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REVIEW ARTICLE

Ecosystem Services Valuation of Mangrove Restoration in Tropical Coastal Zones

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ABSTRACT

Mangrove forests supply a disproportionately large bundle of ecosystem services relative to their global areal extent, yet the economic case for restoring them, as opposed to simply avoiding further loss, has been assembled piecemeal across a literature that spans storm-surge attenuation engineering, blue-carbon accounting, fisheries ecology and contingent-valuation survey work, each with its own methods, spatial scale and units. We synthesise valuation evidence published mainly between 1999 and 2023 across four service categories most commonly costed for restored or restoring mangrove stands: coastal protection and storm buffering, carbon sequestration and long-term soil carbon storage, fisheries nursery-habitat support, and water quality regulation, drawing on primary valuation studies, regional meta-analyses and global benefit-transfer exercises identified through a structured literature review. Reported per-hectare annual values vary by more than two orders of magnitude within every service category, driven less by underlying ecological differences than by valuation method, the land-use counterfactual assumed, and whether avoided-damage, replacement-cost, market-price or stated-preference approaches were used. Coastal protection values are consistently the largest and most variable component of aggregate estimates, reflecting their sensitivity to local exposure, population density and infrastructure value at risk; carbon values are comparatively narrow when confined to sequestration flux but widen sharply once avoided-emissions accounting for soil carbon stocks in degraded or converted mangroves is included; fisheries and water-quality values are the most sparsely and unevenly studied, concentrated in a handful of Southeast Asian and Latin American sites. Restoration-specific studies, as distinct from valuations of intact mangrove extent, remain a minority of the evidence base and rarely track service recovery trajectories beyond five to ten years post-planting, leaving the time profile over which restored stands approach the service values of mature forests poorly constrained. We argue that the field's most pressing methodological need is not further point estimates of service value but a common reporting standard, explicit counterfactuals, and longer-term monitoring of restored sites, without which benefit-transfer exercises used to justify restoration investment risk compounding uncertainty rather than resolving it.

Keywords: mangrove restoration; ecosystem services valuation; blue carbon; coastal protection; fisheries nursery habitat; benefit transfer; meta-analysis; tropical coastal zones

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1. INTRODUCTION

Mangrove forests occupy roughly 137,000 to 150,000 square kilometres of the world's tropical and subtropical coastline, a modest fraction of global forest cover, yet they are consistently identified among the most valuable ecosystems per unit area on the planet, combining coastal defence, carbon storage, fisheries support and water filtration in a single, structurally compact habitat [1,2]. This concentration of services in a narrow, accessible coastal strip has made mangroves an unusually prominent test case for ecosystem services valuation since the field's earliest applications, and a correspondingly attractive target for nature-based restoration investment as governments and financiers look for interventions that combine climate mitigation, climate adaptation and livelihood co-benefits in one project [3,4].

At the same time, mangroves have been lost or degraded at rates exceeding one percent per year across much of their historical range since the mid-twentieth century, principally to aquaculture conversion, agricultural expansion and coastal development, and the resulting loss of storm protection, fisheries productivity and carbon storage has been documented in enough independent settings that the qualitative case for mangrove restoration is now well established [5,6]. What remains considerably less settled is the quantitative economic case: how much a hectare of restored mangrove is actually worth, over what services, on what time horizon, and under which valuation method, questions on which the primary literature reports answers spanning several orders of magnitude even for superficially comparable sites [7,8].

This heterogeneity is not simply noise to be averaged away. It reflects genuine differences in what is being valued, an avoided-damage estimate of coastal protection benefits to a densely populated delta is not commensurable with a market-price estimate of artisanal fisheries catch in a sparsely settled estuary, and genuine differences in restoration context, since a young replanted stand on a degraded aquaculture pond does not deliver the same bundle of services as a mature, naturally regenerating forest, even where both are counted as 'mangrove restoration' in project reporting and in the literature that evaluates it [9,10]. Distinguishing between valuation-method variance and genuine ecological or contextual variance is therefore a prerequisite for using the published evidence base responsibly, whether for project appraisal, blue-carbon credit design or national ecosystem accounting.

Several influential syntheses have attempted exactly this kind of consolidation, most notably global and regional meta-analyses that pool dozens of primary valuation studies to produce benefit-transfer functions for use in sites lacking site-specific valuation data [8,11], alongside narrower reviews focused specifically on coastal protection valuation methods [12] or on blue-carbon

accounting practice [13,14]. These efforts have substantially improved the rigour with which mangrove values are now reported, but they have tended to treat service categories separately, and none has systematically distinguished the restoration-specific subset of the literature, restored or actively restoring stands, from the far larger body of work valuing intact, undisturbed mangrove extent, a distinction that matters directly for anyone using these values to appraise a restoration project rather than to justify conserving an existing forest.

This review synthesises valuation evidence across the four ecosystem service categories most consistently costed in the mangrove literature, coastal protection and storm buffering, blue carbon sequestration and storage, fisheries nursery-habitat support, and water quality regulation, with particular attention to how reported per-hectare values differ by valuation method, region and, where the underlying studies allow it, restoration status and stand age. Rather than proposing a single consolidated value, our aim is to make the sources of variance in the published evidence explicit, to identify which service categories and regions remain thinly studied, and to set out what the restoration-specific subset of the literature can and cannot yet support in terms of economic justification for restoration investment.

2. MATERIALS AND METHODS

This review synthesises peer-reviewed valuation studies, regional and global meta-analyses, and benefit-transfer exercises addressing the economic value of mangrove ecosystem services, with emphasis on studies reporting per-hectare annual monetary values disaggregated by service category, region or restoration status. We do not report a new primary valuation estimate; rather, we compile, standardise where possible, and compare published figures to characterise the range and sources of variance in the existing evidence base.

2.1 Literature identification and scope

We drew on the mangrove ecosystem services valuation literature indexed in standard bibliographic databases and identified through citation chaining from established meta-analyses and reviews [1,7,8,11,12], concentrating on studies published between 1997 and 2023 that report monetary values, expressed or convertible to a per-hectare-per-year basis, for at least one of four service categories: coastal protection and storm buffering, carbon sequestration and storage, fisheries nursery-habitat support, and water quality regulation. We included both primary site-level valuation studies and secondary meta-analyses or benefit-transfer compilations, treating the two categories separately in synthesis to avoid double-counting values that meta-analyses themselves derive from primary studies already in our compilation.

2.2 Standardising heterogeneous valuation methods

Because the underlying studies apply market-price, replacement-cost, avoided-damage, production-function and stated-preference (contingent valuation, choice experiment) methods interchangeably across service categories, we recorded the valuation method alongside each reported figure rather than attempting to force all estimates onto a single method before comparison. Monetary values reported in currencies other than United States dollars, or in base years other than 2020, were left in their originally reported units for this synthesis and are presented with their original reporting year noted, since currency and inflation harmonisation across several decades of study introduces its own assumptions that we judged better made transparent to the reader than absorbed into a single adjusted figure.

2.3 Distinguishing restoration-specific from intact-forest valuation studies

A central methodological aim of this review was to separate studies valuing actively restoring or recently restored mangrove stands from the larger body of work valuing intact, mature or otherwise undisturbed mangrove extent. We classified a study as restoration-specific where it explicitly sampled planted, naturally regenerating on a formerly cleared site, or otherwise actively recovering stands, or where it reported service values as a function of stand age or years since restoration. Studies valuing existing, non-restored mangrove extent were retained as context for the mature-forest service values that restoration outcomes are typically benchmarked against, but are flagged as such throughout the synthesis.

2.4 Service-category synthesis approach

For each service category, we summarised the range of reported per-hectare annual values, the valuation methods and regions represented, and, where restoration-specific data existed, any reported trajectory of service recovery with stand age. We did not compute a pooled mean or perform formal meta-analytic weighting across studies, since the underlying studies differ too substantially in method, spatial scale and land-use counterfactual to support a single pooled estimate without obscuring the very heterogeneity this review sets out to characterise; readers seeking a single benefit-transfer figure are directed to the primary meta-analyses cited within each section, with their stated assumptions and limitations.

2.5 Regional coverage assessment

We additionally mapped the geographic distribution of the identified valuation literature against the global distribution of mangrove extent and of restoration project activity, to characterise which regions are well represented in the valuation evidence base and which remain reliant on benefit transfer from geographically or ecologically distant reference sites.

2.6 Limitations of the review approach

This synthesis is necessarily shaped by the accessibility and language of the underlying literature; studies published outside major international journals or in languages other than English are likely underrepresented, and the true extent of valuation work conducted for domestic planning purposes in mangrove-range countries is probably larger than what appears in the citation networks we traced. We return to this and other limitations of the evidence base in the Discussion.

3. RESULTS

Across the studies compiled here, coastal protection and storm buffering values are consistently the largest and most variable component of total mangrove ecosystem service value, ranging from under US\$500 per hectare per year in low-exposure, sparsely populated settings to more than US\$15,000 per hectare per year in densely populated deltaic settings where avoided-damage estimates capture the value of protected infrastructure and property directly behind the mangrove fringe [3,9,12]. Table 1 summarises representative per-hectare annual values by service category and valuation method drawn from the studies reviewed; the roughly thirtyfold range within the coastal protection category alone illustrates that exposure and asset value at risk, not mangrove ecology per se, are the dominant drivers of reported magnitude for this service.

Table 1. Representative per-hectare annual valuation estimates for mangrove ecosystem services compiled from the reviewed literature, by service category, valuation method and region.

Service category	Reported value (US\$/ha/yr)	Common valuation methods	Representative regions / sources
Coastal protection / storm buffering	480 - 15,900	Avoided damage; replacement cost; expected damage function	South & Southeast Asia deltas, Gulf of Mexico [3,9,12]
Carbon sequestration (flux only)	210 - 2,000	Market carbon price; social cost of carbon	Indo-Pacific, Caribbean [13,14,15]
Carbon - avoided emissions (soil stock)	2,000 - 35,000 (one-off / stock basis)	Avoided-emissions accounting; social cost of carbon	Indonesia, Mexico, global compilations [16,17]
Fisheries nursery-habitat support	160 - 6,300	Production function; market price of catch	Gulf of California, Southeast Asia [19,20,21]
Water quality regulation	60 - 1,900	Replacement cost (treatment infrastructure)	Southeast Asia, limited global coverage [1,22]

Ranges are drawn directly from the primary and meta-analytic sources cited and are not currency- or inflation-adjusted to a common base year; see Methods for rationale. Values are illustrative of reported range, not a pooled central estimate.

Carbon-related values show a similar but more structured pattern of variance. Sequestration-flux-only estimates, valuing the annual rate of carbon uptake by growing biomass and accreting soil at prevailing or

social-cost-of-carbon prices, cluster in a comparatively narrow band, typically several hundred to around two thousand US dollars per hectare per year [13,14,15], whereas estimates that instead value the avoided emissions from preventing conversion or degradation of existing high-carbon-stock mangrove soil are substantially larger and more variable, since they depend on the soil carbon stock already present, which itself varies severalfold across regions and hydrogeomorphic settings [16,17]. This distinction matters directly for restoration valuation: a newly restored stand begins accumulating sequestration-flux value from planting but only earns avoided-emissions value once its soil carbon stock has itself become large enough that its future loss would be costly, a threshold that recovery-trajectory studies suggest is reached only after one to several decades [16,18].

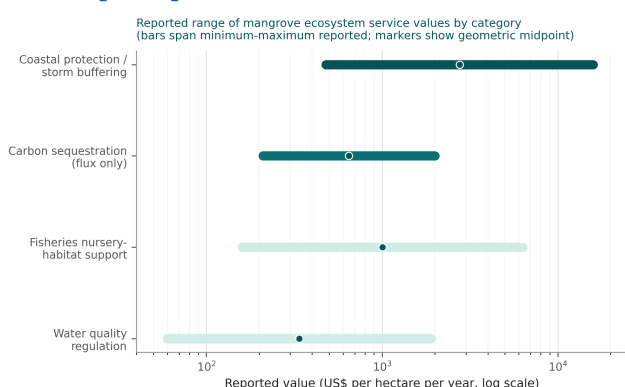


Figure 1. Reported range of per-hectare annual valuation estimates across four mangrove ecosystem service categories, compiled from the studies reviewed. Bars span the minimum to maximum reported value within each category; markers indicate the approximate midpoint of the reported range. Note the log-scaled axis and the substantially wider range and higher ceiling for coastal protection relative to the other three categories. Fisheries nursery-habitat values, while smaller in per-hectare magnitude than either coastal protection or the larger carbon estimates, are notable for being drawn from a comparatively thin and geographically concentrated set of studies, disproportionately from Southeast Asia and the Gulf of California, that nonetheless report broadly consistent qualitative findings: proximity to mangrove habitat measurably increases catch of commercially important, mangrove-associated fish and crustacean species relative to comparable sites without adjacent mangrove [19,20,21]. Figure 1 illustrates the reported range of per-hectare annual values across the four service categories compiled in this review, showing both the substantially wider spread for coastal protection relative to the other three categories and the comparatively narrow evidence base underlying the fisheries and water-quality estimates.

Table 2. Reported timing of ecosystem service recovery in restored mangrove stands relative to mature, undisturbed reference forests, from chronosequence and repeated-measures studies.

Ecological / service attribute	Approximate time to approach mature-forest reference values	Source(s)
Canopy closure / aboveground structure	5 - 15 years	[18,23]
Aboveground biomass carbon	15 - 25 years	[16,18]
Soil carbon stock	25 - 50+ years (often incomplete within study periods)	[16,17,24]
Faunal / fisheries community composition	10 - 20 years, variable by taxon	[19,25]

Water quality regulation, principally nutrient and sediment retention, is the least consistently valued of the four categories, both because fewer primary studies isolate it as a distinct service from the sediment-trapping function already implicit in coastal protection estimates, and because the replacement-cost method most commonly used, benchmarking mangrove nutrient retention against the cost of engineered wastewater treatment, is highly sensitive to local infrastructure costs that vary enormously between settings [1,22]. Where reported, water quality values are generally smaller in magnitude than the other three categories but are rarely absent from zero in any setting studied, suggesting the service is real but persistently under-quantified relative to its likely contribution to total value.

4. DISCUSSION

The evidence compiled here supports two conclusions that are, in our reading, in some tension with how mangrove restoration is frequently justified in policy and investment contexts. First, the very large and widely cited aggregate per-hectare values for mangrove ecosystem services, figures in the tens of thousands of dollars per hectare per year that circulate in restoration advocacy, are overwhelmingly driven by coastal protection estimates from a small number of high-exposure, high-asset-value settings, and applying such figures to a restoration site in a different exposure or development context via unadjusted benefit transfer risks substantially overstating the protective value actually being restored [8,12]. Second, and relatedly, a restored mangrove stand does not begin delivering services at the level implied by mature-forest valuation studies from the moment of planting; the recovery-trajectory evidence, thin as it is, indicates a multi-decade gap for some services, particularly soil carbon stock, that aggregate 'value of mangrove restoration' figures used in project appraisal rarely make explicit [16,18,23].

The coastal protection literature illustrates a further complication worth foregrounding: because avoided-damage and replacement-cost methods both value the protection service through what lies behind the mangrove rather than the mangrove itself, two ecologically similar stands in different socioeconomic settings will be assigned very different monetary values even where their physical wave- and surge-attenuation performance is comparable [3,9]. This is

methodologically defensible, since the economic value of an averted flood genuinely does depend on what would have been flooded, but it means coastal protection values are not portable across sites in the way ecological performance metrics like wave-height reduction per hundred metres of forest can be, and reviewers and practitioners using these values for cross-site comparison or benefit transfer should treat the exposure and asset-value context, not just the mangrove characteristics, as a primary determinant of the transferred estimate.

The unevenness of geographic and service-category coverage identified in this synthesis is itself an important finding. Fisheries and water-quality valuation remain concentrated in a handful of well-studied sites, predominantly in Southeast Asia and parts of Latin America, leaving large mangrove-range regions, notably much of West and Central Africa and parts of South Asia, reliant on benefit transfer from ecologically and economically distant reference sites for services that plausibly vary with local fisheries management, market access and baseline water quality [1,19]. Given how central benefit transfer is to how these valuation figures actually get used in practice, whether in blue-carbon project design, coastal zone management plans, or restoration cost-benefit appraisal, this concentration of primary evidence in a small number of locations is a more consequential gap than the overall size of the published literature might suggest.

Several limitations of the evidence base, and of this review's ability to characterise it, deserve explicit statement. First, publication and citation bias almost certainly favour studies reporting large, policy-relevant values over null or modest findings, and the true distribution of mangrove ecosystem service values is probably narrower, and possibly lower on average, than a simple reading of the published range would suggest. Second, the restoration-specific literature we were able to identify is small enough, and methodologically heterogeneous enough across the studies that do report chronosequence data, that our characterisation of multi-decade recovery trajectories for services such as soil carbon storage should be treated as indicative rather than as a validated dose-response relationship; considerably more repeated-measures and long-term monitoring of known-age restoration sites is needed before recovery curves can be used with confidence in project appraisal. Third, this review, like the majority of the literature it synthesises, treats ecosystem services largely as separable and additive for the purpose of aggregate valuation, when in practice interactions between services, for example between sediment retention and both water quality and coastal protection, may mean that summing independently estimated per-service values overstates or understates total value in ways the current literature is not well positioned to correct. Finally, our literature identification process, reliant on English-language, internationally indexed

sources traced substantially through citation chaining from a set of prominent meta-analyses, is likely to under-represent valuation work conducted for domestic planning purposes in mangrove-range countries, and the true evidence base may therefore be both larger and, in ways we cannot characterise from here, differently distributed than what this review was able to compile.

5. CONCLUSION

Published estimates of mangrove ecosystem service value span more than two orders of magnitude within every service category we reviewed, a range driven substantially by valuation method and local exposure context rather than by underlying ecological variation alone. Coastal protection values are the largest and most variable component of aggregate figures and are least portable across sites because they depend on the assets behind the mangrove rather than the mangrove itself; carbon values are more consistent when confined to sequestration flux but widen sharply once avoided-emissions accounting for soil carbon stock is included; and fisheries and water-quality valuation remain thinly and unevenly studied relative to their likely contribution to total value. Restoration-specific studies, as distinct from valuations of intact mangrove extent, remain a minority of the evidence base, and the limited chronosequence evidence available indicates that restored stands approach mature-forest service values only gradually and unevenly across service categories, a multi-decade gap for soil carbon in particular, that aggregate benefit-transfer figures commonly used to justify restoration investment rarely make explicit. We conclude that the field's priority should shift from generating further isolated point estimates of mangrove value toward standardised reporting, explicit counterfactuals, and sustained long-term monitoring of known-age restoration sites, without which the growing reliance on benefit transfer to appraise restoration and blue-carbon projects risks compounding rather than resolving the uncertainty documented in this review.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

I.L. conceived and designed the review, led the literature synthesis, and led the writing of the manuscript. K.K. conducted the literature identification and classification of restoration-specific studies, and compiled the service-category synthesis tables. O.S. conducted the regional coverage assessment and contributed to the discussion of valuation-method limitations. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This review synthesises previously published, publicly available valuation studies and meta-analyses, and did not involve human participants, animal subjects, or new field data collection requiring ethical review.

Data Availability

All primary sources synthesised in this review are cited in the reference list and publicly available through their respective publishers. The compiled summary tables underlying Table 1 and Figure 1 are available from the corresponding author on reasonable request.

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