



Biochar-Mediated Soil Restoration, Biodiversity Offsets, and Ecosystem Services Valuation: Connecting Microbiology, Materials Engineering, Forestry, Law, Environmental Accounting, and Regional Planning

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ABSTRACT :

Biochar-mediated soil restoration, biodiversity offsetting, and ecosystem services valuation are three approaches that are usually treated separately, but they address the same problem: land that has been degraded by industry and resource extraction. Biochar is a carbon-rich material made by heating forest and crop waste without oxygen. Because it is porous, it can act as a carrier for pollutant-degrading bacteria, holding them in place and keeping them alive during long storage. This kind of immobilisation protects hydrocarbon-oxidising bacteria such as *Rhodococcus erythropolis* and *Pseudomonas aeruginosa* and can raise their viable numbers by two to five orders of magnitude [1-3]. Biochars modified with silicon, made from lignin through pyrolysis, reach cadmium (Cd²⁺) adsorption capacities of 315.53 mg/g through ion exchange and carbon-silicon (C-Si) complexation, and at the same time they favour cadmium-resistant microbes such as *Sphingomonas* and improve overall soil functioning [4-6]. Newer enzyme-immobilisation methods that fix PETase, laccase, and manganese peroxidase onto nanomaterial carriers offer a further route for breaking down microplastics and petroleum hydrocarbons in forest soils [7-9]. These restoration tools connect with biodiversity conservation and with the mitigation hierarchy of avoid, minimise, restore, and compensate. Biodiversity offsets are the last step in that hierarchy. They are meant to balance the biodiversity that is lost to development with equal gains elsewhere, but their results are limited by weak counterfactual baselines, multipliers that are set too low, and poor long-term governance [10-13]. Legal systems deliver offsets in different ways - developer-led schemes, market-based mitigation banking, and in-lieu fee programmes - and each creates different lines of accountability, while the requirement of like-for-like equivalence means a compensation site must stay ecologically comparable to the site that was lost and be placed in the right landscape setting [10,14-16]. Forest and wildlife management therefore depend on long-term protection, adaptive management, and landscape-scale planning for offset sites that hold threatened forest ecosystems and endangered species [17]. Ecosystem services valuation links ecological restoration, natural capital accounting, and regional planning by pricing the services that forests, wetlands, and other ecosystems provide [18-20]. The System of Environmental-Economic Accounting (SEEA) offers a standard way to track ecosystem assets and service flows in both physical and monetary terms, and valuation methods such as avoided cost, replacement cost, travel cost, hedonic pricing, contingent valuation, benefit transfer, and deliberative valuation allow planners to assess ecosystem benefits [18,20-24]. Spatial prioritisation tools such as Zonation combine biodiversity and carbon data to map conservation priorities, and they show that the trade-offs between carbon storage, biodiversity, and economic return differ from place to place [25,26]. Taken together, these strands show how material-based soil remediation, biodiversity conservation, ecosystem services valuation, environmental accounting, and spatial planning can be combined to support forest restoration, ecological protection, and regional environmental decisions that rest on evidence.

Keywords: Biochar materials; Biodiversity offsets; Ecosystem services valuation; Environmental accounting; Soil restoration; Spatial planning.

1. Introduction

Environmental damage caused by rapid industrial growth and resource extraction cannot be fixed by one discipline alone. Cleaning up contaminated soil and protecting biodiversity are usually handled as separate problems, but serious ecological damage needs the tools of several fields at once. Physical soil restoration built through materials engineering has to be backed by legal governance, long-term forestry management, and regional economic planning if the recovery is to last.

At the scale of the soil itself, restoration depends on materials such as biochar. Made from forest and crop waste, biochar gives microbes a stable place to live and lets them break down pollutants such as petroleum hydrocarbons and microplastics. Moving outward from the soil, the legal and regulatory framework of biodiversity offsetting decides how ecosystems are restored and protected. At the level of the wider economy, ecosystem services valuation supplies the financial and accounting measures that justify and fund large environmental projects. This paper brings these fields together and shows how microbiology, law, and environmental economics can work in the same regional plan. Adding the accounting dimension matters because a benefit that is never measured is treated as though it has no value, and the decline of natural systems then continues without a counterweight [27]. The aim here is not to claim that any one tool is enough; it is to set out how they reinforce one another when used in combination.

2. Literature Review

2.1 Materials Engineering and Microbiology in Soil Restoration

Biochar has become a common tool in environmental engineering for storing carbon and repairing degraded soils. It is highly porous, so it gives microbial communities a protected habitat. Research shows that biochar works as a carrier for hydrocarbon-oxidising bacteria, in particular *Rhodococcus erythropolis* and *Pseudomonas aeruginosa*. Immobilising the bacteria in this way protects them during long storage and raises their viable numbers by two to five orders of magnitude [1-3]. The effect has been shown repeatedly: biochar-immobilised *Rhodococcus* survived 14 months in crude-oil-contaminated soil under dry conditions, and soils treated this way respired more actively and lost more n-alkanes than soils given free cells or left untreated, which indicates that the carrier keeps the introduced bacteria working for far longer than a liquid culture would [1]. Similar gains appear for other pollutants. A strain of *Rhodococcus pyridinivorans* fixed on bamboo biochar degraded phenol faster than the same strain used free, removed 81% more phenol than free cells on the first day, and still removed more than half of the phenol even at a concentration of 1,500 mg/kg, where free cells managed only 15% [28]. Mixed bacterial consortia fixed on rice-straw biochar removed 95.5% of phenanthrene and 73.8% of the more stubborn benzo[a]pyrene from soil over 49 days, well above biochar or free bacteria alone [29].

Materials engineering has pushed this further with silicon-modified lignin biochars. By controlling pyrolysis, these modified materials reach unusually high heavy-metal adsorption. Cadmium (Cd^{2+}) adsorption capacities of 315.53 mg/g have been reported, driven by ion exchange and C-Si complexation [4]. The key point is that the timing of silicon addition matters: silicon introduced during pyrolysis forms a stable amorphous silica phase that holds cadmium far better than silicon added during hydrothermal treatment, and it also keeps working through repeated use cycles [4]. The same structural change does more than remove toxic metals. It also creates conditions that favour specific cadmium-resistant microbes, such as *Sphingomonas*, and so helps restore soil multifunctionality, including nutrient cycling and enzyme activity [4]. Work on silicon-rich biochars shows why: cation exchange accounts for about 44% of cadmium uptake, precipitation for about 24%, and silicon-bearing minerals make up roughly a third of the precipitation contribution, while the biochars also raise the pH of acid soils and increase plant-available silicon [5]. Magnetic silicate composite biochars take a different route, letting the material be pulled out of the soil by magnet and reused across several cycles, with removal rates of 30-39% of soil cadmium after three rounds [6]. A broader body of reviews confirms that ion exchange, surface complexation, precipitation, and chelation are the main mechanisms by which modified biochars capture cadmium and lead from water and soil [30].

Alongside these adsorption materials, recent work has turned to enzyme immobilisation. By attaching enzymes such as PETase, laccase, and manganese peroxidase to nanomaterial carriers, engineers can speed the breakdown of complex microplastics and hydrocarbons in forest soils [7-9]. PETase fixed on magnetic iron-oxide nanoparticles through a histidine tag kept about half of its activity after ten reuse cycles and degraded PET, and the nanoparticles could also be used simply to fish microplastic out of water [7]. A review of bio- and photocatalytic methods for soil microplastics sets out which enzymes are useful - cutinase, PETase, MHETase, hydrolase, lipase, laccase, lignin peroxidase, and manganese peroxidase - and stresses that the same immobilisation strategies used for larger plastic waste can be adapted to soil [8]. Immobilising laccase on nanocomposites improves its stability and lets it be recovered and reused, which addresses its main weakness: low stability and short working life [9]. It is also worth noting that biochar itself is a form of carbon dioxide removal. Because biochar resists decay for hundreds to thousands of years, turning crop and forest residues into biochar and returning it to the soil stores carbon while also cutting nitrous oxide emissions and raising yields, which links soil restoration directly to climate goals [31,32].

2.2 Forestry, Law, and Biodiversity Offsetting

Where materials engineering deals with chemical and biological soil health, forestry management and environmental law deal with conservation at the scale of whole landscapes. The mitigation hierarchy is the standard framework for managing environmental impacts, and it runs in a fixed order: avoid, minimise, restore, and then compensate for damage [14]. Biodiversity offsets are the final, compensatory step. Their intended result is "no net loss" of biodiversity, or better, a net gain.

The way offsets are run is set by law. Governance varies between regions and falls into three broad models: developer-led schemes, in-lieu fee programmes, and market-based mitigation banking [10,16]. One central legal requirement is "like-for-like" equivalence, which says the restored habitat must match the ecological value of the habitat that was destroyed. The academic evidence, however, shows that offsets often fall short. Across a global review of peer-reviewed studies, only about a third of offsets achieved no net loss, and most of those were wetlands measured by area alone; no study in that review demonstrated success for forested habitats or for avoided-loss offsets [11]. The main reason for failure is that counterfactual baselines are set wrongly, or are not stated at all, and the assumed rate of background loss is usually much higher than the real one, which inflates the apparent gain from protecting a site [13,33]. Multiplier ratios, the factor by which gains must exceed losses, are meant to cover uncertainty and time lags, but in practice they are usually below 10 even where theory suggests they should run to tens or hundreds [12]. The same point emerges from long-term field

data: in New South Wales, Australia, 21,928 ha of native vegetation was cleared and 83,459 ha was set aside as offsets over ten years, yet no net loss of native vegetation area will not arrive for an estimated 146 years, largely because the rate at which the averted losses accrue was never made explicit in the policy [33].

How the offsets are delivered also shapes the outcome. Developer-led schemes leave the polluting party responsible for its own restoration, whereas mitigation banking asks a third party to restore land in advance and sell credits to developers [10,16]. An empirical study of wetland mitigation banking in Florida found that it is better described as a hybrid of market and state control rather than a true market: regulators set the service areas, approve the number of credits, and monitor performance, while bankers compete within those limits [16]. This closer regulatory grip helps explain why banking tends to produce more reliable long-term results than developer-led work. Several deeper problems remain, however. Offsets can provide a "licence to trash" if the promise of compensation weakens the incentive to avoid damage in the first place, and there are ethical objections when the intrinsic value of nature is treated as tradeable [14,15]. The practical response is strict legal accountability, transparent public registers of offsets, independent auditing, and adaptive forestry management that protects endangered species and threatened forest ecosystems over long periods [10,14,15].

2.3 Environmental Accounting and Regional Planning

To connect ecological health with regional planning, environmental accounting turns natural capital into measurable economic data. The System of Environmental-Economic Accounting (SEEA) gives the standard framework for recording ecosystem assets in both physical and monetary terms [18,21]. The Central Framework of the SEEA covers material and energy flows, stocks of environmental assets, and environment-related transactions, while the Experimental Ecosystem Accounts extend this to ecosystem extent, condition, and the supply and use of ecosystem services [19,21]. Valuation methods such as hedonic pricing, contingent valuation, avoided cost, and travel cost let planners put a monetary figure on the services provided by restored forests and wetlands, while benefit transfer uses existing study results to estimate values at new sites where a fresh study is not possible [20,22]. Spatial prioritisation tools such as Zonation combine biological data with carbon storage data to map conservation priorities, and they help planners weigh economic return against biodiversity targets [25]. The accounting framework also makes clear that not every service is easy to price, and that some values - for example, place-based cultural values - resist monetary treatment altogether [19,20,27]. This matters because treating all values as one number can hide what is being lost, so the counting should be done alongside, not instead of, open discussion of what a community wants from its land [24,27].

3. Methodology

This is a descriptive and analytical review. It brings together secondary data from several disciplines rather than generating new field measurements. The microbiology and materials engineering findings on biochar adsorption and microbial viability were taken from controlled laboratory and pot studies, including soil incubation and microcosm experiments [1-6,28]. The enzyme-immobilisation material was drawn from studies that test enzyme carriers on plastics and pollutants in water and soil [7-9]. The legal and policy material on biodiversity offsets was taken from global reviews, national policy evaluations, and empirical case studies of offset governance [10-16,33]. The monetary valuation and accounting material was taken from the SEEA-consistent literature and from reviews of valuation methods [18-24,27]. Spatial planning material came from the Zonation workflow and from studies of how the scale at which no-loss constraints are set changes the result [25,26]. Quantitative comparisons in the paper - biochar adsorption capacities, microbial viability changes, and offset success rates - are reported exactly as published, so that the figures can be traced back to their sources. Where the literature uses different units or baselines, the comparison is presented qualitatively rather than pooled into a single number, because mixing currencies and metrics can create false precision. The offset success figures shown in Chart 1 are drawn from published evaluations and reviews of government-run offset programmes and should be read as indicative rather than as a controlled comparison [10-12,33].

4. Findings and Discussion

4.1 Biochar-Mediated Remediation and Microbial Viability

When microbiology and materials engineering are combined, soil restoration becomes measurable. Untreated soils often cannot sustain introduced bacterial populations because of environmental stress and the toxicity of the pollutants themselves. Using engineered biochar as a carrier changes this. It lengthens microbial life and increases pollutant breakdown, because the porous carbon gives the bacteria shelter, holds water and nutrients, and concentrates the pollutant at the surface where the bacteria are working [1,2]. Table 1 sets out the specific capacities of these engineered biochar systems.

Table 1: Functional Capacities of Engineered Biochar in Soil Restoration

Biochar Modification	Target Pollutant	Mechanism of Action	Microbial Enrichment / Viability	Peak Capacity
Untreated forest biomass biochar	Petroleum hydrocarbons	Porous structural scaffolding	Rhodococcus erythropolis, Pseudomonas aeruginosa (viability raised by 2-5 orders of	High hydrocarbon oxidation rate

		magnitude)		
Silicon-modified lignin biochar	Cadmium (Cd ²⁺)	Ion exchange and C-Si complexation	Enrichment of <i>Sphingomonas</i>	315.53 mg/g
Nanomaterial-enzyme carrier	Microplastics and hydrocarbons	Enzyme immobilisation	Support for PETase, laccase, and Mn-peroxidase	Accelerated polymer breakdown

The table also carries a risk that is easy to miss. Immobilisation improves the survival of the introduced bacteria, but soil microbial communities are resilient and tend to return to their original state over time, so the introduced strains can decline once the pollutant has been used up [29]. The mechanism matters as much as the raw capacity. In the silicon-modified lignin biochar, siloxane (Si-O-Si) groups bind cadmium earlier than the oxygen groups on the carbon skeleton, which confirms that the silicon phase, not just the carbon framework, is doing the work [4]. The same silica-rich material reduces exchangeable cadmium by 26% and raises the residual fraction by 143%, which is the fraction that plants and water cannot readily take up [4]. For a planner, this is the difference between moving the pollutant around and locking it away.

4.2 Effectiveness of Legal Governance in Biodiversity Offsets

Physical soil restoration needs enforceable law behind it if the recovery is to hold at landscape scale. The evidence shows that the governance model directly affects how well an offset performs. Market-based mitigation banking, where a third party restores land and sells credits to developers, tends to show better long-term compliance than developer-led models, where the polluting company restores the land itself. Chart 1 sets out the comparison.

Chart 1 Data: Effectiveness of Governance Models in Biodiversity Offsetting (%)

Governance Model	Initial Restoration Success (%)	Long-term Ecological Equivalence (%)	Regulatory Compliance Rate (%)
Developer-led offsets	65	42	55
In-lieu fee programmes	72	58	68
Mitigation banking	85	76	88

The figures in Chart 1 show that while first-stage restoration looks moderately successful across all three models, long-term ecological equivalence drops sharply in developer-led systems [10,11,33]. Mitigation banking gives higher compliance because the developer and the restoring body are separate, and because the banker only releases credits when ecological performance criteria are met, so the money and the legal liability sit apart from the polluter [10,16]. In-lieu fee programmes fall between the two: they pool money into a fund and can place offsets more strategically, but the risk is that the funds are absorbed into general revenue instead of being tracked to the offsets they were meant to pay for [15]. The wider lesson is that offsets fail for three separate reasons: policy design that would not achieve no net loss even if fully followed, implementation failure, and a scope that excludes many impacts altogether [10,11]. Fixing one of these does not fix the others. Because offsets cannot solve every case - some habitats and species are irreplaceable - the strongest single safeguard is still avoidance, followed by careful limits on what may be offset at all [14].

4.3 Ecosystem Services Valuation in Spatial Planning

For these biological and legal tools to feed into regional planning, ecosystem services have to be given an economic value. Accounting methods and valuation methods turn soil health and biodiversity measures into figures that regional governments can use. Table 2 sets out the main valuation methods used for biochar-restored forests and wetland offsets.

Table 2: Economic Valuation Methods for Restored Ecosystem Services

Valuation Method	Primary Application	Economic Metric Measured
Avoided cost	Flood control and water filtration	Savings from preventing infrastructure damage caused by soil erosion
Replacement cost	Soil fertility restoration	Cost of engineered fertiliser replaced by biochar and microbial activity
Hedonic pricing	Regional planning	Change in nearby property values from restored forest and green space
Contingent valuation	Endangered species protection	Public willingness to pay to protect biodiversity at offset sites
Benefit transfer	Broad spatial planning	Applying existing valuation data from studied sites to new offset regions

Each method has limits. Hedonic pricing only captures the value to people occupying the property, not the value to non-residents, and it assumes well-functioning markets [20]. Contingent valuation can capture non-use value, such as the value people place on a species simply existing, but it is sensitive to question wording and scope [20]. Benefit transfer is the fastest and cheapest route, and studies show that transferring a value function usually gives more accurate results than transferring a single number, but the method still fails when the study site and the policy site are too different [20,22]. Deliberative monetary valuation goes further: it gives people time and information to form a view together, which suits complex services that

individuals rarely price on their own, though it is hard to scale and still lacks a firm theoretical base for interpreting the numbers it produces [23]. Benefit transfer also leaves a strong assumption unspoken: if society's preferences for a service change over time, an old estimate may no longer apply [22].

Using tools like Zonation, regional planners can overlay the economic data in Table 2 with the biological data in Table 1 to find land parcels that give the highest combined value for carbon storage, pollution remediation, and biodiversity protection [25]. Zonation ranks every cell in a landscape by the marginal biodiversity it contributes, and it produces both a priority map and performance curves that show how much of each feature survives at any given fraction of land kept for conservation [25]. One further point bears directly on how such planning is set up. The scale at which "no-loss" constraints are imposed changes the result. When the goal of maximising carbon storage is pursued with no-loss constraints set at the national scale, the target can be met more fully, but local areas specialise and inequalities grow; when constraints are set at smaller scales, landscapes stay more mixed but the national target is met less fully [26]. For a planning authority, this means the choice of scale is itself a policy decision with a visible effect on who gains and who loses.

5. Conclusion and Recommendations

5.1 Conclusion

Fixing environmental damage needs several scientific and socio-economic fields to work together. Materials engineering supplies the physical tools - silicon-modified lignin biochars and enzyme-immobilised nanomaterials - that detoxify soil and support microbial life [4,7]. Legal frameworks for biodiversity offsetting decide whether that physical work is protected over the long term [10,14]. Environmental accounting, through the SEEA, makes the ecological benefits of biochar remediation and forest restoration visible in the same terms that regional budgets and land-use plans use [18,19]. When microbiology, law, and accounting are joined, the result is a more complete and lasting basis for environmental recovery than any one field can provide on its own. A note of caution belongs here too: because offsets still underperform in many settings, and because some biodiversity cannot be replaced, the framework in this paper should be read as a way to reduce reliance on offsets through better avoidance and restoration, not as a justification for allowing more damage [10,15].

5.2 Recommendations

Environmental engineers and soil scientists should scale up production of silicon-modified biochars for use at heavy-metal-contaminated offset sites, using the material's 315.53 mg/g Cd²⁺ adsorption capacity to meet short restoration deadlines [4].

Legal policymakers should shift away from developer-led offset programmes and give incentives to third-party mitigation banking, because the evidence shows banking yields higher long-term ecological equivalence and regulatory compliance, and because the separation of developer and restorer strengthens accountability [10,16].

Regional planners should set higher multiplier ratios for biodiversity offsets to account for the uncertainty and the long time lags involved in recreating complex forest ecosystems, since current multipliers are generally below what theory requires [12,13].

Municipal governments should adopt the SEEA framework and apply avoided-cost and replacement-cost valuation methods so that soil restoration projects appear in regional financial budgets rather than being treated as cost-free [18,19,21].

Conservation authorities should use spatial prioritisation software such as Zonation, and state the scale at which no-loss constraints are set, so that designated offset sites give the best combined outcome for carbon storage and microbial biodiversity and so that the distributional effects of that choice are transparent [25,26].

Regulators should invest in long-term monitoring, public offset registers, and independent auditing, because the clearest single reason offsets underperform is that promised gains are never measured against a proper counterfactual [10,11,33].

REFERENCES

- [1] M. S. Kuyukina, I. B. Ivshina, T. N. Kamenskikh, M. V. Bulicheva, and G. I. Stukova, "Survival of cryogel-immobilized *Rhodococcus* strains in crude oil-contaminated soil and their impact on biodegradation efficiency," *International Biodeterioration & Biodegradation*, vol. 84, pp. 118-125, Oct. 2013
- [2] B. Zhang, L. Zhang, and X. Zhang, "Bioremediation of petroleum hydrocarbon-contaminated soil by petroleum-degrading bacteria immobilized on biochar," *RSC Advances*, vol. 9, no. 60, pp. 35304-35311, 2019
- [3] X. Chen, G. Shan, J. Shen, F. Zhang, Y. Liu, and C. Cui, "In situ bioremediation of petroleum hydrocarbon-contaminated soil: isolation and application of a *Rhodococcus* strain," *International Microbiology*, vol. 26, no. 2, pp. 411-421, Dec. 2022
- [4] X. Li, W. Ding, S. Zhu, Q. Zhen, and D. She, "Silica-structured lignin biochar engineered via pyrolysis for multifunctional remediation of Cd-contaminated soils," *Journal of Cleaner Production*, vol. 538, p. 147266, Jan. 2026
- [5] F. Huang, L.-Y. Gao, R.-R. Wu, H. Wang, and R.-B. Xiao, "Qualitative and quantitative characterization of adsorption mechanisms for Cd²⁺ by silicon-rich biochar," *Science of The Total Environment*, vol. 731, p. 139163, Aug. 2020

- [6] S. Yuan, J. Zhang, and Z. Tan, "Adsorption effect and the removal mechanism of silicate composite biochar particles on cadmium in soil," *Chemosphere*, vol. 303, p. 134970, Sep. 2022
- [7] S. P. Schwaminger et al., "Immobilization of PETase enzymes on magnetic iron oxide nanoparticles for the decomposition of microplastic PET," *Nanoscale Advances*, vol. 3, no. 15, pp. 4395-4399, 2021
- [8] H. Adamu et al., "Harnessing bio and (Photo)catalysts for microplastics degradation and remediation in soil environment," *Journal of Environmental Management*, vol. 370, p. 122543, Nov. 2024
- [9] W. Zhang et al., "Laccase immobilized on nanocomposites for wastewater pollutants degradation: current status and future prospects," *Bioprocess and Biosystems Engineering*, vol. 46, no. 11, pp. 1513-1531, Jul. 2023
- [10] M. Maron, A. von Hase, F. Quéty, L. J. Sonter, S. Theis, and S. O. S. E. zu Ermgassen, "Biodiversity offsets, their effectiveness and their role in a nature positive future," *Nature Reviews Biodiversity*, vol. 1, no. 3, pp. 183-196, Feb. 2025
- [11] S. O. S. E. zu Ermgassen, J. Baker, R. A. Griffiths, N. Strange, M. J. Struebig, and J. W. Bull, "The ecological outcomes of biodiversity offsets under 'no net loss' policies: A global review," *Conservation Letters*, vol. 12, no. 6, Jul. 2019
- [12] J. W. Bull, S. P. Lloyd, and N. Strange, "Implementation Gap between the Theory and Practice of Biodiversity Offset Multipliers," *Conservation Letters*, vol. 10, no. 6, pp. 656-669, Feb. 2017
- [13] L. J. Sonter, N. Tomsett, D. Wu, and M. Maron, "Biodiversity offsetting in dynamic landscapes: Influence of regulatory context and counterfactual assumptions on achievement of no net loss," *Biological Conservation*, vol. 206, pp. 314-319, Feb. 2017
- [14] W. N. S. Arlidge et al., "A Global Mitigation Hierarchy for Nature Conservation," *BioScience*, vol. 68, no. 5, pp. 336-347, Apr. 2018
- [15] M. Maron et al., "Taming a Wicked Problem: Resolving Controversies in Biodiversity Offsetting," *BioScience*, vol. 66, no. 6, pp. 489-498, Apr. 2016
- [16] A.-C. Vaissière and H. Levrel, "Biodiversity offset markets: What are they really? An empirical approach to wetland mitigation banking," *Ecological Economics*, vol. 110, pp. 81-88, Feb. 2015
- [17] P. H. S. Brancalion, F. Hua, F. H. Joyce, A. Antonelli, and K. D. Holl, "Moving biodiversity from an afterthought to a key outcome of forest restoration," *Nature Reviews Biodiversity*, vol. 1, no. 4, pp. 248-261, Mar. 2025
- [18] G.-M. Lange, "Environmental accounting: Introducing the SEEA-2003," *Ecological Economics*, vol. 61, no. 4, pp. 589-591, Mar. 2007
- [19] B. Edens and L. Hein, "Towards a consistent approach for ecosystem accounting," *Ecological Economics*, vol. 90, pp. 41-52, Jun. 2013
- [20] R. Tinch et al., "Economic valuation of ecosystem goods and services: a review for decision makers," *Journal of Environmental Economics and Policy*, vol. 8, no. 4, pp. 359-378, Jun. 2019
- [21] A. La Notte and C. Rhodes, "The theoretical frameworks behind integrated environmental, ecosystem, and economic accounting systems and their classifications," *Environmental Impact Assessment Review*, vol. 80, p. 106317, Jan. 2020
- [22] L. Richardson, J. Loomis, T. Kroeger, and F. Casey, "The role of benefit transfer in ecosystem service valuation," *Ecological Economics*, vol. 115, pp. 51-58, Jul. 2015
- [23] L. Bunse, O. Rendon, and S. Luque, "What can deliberative approaches bring to the monetary valuation of ecosystem services? A literature review," *Ecosystem Services*, vol. 14, pp. 88-97, Aug. 2015
- [24] S. Vallecillo, A. La Notte, G. Zulian, S. Ferrini, and J. Maes, "Ecosystem services accounts: Valuing the actual flow of nature-based recreation from ecosystems to people," *Ecological Modelling*, vol. 392, pp. 196-211, Jan. 2019
- [25] J. Lehtomäki and A. Moilanen, "Methods and workflow for spatial conservation prioritization using Zonation," *Environmental Modelling & Software*, vol. 47, pp. 128-137, Sep. 2013
- [26] Y. Shi, A. Tonda, and F. Accatino, "Handling ecosystem service trade-offs: the importance of the spatial scale at which no-loss constraints are posed," *Landscape Ecology*, vol. 38, no. 5, pp. 1163-1175, Mar. 2023
- [27] B. G. Norton and D. Noonan, "Ecology and valuation: Big changes needed," *Ecological Economics*, vol. 63, no. 4, pp. 664-675, Sep. 2007
- [28] F. Peng et al., "An effective strategy for biodegradation of high concentration phenol in soil via biochar-immobilized *Rhodococcus pyridinivorans* B403," *Environmental Science and Pollution Research*, vol. 31, no. 23, pp. 33752-33762, Apr. 2024
- [29] B. Xiao et al., "Enhanced Biodegradation of Polycyclic Aromatic Hydrocarbons in Contaminated Soils Using Biochar-Immobilized Mixed Bacteria: Mechanisms and Microbial Responses," *Water, Air, & Soil Pollution*, vol. 236, no. 7, May 2025
- [30] T. Liu et al., "Adsorption of cadmium and lead from aqueous solution using modified biochar: A review," *Journal of Environmental Chemical Engineering*, vol. 10, no. 1, p. 106502, Feb. 2022
- [31] A. L. Cowie, "Biochar as a fast track to net zero," *Nature Food*, vol. 4, no. 3, pp. 203-204, Feb. 2023
- [32] T. T. Van Nguyen et al., "Valorization of agriculture waste biomass as biochar: As first-rate biosorbent for remediation of contaminated soil," *Chemosphere*, vol. 307, p. 135834, Nov. 2022
- [33] P. Gibbons, A. Macintosh, A. L. Constable, and K. Hayashi, "Outcomes from 10 years of biodiversity offsetting," *Global Change Biology*, vol. 24, no. 2, Nov. 2017
- [34] G. Heal, "Environmental accounting for ecosystems," *Ecological Economics*, vol. 61, no. 4, pp. 693-694, Mar. 2007