence, this study develops a valuation framework that translates avoided soil loss into ecosystem service benefits across three systems. Scenario-based analysis shows that the total economic value of biochar-mediated erosion control ranges from €20 to €300 ha⁻¹ yr⁻¹, depending on environmental conditions and economic parameters. The climate system contributes €10–150 ha⁻¹ yr⁻¹ through the preservation of soil organic carbon, while the food system contributes €5–100 ha⁻¹ yr⁻¹ via avoided productivity losses, and the water system contributes €5–50 ha⁻¹ yr⁻¹ through reduced sediment-related impacts.

Evidence from Mediterranean systems demonstrates substantially stronger responses, with erosion reductions reaching up to 65–67% and significant increases in soil water retention and vegetation cover, indicating that ecosystem service values may exceed global averages under high erosion pressure. These findings highlight the role of biochar as a multifunctional land management strategy that supports climate mitigation, agricultural resilience, and water quality. The results provide a basis for integrating soil erosion control into carbon removal, natural capital, and carbon-neutral land management frameworks, particularly in regions vulnerable to climate change and land degradation.

1. Introduction

Global environmental change is reshaping terrestrial systems through the combined pressures of climate change, land degradation, and intensified resource use (IPCC, 2022; Borrelli et al., 2020). Among these pressures, soil degradation has emerged as a critical challenge affecting ecosystem functioning, agricultural productivity, and environmental sustainability. Soil erosion represents a major process of land degradation, driving the redistribution of soil, nutrients, and organic carbon across landscapes and altering the functioning of climate, food, and water systems (Montgomery, 2007; Yoon et al., 2025). At the global scale, soil erosion is estimated to affect billions of tonnes of soil annually, with substantial implications for ecosystem functioning and land productivity (Borrelli et al., 2020; Pimentel et al., 1995).

In Europe, soil erosion is already a widespread environmental issue, affecting a substantial share of agricultural land and contributing to declining soil quality and ecosystem functioning (Panagos et al., 2015; Verheijen et al., 2009). Recent assessments indicate that approximately 24% of land in the European Union is affected by unsustainable water-driven soil erosion, with total soil losses reaching around 1 billion tonnes per year (Panagos et al., 2015). Projections suggest further increases in erosion intensity under future climate scenarios, with mean soil loss in agricultural land expected to rise by up to

13–25% by 2050, depending on climatic and land use trajectories (Panagos et al., 2021; Borrelli et al., 2020). Mediterranean landscapes are especially sensitive due to the combined effects of climatic variability, low soil organic carbon content, and increasing frequency of extreme events such as droughts and wildfires (Rodrigo-Comino et al., 2017; Eiras-Barca et al., 2021; de Brogniez et al., 2015; Gholamahmadi, 2026). This is particularly relevant for perennial systems such as vineyards, where long-term management practices influence resilience to climatic variability. Long-term evidence from European viticulture shows that agroecological systems can overcome initial yield gaps and even outperform conventional systems under hot and dry conditions, highlighting the adaptive capacity of soil–plant systems under climate stress (Baronti et al., 2022; Döring et al., 2026). These conditions highlight the importance of identifying effective land management strategies capable of reducing soil loss and maintaining soil function under environmental change.

Soil erosion is not only a localised process of soil loss but also a systemic driver of environmental change with far-reaching consequences. The removal and transport of topsoil selectively deplete fine particles, organic matter, and nutrients, thereby reducing soil fertility and altering biogeochemical cycles (Lal, 1998; Montgomery, 2007). At the same time, erosion redistributes soil organic carbon across landscapes, influencing carbon storage and atmospheric exchanges (Yoon et al., 2025; Wei et al., 2025). These processes directly affect agricultural productivity and contribute to long-term declines in land capacity to support food production. In addition, eroded sediments and associated nutrients are transported into freshwater systems, degrading water quality and increasing the contamination and burden on water management infrastructure (Issaka & Ashraf, 2017; Blanco-Canqui, 2019; Rashmi et al., 2022). As a result, soil erosion represents a key link between land degradation and the interconnected dynamics of climate regulation, food systems, and water resources under global environmental change.

Biochar has emerged as a promising land management strategy for improving soil properties and enhancing ecosystem functioning (Lehmann et al., 2021; Schmidt et al., 2021). Produced through the pyrolysis of biomass, biochar is characterized by high carbon stability and a porous structure that can improve soil aggregation, increase water retention, and enhance nutrient availability (Blanco-Canqui, 2017; Edeh et al., 2020; Omondi et al., 2016; Razzaghi et al., 2020; Islam et al., 2021; Wei et al., 2023). These properties have led to growing interest in biochar as a tool for climate mitigation through carbon sequestration, as well as for improving soil fertility and resilience in agricultural systems. In addition to these widely studied benefits, biochar can influence hydrological processes at the soil surface, including infiltration and runoff dynamics, suggesting a potential role in reducing soil erosion (Jien & Wang, 2013; Sharma, 2024; Sharma et al., 2025).

An increasing body of experimental and synthesis-based research indicates that biochar application can significantly reduce soil erosion and surface runoff across a range of environmental conditions (Gholamahmadi et al., 2023; Lu et al., 2024; Sharma et al., 2025). Global meta-analytical evidence shows that biochar reduces soil erosion by 16% and surface runoff by 25% on average (Gholamahmadi et al., 2023), with stronger effects observed under specific conditions such as vegetated soils and moderate biochar application rates (Li et al., 2017; Li et al., 2019b; Gholamahmadi et al., 2023). Field-based

evidence from erosion-prone environments, including Mediterranean agricultural systems, further demonstrates that biochar can substantially reduce soil loss and improve soil water retention under conditions of high erosion pressure (Prats et al., 2021; Canedo et al., 2025; Gholamahmadi et al., 2025a, 2025b; Campino et al., 2026). Despite this growing body of evidence, the broader implications of erosion reduction for environmental systems remain insufficiently explored.

Reductions in soil erosion have implications that extend beyond soil conservation, influencing a range of ecosystem services that underpin environmental sustainability and human well-being. By limiting the loss of soil organic carbon, erosion control contributes to climate regulation through the preservation of carbon stocks in terrestrial systems (Yoon et al., 2025; Gholamahmadi & Kammann, 2026). At the same time, retaining nutrient-rich topsoil supports soil fertility and helps sustain agricultural productivity, which is essential for maintaining stable food systems (Blanco-Canqui & Lal, 2010; Jeffery et al., 2011, 2017; Jelinčić et al., 2026). In addition, reduced soil loss is closely linked to lower sediment and nutrient transport into freshwater systems, contributing to improved water quality and reduced pressures on water management infrastructure (Issaka & Ashraf, 2017; Blanco-Canqui, 2019). These interconnected effects highlight that soil erosion operates as a central process linking climate, food, and water systems, and that interventions reducing erosion can generate multiple co-benefits across these domains.

Despite growing recognition of the environmental importance of soil erosion and the demonstrated capacity of biochar to reduce soil loss and runoff, the broader socioeconomic implications of these effects remain poorly understood. Existing studies have largely focused on the biophysical performance of biochar (Schmidt et al., 2021; Sharma, 2024; Sharma et al., 2025), while the economic value of erosion-related ecosystem services has received limited attention (Pimentel et al., 1995; Pimentel & Burgess, 2013). There is a lack of integrated approaches that translate reductions in soil erosion into quantifiable benefits across climate regulation, agricultural productivity, and water systems. This gap limits the ability to assess the full contribution of biochar as a land management strategy and constrains its integration into environmental policy and decision-making frameworks.

This study addresses this gap by developing a framework for the economic valuation of ecosystem services derived from biochar-mediated soil erosion control under global environmental change. Building on global evidence of erosion and runoff reduction, including synthesis studies and meta-analyses (Gholamahmadi et al., 2023), the analysis links biochar-induced changes in soil processes to three interconnected environmental systems: climate regulation through the preservation of soil organic carbon (Gholamahmadi & Kammann, 2026), food systems through the maintenance of soil fertility and productive capacity, and water systems through reductions in sediment transport and runoff. A scenario-based valuation approach is proposed to estimate the economic significance of these services under varying environmental conditions. By translating reductions in soil erosion into ecosystem service values, this study provides a system-level perspective on the role of biochar in supporting sustainable and carbon-neutral land management under global environmental change.

2. Conceptual framework: linking biochar-mediated erosion control to ecosystem service valuation

Understanding the broader implications of soil erosion control under global environmental change requires an integrated perspective that connects biophysical processes with environmental systems and socioeconomic outcomes. This study adopts a conceptual framework in which biochar-mediated reductions in soil erosion and runoff are interpreted as mechanisms for preserving soil natural capital and sustaining multiple ecosystem services (FAO, 2025; IPCC, 2022) across interconnected climate, food, and water systems (Fig. 1).

At the core of the framework is biochar as a land management intervention that modifies soil physical and hydrological properties. By enhancing soil aggregation, increasing infiltration capacity, and reducing surface runoff, biochar application decreases the detachment and transport of soil particles (Blanco-Canqui, 2017; Edeh et al., 2020; Islam et al., 2021; Wei et al., 2023; Ghorbani and Amirahmadi, 2024). These changes result in measurable reductions in soil erosion and sediment fluxes, as demonstrated by global experimental and synthesis-based evidence. In this framework, reductions in erosion and runoff represent the primary biophysical entry points linking land management practices to broader environmental system responses (Gholamahmadi et al., 2023).

The framework explicitly connects these biophysical processes to three interdependent environmental systems. In the climate system, reduced soil erosion limits the displacement of soil organic carbon, contributing to the preservation of terrestrial carbon stocks and influencing carbon cycling dynamics (Yoon et al., 2025; Gholamahmadi & Kammann, 2026). In the food system, the retention of nutrient-rich topsoil supports soil fertility, maintains soil structure, and sustains agricultural productivity under changing environmental conditions (Blanco-Canqui & Lal, 2010; Jeffery et al., 2011; 2017). In the water system, reductions in runoff and sediment transport decrease the movement of sediments and associated nutrients into freshwater bodies, contributing to improved water quality and reduced pressure on water management systems (Blanco-Canqui, 2019; Issaka & Ashraf, 2017).

As illustrated in Fig. 1, the framework links biophysical changes induced by biochar application to ecosystem service provision across climate, food, and water systems. These pathways are interpreted through a natural capital perspective, where soil is considered a fundamental asset that underpins ecosystem functioning and the provision of services essential for human well-being (FAO, 2025). In this context, reductions in soil loss represent the preservation of natural capital, which generates benefits across multiple environmental domains. The framework therefore, links changes in soil processes to ecosystem service provision and, ultimately, to socioeconomic outcomes.

To capture these outcomes, the framework integrates an economic valuation component that translates reductions in soil erosion and runoff into quantifiable ecosystem service values. These values are associated with carbon retention in the climate system, maintaining agricultural productivity in the food system, and reducing sediment-related impacts in the water system (Pimentel et al., 1995). By

expressing these benefits in economic terms, the framework enables comparison across environmental processes and supports the assessment of land management strategies within decision-making contexts.

The framework is applied within a scenario-based approach that accounts for variability in environmental conditions and economic parameters under global environmental change. Scenarios represent differences in erosion intensity, soil carbon content, land use, and economic conditions such as carbon pricing and agricultural market values. This allows the analysis to explore how the benefits of biochar-mediated erosion control may vary across regions and future environmental trajectories, including erosion-prone systems such as Mediterranean agricultural landscapes (Rodrigo-Comino et al., 2017; Gholamahmadi et al., 2025a, 2025b; Campino et al., 2026).

Overall, the conceptual framework positions biochar-mediated soil erosion control as a multifunctional land management strategy that operates within coupled nature–human systems. By linking biophysical processes to ecosystem service valuation and decision-relevant outcomes, the framework provides a structured basis for assessing the role of soil conservation in addressing the interconnected challenges of climate change, food system sustainability, and water resource management.

3. Data sources and empirical basis

The valuation framework developed in this study is grounded in a combination of global synthesis evidence and literature-derived parameters describing soil, carbon, agricultural, and water system processes (Gholamahmadi et al., 2023; Sharma et al., 2025). The analysis builds on empirical evidence quantifying the effects of biochar on soil erosion and surface runoff, which serve as the primary biophysical inputs linking land management interventions to ecosystem service outcomes.

The core empirical basis of the study is derived from global meta-analytical evidence assessing the impact of biochar application on soil erosion and runoff across diverse environmental conditions. These synthesis studies provide representative estimates of proportional reductions in soil loss and surface runoff following biochar amendment, with average reductions of approximately 16% for soil erosion and 25% for surface runoff (Gholamahmadi et al., 2023). The magnitude of these effects varies depending on soil type, climatic conditions, vegetation cover, and biochar application rate, with stronger responses often observed in erosion-prone environments and under conditions where soil structure and infiltration processes are limiting (Jien & Wang, 2013; Li et al., 2017; Li et al., 2019b).

Additional evidence from field-based studies further supports the role of biochar in reducing soil erosion under high-risk conditions. Experimental results from Mediterranean agricultural systems demonstrate that biochar application can substantially reduce soil loss and enhance soil water retention in environments characterised by high erosion pressure and climatic variability (Gholamahmadi et al., 2025a, 2025b; Campino et al., 2026; Biancalani et al., 2026). These findings are consistent with the broader synthesis evidence and highlight the relevance of biochar-mediated erosion control in regions where land degradation and climate stressors are closely linked (Wu et al., 2020; Wei et al., 2023).

To contextualise these effects within global environmental change, the study incorporates data and assessments from European soil monitoring and environmental reporting frameworks. In the European Union, soil erosion represents a major component of land degradation, affecting a significant proportion of agricultural land and contributing to declines in soil quality and ecosystem functioning (Verheijen et al., 2009; Panagos et al., 2015). Current estimates indicate that unsustainable levels of water-driven erosion affect approximately one quarter of European land, with total soil losses reaching on the order of billions of tonnes annually (Panagos et al., 2015). Projections suggest that erosion intensity may increase further under future climate scenarios, particularly in regions exposed to changing rainfall patterns and land use pressures (Borrelli et al., 2020; Panagos et al., 2021; Vieira et al., 2026). The broader global context of present erosion patterns and projected changes under alternative development pathways is illustrated in Fig. 2 (Borrelli et al., 2020).

The translation of erosion and runoff reductions into ecosystem service values requires additional parameters describing the relationships between soil loss and environmental processes. For the climate system, literature-based estimates of soil organic carbon content and enrichment ratios in eroded sediments are used to quantify carbon displacement associated with soil erosion (de Brogniez et al., 2015; Yoon et al., 2025; Wei et al., 2025). For the food system, empirical relationships linking soil erosion to reductions in agricultural productivity are used to estimate the impact of soil loss on crop yields (Montgomery, 2007; Blanco-Canqui & Lal, 2010; Pimentel & Burgess, 2013). For the water system, sediment delivery processes and associated management costs are derived from watershed and environmental management studies, enabling the estimation of economic implications related to sediment transport and water quality (Issaka & Ashraf, 2017; Blanco-Canqui, 2019).

The integration of these data sources enables the development of a coherent analytical framework linking biochar-mediated reductions in soil erosion and runoff to ecosystem service outcomes. By combining global synthesis evidence with regionally relevant environmental data and literature-based parameters, the approach provides a robust empirical basis for assessing the economic value of soil conservation under global environmental change.

4. Valuation framework for ecosystem services

To quantify the environmental and socioeconomic implications of biochar-mediated soil erosion control, this study develops a valuation framework that translates reductions in soil erosion and runoff into ecosystem service benefits across climate, food, and water systems (Fig. 1) (Blanco-Canqui & Lal, 2010; Blanco-Canqui, 2019; Yoon et al., 2025). The framework operationalises the linkage between soil conservation and natural capital preservation by expressing avoided soil loss as a measurable physical quantity that can be connected to ecosystem processes and economic outcomes.

At the core of the framework is the estimation of avoided soil loss resulting from biochar application. Using baseline erosion rates and proportional reductions derived from global synthesis evidence, the analysis quantifies the amount of soil retained due to biochar-mediated erosion control. This retained

soil represents the primary physical variable from which ecosystem service benefits are derived across environmental systems.

4.1 Climate system: preservation of soil organic carbon

In the climate system, soil erosion contributes to the displacement of soil organic carbon (SOC) through the selective removal of carbon-rich fine particles (Li et al., 2019a; Yoon et al., 2025; Wei et al., 2025). The valuation framework estimates the amount of carbon retained in soils because of reduced erosion by combining soil loss with soil carbon content and enrichment factors associated with eroded sediments. The avoided loss of carbon is then converted into carbon dioxide equivalents and valued using representative carbon price scenarios. This approach captures the contribution of erosion control to climate regulation by maintaining soil carbon stocks that would otherwise be displaced through erosion processes (Gholamahmadi & Kammann, 2026).

4.2 Food system: preservation of soil fertility and productivity

In the food system, soil erosion affects agricultural productivity through the removal of nutrient-rich topsoil and the degradation of soil structure (Pimentel et al., 1995; Montgomery, 2007; Pimentel & Burgess, 2013). The framework captures this effect by linking soil loss to changes in crop productivity using relationships reported in the literature between erosion and yield response. By estimating the extent to which biochar-mediated erosion control reduces soil loss, the analysis derives the corresponding avoided reduction in agricultural productivity. This avoided productivity loss is then expressed in economic terms using representative crop values, providing an estimate of the value of maintaining soil fertility and productive capacity.

4.3 Water system: reduction of sediment transport and runoff impacts

In the water system, soil erosion and runoff are primary drivers of sediment and nutrient transport into freshwater bodies (Issaka & Ashraf, 2017; Blanco-Canqui, 2019). The valuation framework estimates reductions in sediment export associated with decreased soil erosion and runoff, accounting for sediment delivery processes at the landscape scale. These reductions are then linked to economic metrics using estimates of sediment management and water treatment costs derived from watershed and environmental management studies. This pathway reflects the role of soil conservation in reducing off-site environmental impacts associated with sediment and nutrient transport.

4.4 Integrated ecosystem service value and scenario analysis

The total ecosystem service value of biochar-mediated erosion control is calculated by integrating the contributions from the climate, food, and water pathways. This integrated value reflects the

multifunctional role of soil conservation in sustaining ecosystem services across interconnected environmental systems.

To account for variability in environmental and economic conditions, the framework is applied within a scenario-based approach. Scenarios represent differences in erosion intensity, soil carbon content, land use conditions, and economic parameters, including carbon price levels, crop values, and sediment management costs. This approach enables the assessment of ecosystem service values across a range of environmental contexts and supports the evaluation of biochar-mediated erosion control under future global environmental change scenarios (Borrelli et al., 2020; Panagos et al., 2021).

4.5 Quantitative formulation of ecosystem service valuation

To operationalise the valuation framework, the relationships between soil erosion, ecosystem processes, and economic value are expressed using a set of simplified analytical equations. These equations translate biochar-induced reductions in soil erosion and runoff into quantifiable ecosystem service benefits.

The reduction in soil erosion due to biochar application is defined as:

$$\Delta E = E0 \times re$$

where ΔE is the avoided soil erosion ($\text{t ha}^{-1} \text{yr}^{-1}$), $E0$ is the baseline soil erosion rate, and re is the proportional reduction in erosion associated with biochar application.

4.5.1 Climate system valuation

The amount of soil organic carbon (SOC) preserved through reduced erosion is estimated as:

$$\Delta C = E0 \times SOC \times ER \times re$$

where SOC represents soil organic carbon content and ER is the enrichment ratio of carbon in eroded sediments. The avoided carbon loss is converted to carbon dioxide equivalents:

$$\Delta CO_2 = \Delta C \times 3.67$$

The economic value of carbon preservation is then calculated as:

$$V_c = \Delta CO_2 \times P_c$$

where P_c is the carbon price.

4.5.2 Food system valuation

The avoided reduction in agricultural productivity is estimated by linking soil erosion to yield change:

$$\Delta Y = E0 \times \beta_y \times re$$

where β_y It is the yield response coefficient to soil erosion. The economic value of preserved productivity is:

$$V_f = \Delta Y \times P_y$$

where P_y is the crop price.

4.5.3 Water system valuation

The reduction in sediment delivery associated with avoided erosion is estimated as:

$$S_{\text{saved}} = \Delta E \times SDR$$

where SDR is the sediment delivery ratio. The corresponding economic value is:

$$V_w = S_{\text{saved}} \times P_s$$

where P_s represents the sediment management or water treatment cost per unit of sediment.

4.5.4 Total ecosystem service value

The total economic value of ecosystem services is calculated as:

$$V_{\text{total}} = V_c + V_f + V_w$$

These equations provide a transparent and flexible structure for estimating the economic implications of biochar-mediated soil erosion control under varying environmental and economic conditions. Parameter values are derived from literature ranges and applied within scenario-based analyses to capture variability across systems (Gholamahmadi et al., 2023; Yoon et al., 2025; Trapero et al., 2025).

5. Scenario-based valuation of ecosystem service benefits

The scenario-based valuation presented in this section builds on the parameter ranges summarised in Table 1 and the illustrative calculations reported in Supplementary Table S1, which compile representative values from global synthesis studies, environmental assessments, and economic literature (Pimentel et al., 1995; Panagos et al., 2021; Gholamahmadi et al., 2023; Trapero et al., 2025). These parameters define the biophysical and economic boundaries of the analysis and enable the consistent estimation of ecosystem service values across climate, food, and water systems under varying environmental conditions.

Table 1

Parameter ranges and sources used in the valuation of ecosystem services associated with biochar-mediated soil erosion control.

Parameter	Symbol	Unit	Range / Value	Description	Source
Baseline soil erosion rate	($E0$)	t ha ⁻¹ yr ⁻¹	1–30+	Representative erosion rates across stable to degraded systems	Panagos et al., 2015; Panagos et al., 2015; Panagos et al., 2021
Erosion reduction (biochar)	(re)	–	0.16	Mean reduction in soil erosion due to biochar	Gholamahmadi et al. (2023)
Soil organic carbon	(SOC)	t C t ⁻¹ soil	0.01–0.05	Carbon content of eroded topsoil	de Brogniez et al., 2015; Yoon et al., 2025
Enrichment ratio	(ER)	–	1.2–2.0	Carbon enrichment in eroded sediments	Yoon et al., 2025
CO ₂ conversion factor	–	–	3.67	Conversion from C to CO ₂	IPCC, 2022
Carbon price	(P_c)	€ t ⁻¹ CO ₂	50–150	Carbon market price range	CDR.fyi, 2025
Yield response coefficient	(ΔY)	t crop t ⁻¹ soil	0.001–0.01	Yield sensitivity to soil loss	Montgomery, 2007; Pimentel & Burgess, 2013
Crop price	(P_y)	€ t ⁻¹	150–400	Representative crop market values	FAO, 2025
Sediment delivery ratio	(SDR)	–	0.1–0.5	Fraction of eroded soil reaching water bodies	Panagos et al., 2015; Borrelli et al., 2020
Sediment management cost	(P_s)	€ t ⁻¹ sediment	5–50	Cost of sediment removal/treatment	Issaka & Ashraf, 2017; Blanco-Canqui, 2019

Parameter ranges represent typical values reported in the literature and are used to define scenario-based valuation conditions. The proportional reduction in soil erosion ($re = 0.16$) is derived from global synthesis evidence. Economic parameters reflect indicative ranges relevant to current environmental markets and agricultural systems.

5.1 Baseline conditions and scenario definition

To illustrate the economic implications of biochar-mediated soil erosion control, the valuation framework was applied under a set of representative environmental and economic scenarios. These scenarios

reflect variability in erosion intensity, soil properties, and economic parameters across agricultural systems.

Baseline soil erosion rates (E_0) were defined to represent three generalised conditions:

- Low erosion: $< 5 \text{ t ha}^{-1} \text{ yr}^{-1}$ (stable systems)
- Moderate erosion: $5\text{--}15 \text{ t ha}^{-1} \text{ yr}^{-1}$ (managed agricultural systems)
- High erosion: $> 15 \text{ t ha}^{-1} \text{ yr}^{-1}$ (degraded or erosion-prone systems)

The proportional reduction in soil erosion associated with biochar application (re) was set at 0.16 (Gholamahmadi et al., 2023), consistent with global meta-analytical evidence, while runoff reductions (e.g. 25%) were incorporated into the water system valuation through sediment transport effects (Gholamahmadi et al., 2023).

Soil organic carbon content (SOC), enrichment ratios (ER), and sediment delivery ratios (SDR) were defined using literature-derived ranges representative of agricultural soils. Economic parameters were defined using indicative values reflecting current and emerging environmental markets:

- Carbon price (P_c): $50\text{--}150 \text{ € t}^{-1} \text{ CO}_2$
- Crop value (P_y): region-dependent (indicative global range)
- Sediment management cost (P_s): derived from watershed management and water treatment estimates

These parameter ranges enable the assessment of ecosystem service values across a spectrum of environmental and economic conditions relevant to global environmental change (Carbonfuture, 2024; Trapero et al., 2025; CDR.fyi, 2025).

5.2 Climate system: value of soil carbon preservation

Across all scenarios, reductions in soil erosion translate into measurable preservation of soil organic carbon. Under moderate erosion conditions, the estimated avoided soil loss corresponds to a proportional retention of SOC that would otherwise be displaced through erosion processes.

The conversion of retained carbon into CO_2 -equivalent values, combined with representative carbon prices, indicates that the economic value of soil carbon preservation increases nonlinearly with erosion intensity (Yoon et al., 2025; Gholamahmadi & Kammann, 2026). Under high erosion scenarios, avoided carbon loss becomes a dominant component of total ecosystem service value, reflecting the coupling between erosion processes and carbon cycling.

These findings highlight that biochar-mediated erosion control contributes not only to soil conservation but also to climate regulation by maintaining carbon stocks within agricultural systems. The magnitude of this benefit is particularly relevant under emerging carbon market frameworks, where soil carbon stability and permanence are critical considerations (European Parliament & Council of the European

Union, 2024; Carbonfuture, 2024; CDR.fyi, 2025). The durability of biochar as a carbon removal pathway is increasingly recognised in policy and scientific literature, with residence times on the order of centuries, although persistence depends on both material properties and environmental conditions (Schmidt et al., 2025).

5.3 Food system: value of maintained productivity

The reduction in soil erosion directly supports agricultural productivity by preserving topsoil, nutrient availability, and soil structure. Under moderate to high erosion conditions, avoided soil loss translates into measurable reductions in productivity decline (Montgomery, 2007; Blanco-Canqui & Lal, 2010; Jeffery et al., 2011).

The valuation results indicate that the economic value of maintained productivity is strongly dependent on baseline erosion intensity and crop value, with greater benefits observed in systems where soil degradation is a limiting factor for production. In erosion-prone environments, even modest reductions in soil loss can lead to significant long-term gains in productive capacity.

These results emphasise the role of soil conservation as a foundational component of food system resilience. By maintaining soil fertility and reducing degradation pressures, biochar-mediated erosion control contributes to stabilising agricultural outputs under conditions of increasing climatic variability (Yaseen et al., 2025).

5.4 Water system: value of reduced sediment and runoff impacts

Reductions in soil erosion and runoff decrease sediment transport to downstream water bodies, with direct implications for water quality and management costs (Issaka & Ashraf, 2017; Blanco-Canqui, 2019). Under all scenarios, the avoided soil loss results in lower sediment delivery, particularly in landscapes with higher sediment connectivity.

The valuation results suggest that the economic value of reduced sediment transport becomes increasingly significant in high erosion scenarios, where sediment loads impose substantial pressures on water management systems. These benefits are reflected in reduced requirements for sediment removal, lower water treatment costs, and improved water quality.

The inclusion of runoff reduction effects further strengthens this pathway, as decreased surface flow contributes to lower transport of sediments and associated pollutants. This highlights the role of biochar in supporting water system sustainability through both on-site and off-site mechanisms (Blanco-Canqui, 2019; Peng et al., 2019; Mao et al., 2019; Acharya et al., 2024).

5.5 Integrated ecosystem service value

The integration of climate, food, and water system values reveals that biochar-mediated soil erosion control generates multifunctional ecosystem service benefits. Across all scenarios, the total economic

value increases with erosion intensity, reflecting the greater potential for avoided losses in degraded systems.

Importantly, the relative contribution of each pathway varies across scenarios:

- Climate benefits dominate under high SOC and high erosion conditions
- Food system benefits are more prominent in productive agricultural systems
- Water system benefits increase in landscapes with strong sediment connectivity

This variability underscores the importance of context-specific assessment when evaluating the benefits of soil conservation interventions (Borrelli et al., 2020; Panagos et al., 2021).

The integrated ecosystem service values across erosion scenarios are illustrated in Fig. 3, highlighting the relative contributions of climate, food, and water system benefits.

5.6 Implications under global environmental change

The scenario-based analysis demonstrates that the value of biochar-mediated soil erosion control is closely linked to key drivers of global environmental change, including climate variability, land degradation, and increasing pressures on food and water systems, as reflected in the increasing ecosystem service values across erosion scenarios (Fig. 3). In regions such as the Mediterranean, where soil erosion, water scarcity, and climatic stress intersect, the combined ecosystem service benefits of erosion control are particularly pronounced (Rodrigo-Comino et al., 2017; Prats et al., 2021; Eiras-Barca et al., 2021; Gholamahmadi et al., 2025a, 2025b). Similarly, at the European scale, where soil degradation remains a major environmental challenge, the valuation results highlight the potential of soil management strategies to contribute to climate mitigation, agricultural sustainability, and water resource management (Verheijen et al., 2009; Panagos et al., 2021). Overall, the results indicate that soil erosion control represents a critical but under-recognised pathway through which land management interventions can generate measurable environmental and economic benefits (Gholamahmadi & Kammann, 2026). By linking biophysical processes to economic valuation, the framework provides a basis for integrating soil conservation into broader environmental and policy decision-making.

Box 1. Mediterranean hotspot evidence: ecosystem service gains can exceed global mean erosion responses

Global synthesis evidence indicates that biochar application reduces soil erosion by 16% and runoff by 25% on average across diverse conditions (Gholamahmadi et al., 2023). In Mediterranean systems, however, stronger responses can emerge under high erosion pressure. In vineyard soils, biochar reduced runoff by 45% and erosion by 65%, while increasing stored soil water by 73% (Gholamahmadi et al., 2025a). In a second Mediterranean vineyard experiment, biochar reduced erosion by 58%, increased infiltration by 50%, increased water retention by 59%, and enhanced vegetation cover by 263% (Gholamahmadi et al., 2025b).

Additional Portuguese evidence from post-fire and mulched systems confirms that biochar-based or biochar-related interventions can strongly influence runoff, erosion, and vegetation recovery under extreme rainfall conditions (Prats et al., 2021; Canedo et al., 2025). In general, these findings indicate that Mediterranean agroecosystems and post-fire landscapes can generate ecosystem-service gains substantially above global mean estimates, supporting the use of context-specific valuation and targeted deployment strategies.

Beyond erosion control, long-term viticulture experiments indicate that agroecological management systems can improve yield stability and performance under warm and dry conditions, suggesting that soil-mediated processes contribute to climate resilience in perennial cropping systems (Baronti et al., 2022; Biancalani et al., 2026).

In high-impact scenarios, particularly in erosion-prone Mediterranean systems, ecosystem service values may exceed €500 ha⁻¹ yr⁻¹, indicating that global average estimates may substantially underestimate the benefits of targeted biochar deployment.

6. Discussion

6.1 From soil conservation to economic valuation of ecosystem services

This study advances the understanding of soil erosion control by explicitly linking biophysical processes to economic valuation across climate, food, and water systems. While previous research has extensively documented the capacity of biochar to reduce soil erosion, improve soil structure, and enhance hydrological function, these benefits have largely been assessed in isolation or expressed in physical terms. The framework developed here extends this knowledge by translating erosion control into quantifiable ecosystem service values, thereby bridging the gap between soil science and environmental economics (Pimentel et al., 1995; Pimentel & Burgess, 2013).

By treating avoided soil loss as a proxy for natural capital preservation, the approach provides a coherent basis for integrating soil conservation into broader sustainability assessments. This perspective is particularly relevant in the context of global environmental change, where land degradation, climate pressures, and resource constraints interact across scales and systems (Du et al., 2022).

6.2 Comparison with existing literature and contribution to knowledge

Existing reviews and meta-analyses have demonstrated that biochar can reduce soil erosion and runoff across a wide range of conditions, with reported average reductions broadly consistent with the values used in this study (Gholamahmadi et al., 2023; Lu et al., 2024; Sharma, 2024; Sharma et al., 2025). However, these studies have primarily focused on biophysical mechanisms, such as aggregate stability,

infiltration enhancement, and vegetation responses, without extending the analysis to economic valuation.

More recent contributions have begun to recognise the role of soil erosion control in supporting climate regulation, agricultural productivity, and water quality (Sharma et al., 2025; Gholamahmadi & Kammann, 2026). Nevertheless, these links are often discussed qualitatively or within single-system perspectives. The present study contributes to the literature by integrating these pathways within a unified valuation framework that captures the multifunctional nature of soil conservation.

Importantly, the use of scenario-based valuation enables the exploration of how ecosystem service benefits vary under different environmental and economic conditions. This represents a methodological advance beyond static assessments and aligns with emerging approaches in global environmental change research that emphasise system dynamics and uncertainty.

6.3 Implications for climate policy and carbon removal strategies

The findings highlight that soil erosion control plays a critical role in maintaining soil carbon stocks, which are increasingly recognised as a component of climate mitigation strategies (Lehmann et al., 2021; Yoon et al., 2025; Gholamahmadi & Kammann, 2026). In current carbon accounting frameworks, soil organic carbon dynamics are often considered in terms of sequestration and storage, while the role of erosion as a pathway of carbon redistribution and loss remains underrepresented. However, biochar permanence is not absolute and reflects a balance between stabilisation and slow mineralisation processes, reinforcing the need for conservative accounting approaches in carbon removal frameworks (Schmidt et al., 2025).

By quantifying the economic value of avoided carbon loss, this study provides a basis for incorporating erosion processes into carbon removal and climate policy frameworks. This has direct relevance for emerging mechanisms such as carbon certification systems, where the durability and permanence of carbon storage are central concerns (European Parliament & Council of the European Union, 2024; CDR.fyi, 2025). Soil erosion control, as enhanced through biochar application, can contribute to stabilising carbon stocks and reducing uncertainty associated with carbon retention in terrestrial systems.

6.4 Implications for food systems and agricultural resilience

Soil erosion is a major driver of long-term declines in agricultural productivity, particularly in regions exposed to climatic variability and land degradation (Lal, 1998; Montgomery, 2007; Blanco-Canqui & Lal, 2010; Pimentel & Burgess, 2013). The results of this study demonstrate that the economic value of maintaining soil fertility through erosion control can be substantial, especially under moderate to high erosion conditions.

By preserving topsoil and supporting soil structure, biochar-mediated erosion control contributes to the resilience of agricultural systems. This is particularly relevant in the context of increasing climate variability, where extreme rainfall events and drought periods can exacerbate soil degradation processes. The integration of soil conservation into economic valuation frameworks provides a pathway for recognising the role of soil management in sustaining food production and stabilising agricultural systems (Jeffery et al., 2011; 2017).

6.5 Implications for water systems and environmental management

The reduction of sediment transport resulting from decreased soil erosion has significant implications for water quality and management. Sediment and nutrient loading from agricultural land are key drivers of water quality degradation, requiring costly interventions in water treatment and watershed management (Issaka & Ashraf, 2017; Blanco-Canqui, 2019).

The valuation results presented in this study indicate that soil conservation can generate measurable economic benefits through reduced sediment loads and improved water system functioning. These benefits extend beyond individual fields, highlighting the importance of considering off-site impacts in land management decisions.

By linking erosion control to water system outcomes, the framework supports the integration of soil conservation into broader environmental management strategies, including watershed planning and pollution mitigation.

6.6 Policy relevance and integration into carbon-neutral land management frameworks

The integration of ecosystem service valuation into soil erosion research has important implications for policy and decision-making. In the European context, soil degradation and erosion remain significant challenges, with implications for climate mitigation, agricultural sustainability, and water resource management (Panagos et al., 2015; Panagos et al., 2021; FAO, 2025).

The framework developed in this study aligns with emerging policy directions that emphasise the multifunctional role of soils, including initiatives related to soil health monitoring, climate mitigation, and sustainable land management (European Parliament & Council of the European Union, 2024; Li et al., 2025; Panagos et al., 2025). By providing a quantitative basis for valuing soil conservation, the approach supports the development of policy instruments that recognise the economic importance of maintaining soil natural capital.

At a broader scale, the results contribute to ongoing discussions on how land-based interventions can support global environmental change mitigation and adaptation. The integration of climate, food, and water systems within a single valuation framework reflects the interconnected nature of environmental challenges and the need for integrated solutions.

6.7 Limitations and future research directions

While the framework provides a structured approach for valuing ecosystem services associated with soil erosion control, several limitations should be acknowledged. First, the analysis relies on literature-derived parameters and generalised relationships, which may not capture site-specific variability in soil properties, climate conditions, and management practices.

Second, the valuation approach focuses on three primary ecosystem service pathways, while other benefits of biochar application, such as biodiversity enhancement or nutrient cycling, are not explicitly quantified. Expanding the framework to include additional ecosystem services could provide a more comprehensive assessment of the benefits of soil management interventions.

Third, the scenario-based approach captures variability across a range of conditions but does not explicitly model temporal dynamics or feedback processes. Future research could integrate dynamic modelling approaches to better represent long-term interactions between soil processes, climate change, and land management (Maslouski et al., 2025).

Finally, empirical validation of the valuation framework through field-scale and regional studies would strengthen its applicability and support its integration into policy and decision-making contexts (Sadeghi et al., 2020; Zanutel & Biolders, 2023; Ni et al., 2024; Gholamahmadi, 2024; Canedo et al., 2025; Costanzo et al., 2025).

7. Conclusion

This study demonstrates that biochar-mediated soil erosion control represents a critical but under-recognised pathway for delivering ecosystem service benefits across climate, food, and water systems. By reducing soil loss and runoff, biochar contributes to the preservation of soil organic carbon, the maintenance of agricultural productivity, and the protection of water quality, with total economic values ranging from €20 to €300 ha⁻¹ yr⁻¹ under different environmental conditions.

Importantly, the results show that ecosystem service gains can be substantially higher in erosion-prone regions such as Mediterranean landscapes, where reductions in soil erosion may exceed 60% and lead to amplified benefits across multiple systems. This highlights the importance of context-specific deployment and supports the integration of biochar into land management strategies targeting climate adaptation and resilience.

From a climate perspective, the findings reinforce the role of biochar as a durable carbon removal pathway, while also acknowledging that persistence reflects long-term but dynamic processes requiring conservative accounting and robust monitoring. Integrating soil erosion control into carbon removal frameworks can therefore improve the representation of land-based carbon dynamics and strengthen the environmental integrity of carbon markets.

Overall, this study provides a quantitative basis for linking soil conservation to ecosystem service valuation and demonstrates how biochar can function as a multifunctional environmental intervention. Incorporating soil erosion control into climate, agricultural, and water policy frameworks can support the transition towards sustainable and carbon-neutral land management under accelerating global environmental change.

Declarations

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Conflict of Interest Statement

The analysis and interpretations presented are independent and not influenced by commercial interests.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors utilised AI-assisted tools, including ChatGPT (OpenAI) for improving readability, language editing, and formatting references, and Grammarly for grammar checking. After using these tools, the author conducted a thorough review and editing of the manuscript.

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Figures

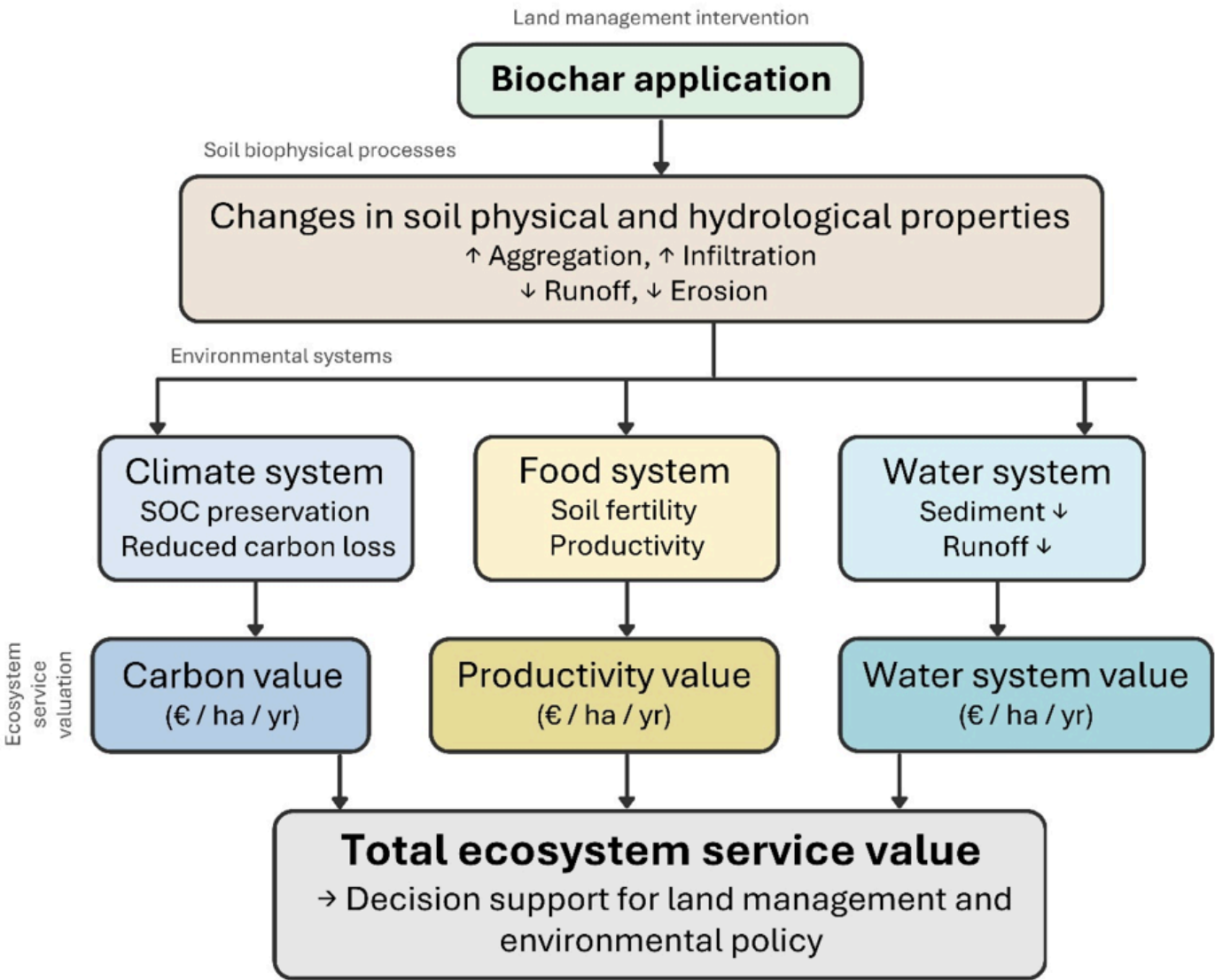


Figure 1

Conceptual framework linking biochar-mediated soil erosion control to ecosystem service valuation under global environmental change. Biochar application modifies soil physical and hydrological

properties, reducing soil erosion and runoff. These changes influence interconnected climate, food, and water systems through soil organic carbon preservation, maintenance of soil fertility and productivity, and reduced sediment transport. The resulting ecosystem service benefits are expressed in economic terms and integrated to support land management and environmental policy decisions.

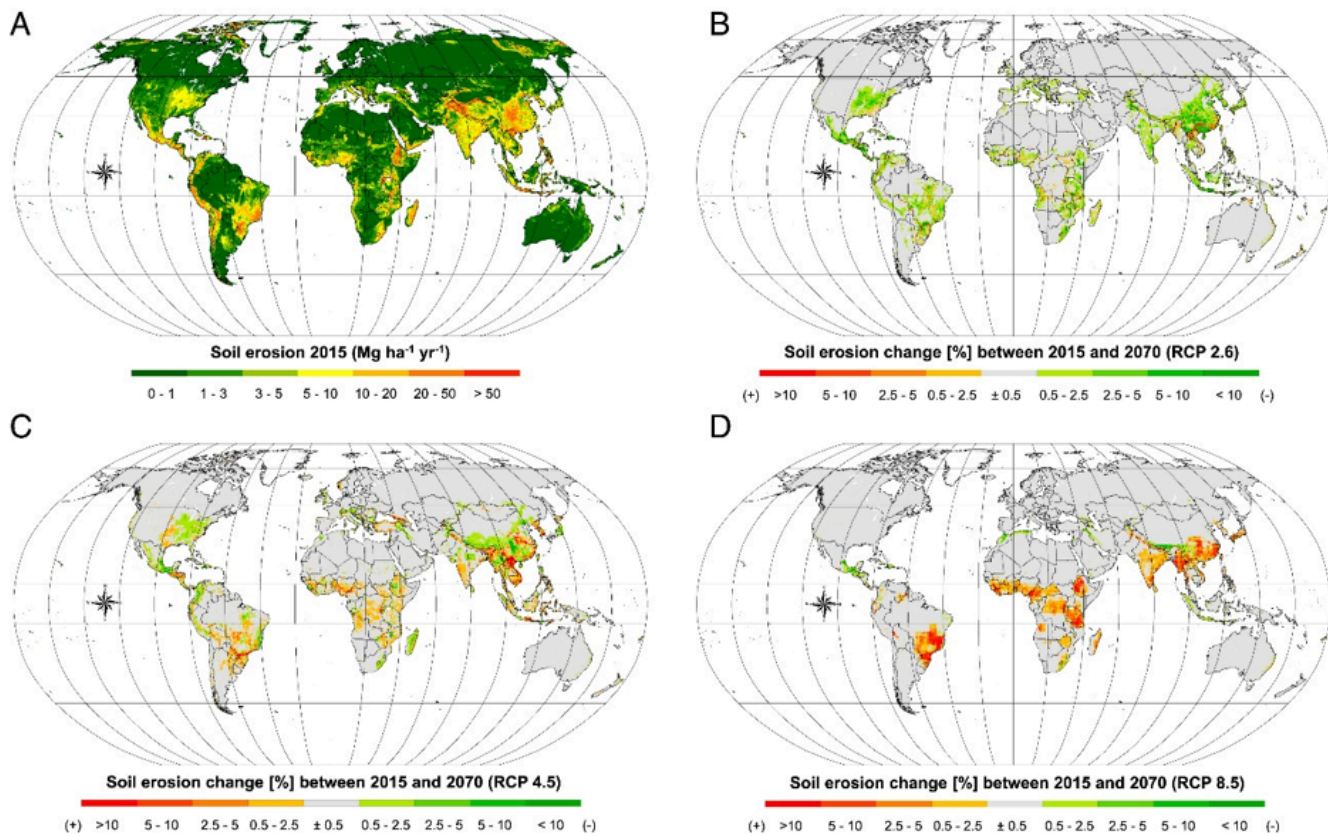


Figure 2

Global soil erosion estimates and projected changes under alternative greenhouse gas trajectories. Panel (A) shows modelled soil erosion rates for 2015, grouped according to the European Soil Bureau classification. Panels (B–D) show projected percentage changes in annual average soil erosion between 2015 and 2070 under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. In panels (B–D), the projected changes refer to land-use change effects only while holding the climate of 2015 constant. Adapted from Borrelli et al. (2020), licensed under CC BY 4.0.

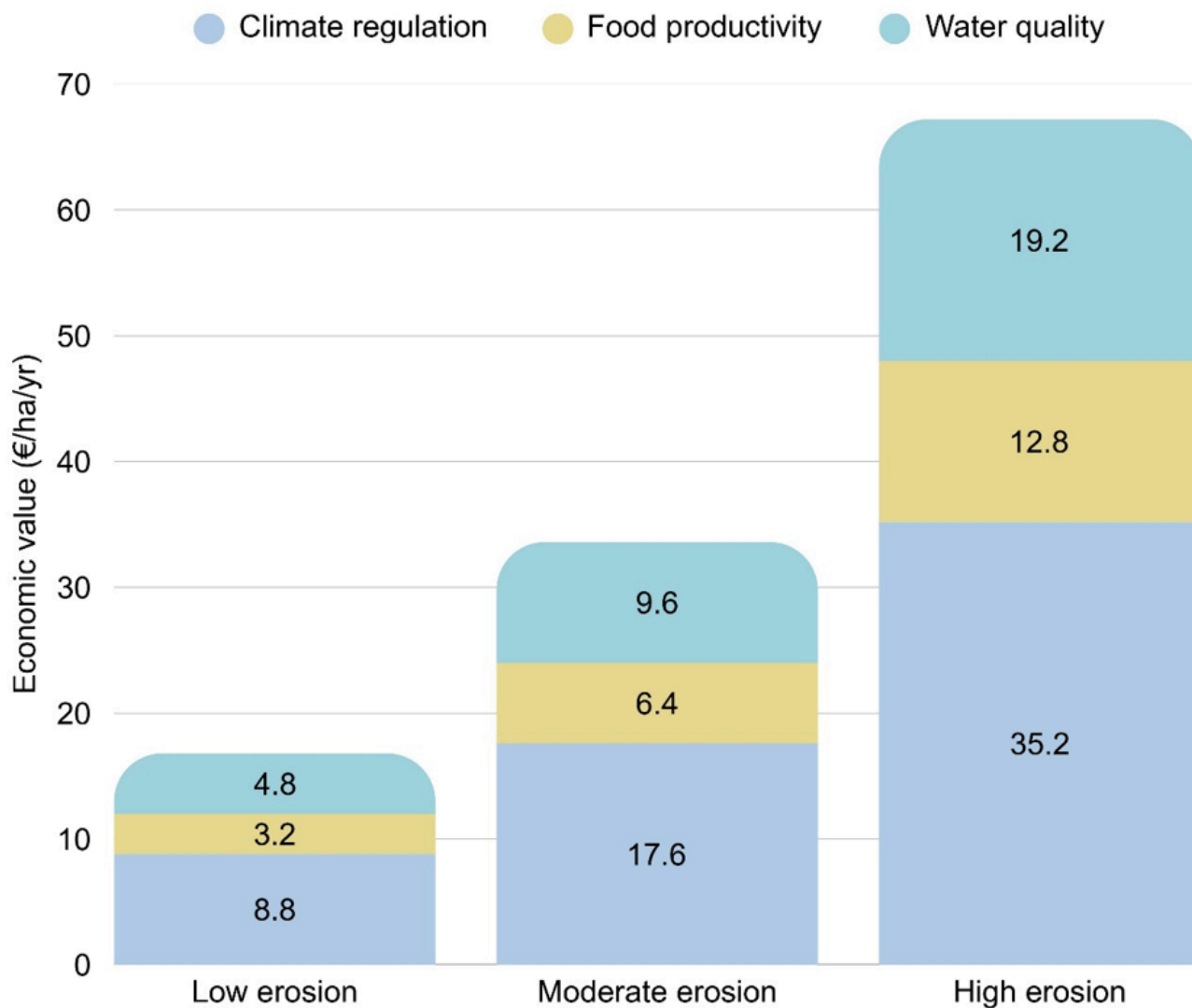


Figure 3

Scenario-based economic valuation of ecosystem services associated with biochar-mediated soil erosion control. Stacked bars represent the contributions of climate regulation (soil carbon preservation), food system productivity, and water system benefits under increasing erosion intensity scenarios. Total economic value increases with erosion intensity, reflecting the greater potential for avoided losses in degraded systems.