International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 12; Issue: 12; December 2025
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Review Paper

# Toward Regenerative Coastal Seascapes: Integrating Blue Carbon, Restoration Ecology, and Spatial Planning Across Marine and Coastal Ecosystems

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**DOI: https://doi.org/10.52403/ijrr.20251245**

## ABSTRACT

Coastal and marine ecosystems mangroves, tidal marshes, seagrasses, oyster reefs, coral reefs, kelp forests and sandy shores are central to climate mitigation, biodiversity conservation and coastal protection, yet they are rapidly degrading under the combined pressures of climate change, sea-level rise, pollution and unsustainable development. Recent advances in blue carbon science, restoration ecology, seascape ecology and marine spatial planning (MSP) offer new opportunities to regenerate these systems and upscale restoration in line with global targets such as the Kunming Montreal Global Biodiversity Framework. Building on earlier syntheses of coastal restoration and blue carbon, this review integrates recent literature spanning ecosystem-specific restoration experiments, decision-support tools, legal and governance innovations, and bibliometric analyses of blue carbon and sea-level rise research. We first summarise how ecological theory and empirical evidence have refined understanding of restoration feasibility, co-benefits and trade-offs across vegetated blue carbon ecosystems and biogenic reefs. We then examine emerging spatial planning and modelling tools, including Marxan based approaches, connectivity analyses, environmental niche and habitat suitability models, and multi-criteria GIS frameworks for identifying resilient restoration sites and prioritising interventions. A third theme explores the social, legal and governance dimensions of upscaling marine and coastal restoration, highlighting the roles of social data, participatory mapping, rights, tenure and risk allocation. Finally, we synthesise cross cutting knowledge gaps and propose a research agenda centred on system wide carbon accounting, social ecological integration, and climate-resilient restoration pathways. By consolidating multi-disciplinary evidence, this review aims to support more strategic, just and climate-smart restoration of coastal seascapes and to inform science, policy and practice at landscape and seascape scales.

***Keywords:*** Blue carbon restoration, Coastal and marine ecosystems, Marine spatial planning, Seascape ecology and connectivity, Climate change and sea-level rise, Ecosystem services and co-benefits, Nature-based coastal protection

## INTRODUCTION

Coastal and marine ecosystems deliver disproportionate benefits relative to their area, including carbon sequestration, nursery habitat, shoreline stabilisation, nutrient retention and cultural values (Jones et al., 2024; Arkema et al., 2024; McHenry et al., 2023; Sievers et al., 2023). Yet they are simultaneously among the most threatened ecosystems on Earth, facing accelerating sea-level rise, warming, ocean acidification, eutrophication and habitat conversion (Khojasteh et al., 2023; Velázquez-Ochoa & Enríquez, 2023; He et al., 2025). In response, coastal and marine ecological restoration has moved from a niche activity to a central pillar of global climate and biodiversity agendas, particularly through the concept of blue carbon (Hagger et al., 2024; Lester, 2023; Yin et al., 2023; Wang et al., 2024).

Historically, restoration science and practice were often ecosystem-specific and site-focused seagrass planting, oyster reef construction, marsh re-flooding implemented largely independently of broader spatial planning, governance reform and social context (Hart et al., 2024; Zakaria et al., 2025). Recent literature emphasises that successful, scalable restoration must be embedded within seascape ecology, MSP, and integrative socio-legal frameworks that account for connectivity, cumulative impacts, human activities and climate trajectories (Wedding et al., 2025; Manea et al., 2023; Saunders et al., 2024; Bell-James et al., 2025; Baker-Médard et al., 2024).

At the same time, bibliometric studies highlight an explosion of research on blue carbon, carbon cycling and sea-level rise, with clear shifts from pure discovery science toward solution-oriented work on adaptation, restoration and nature-based climate solutions (Khojasteh et al., 2023; Yin et al., 2023; Wang et al., 2024). These trends create both opportunities and challenges: how can we align diverse advances ecological theory, carbon accounting, spatial decision tools, social data and law into coherent strategies that regenerate entire coastal seascapes?

Building on the foundational reference set (RIS) and integrating recent literature exported as abstracts and metadata (DOC), this review pursues four objectives:

Synthesize current understanding of coastal and marine restoration across key ecosystem types, with particular attention to blue carbon and ecosystem services (Jones et al., 2024; Hagger et al., 2024; Sievers et al., 2023).

Assess emerging tools and frameworks for spatial prioritisation, connectivity-informed planning and restoration suitability under climate change (Nuyts et al., 2024; Araya-López et al., 2025; Dalby et al., 2025; Pastor et al., 2023; Howie et al., 2024; Rummell et al., 2023).

Integrate social, legal and governance perspectives, including stakeholder engagement, social data layers, permitting and risk allocation (Bell-James et al., 2025; Baker-Médard et al., 2024; Howie et al., 2024; Nelms, 2025; Musendekwa, 2025).

Identify cross-cutting knowledge gaps and priorities for climate-resilient, socially just and scalable restoration across seascapes (Silliman et al., 2024; Manea et al., 2023; Saunders et al., 2024).

Throughout, we emphasise seascape and "socialscape" perspectives how spatial configuration, connectivity and social processes jointly shape restoration potential and outcomes (Wedding et al., 2025; Stuart et al., 2025; Baker-Médard et al., 2024; Goodridge Gaines et al., 2024).

## Blue carbon ecosystems and climate mitigation

Blue carbon ecosystems (BCEs) mangroves, tidal marshes and seagrasses—are now thoroughly recognised as high-value natural climate solutions, owing to their capacity to sequester and store large quantities of carbon in biomass and soils while providing multiple co-benefits (Jones et al., 2024; Hagger et al., 2024; Lester, 2023; Yin et al., 2023). Bibliometric analyses show rapid growth in blue carbon publications, increasingly framed around restoration, conservation and carbon markets (Yin et al., 2023; Wang et al., 2024).

Recent syntheses underscore that coastal wetland restoration contributes to climate mitigation only when criteria such as additionality, permanence and feasibility are satisfied (Jones et al., 2024). Additionality requires that carbon benefits would not occur without intervention; permanence is challenged by sea-level rise, erosion and landward migration; feasibility depends on biophysical conditions, governance and financing (Jones et al., 2024; Hagger et al., 2024; Nuyts et al., 2024).

Empirical work on coastal wetland restoration in Australia, for example, demonstrates large but spatially variable opportunities for tidal restoration, constrained by hydrological modifications, agricultural land use, and threatened species distributions (Hagger et al., 2024). Spatial decision-support tools can reveal where blue carbon projects yield co-benefits for biodiversity, fisheries, water quality and cultural values, but economic feasibility remains sensitive to carbon price and opportunity costs (Hagger et al., 2024; Nuyts et al., 2024).

**Restoration ecology and ecological theory**

Ecosystem restoration has matured conceptually from site-specific replanting toward theory-informed interventions that seek to harness positive interactions, threshold dynamics and spatial processes (Silliman et al., 2024). A key message is that integrating foundational ecological theories—from facilitation cascades and meta-ecosystem dynamics to macroecology and biodiversity–function relationships—can dramatically increase restoration success and cost-effectiveness (Silliman et al., 2024). For coastal systems, this includes recognising foundation species (oysters, seagrasses, mangroves, marsh plants) whose physical structures and ecological roles create habitats for diverse communities and stabilise sediments (Hart et al., 2024; Zakaria et al., 2025; McHenry et al., 2023). The success of restoration often depends on matching species traits to environmental stress gradients, anticipating biotic interactions (e.g., herbivory, predation, bioengineering), and exploiting positive feedbacks in sediment accretion and water clarity (Hart et al., 2024; Jones et al., 2024; Silliman et al., 2024; Zakaria et al., 2025).

**Seascape and socialscape ecology**

Seascape ecology applies landscape-ecology concepts to marine and coastal settings, emphasising spatial configuration, habitat mosaics and connectivity (Wedding et al., 2025; Stuart et al., 2025; Pastor et al., 2023). Recent work demonstrates that seascape context strongly shapes nutrient fluxes, biodiversity patterns and restoration outcomes—for example, seafloor curvature and depth modulate seabird-derived nutrient enrichment of coral reefs (Stuart et al., 2025), and connectivity among seagrass meadows governs dispersal and recovery potential (Pastor et al., 2023).

Concurrently, the concept of socialscape ecology extends this spatial lens to human activities, values and governance. Analyses of Marxan-based conservation planning show increasing integration of social cost surfaces, access rights and socio-environmental change, but also reveal gaps in the systematic inclusion of social processes (Baker-Médard et al., 2024). Socialscape perspectives highlight that restoration and conservation must address not only where habitats and services are located, but also who uses them, under what rules, and how benefits and burdens are distributed (Baker-Médard et al., 2024; Bell-James et al., 2025; Howie et al., 2024).

**Research trajectories in blue carbon, coastal wetlands and sea-level rise**

Bibliometric analyses are particularly informative for understanding how research foci evolve and where restoration fits in the broader climate and coastal science landscape.

**Blue carbon and carbon cycling**

Two complementary bibliometric studies synthesise trends in blue carbon and carbon cycling research across vegetated coastal ecosystems (Yin et al., 2023; Wang et al., 2024). These analyses reveal:

Exponential growth in publications since the early 2000s, with mangroves receiving disproportionate attention relative to salt marshes and seagrasses (Yin et al., 2023; Wang et al., 2024).
A shift from basic process studies (e.g., productivity, decomposition, food webs) toward climate mitigation, restoration and carbon-market applications (Yin et al., 2023).
Increasing focus on lateral carbon exchange, carbonate burial, methane emissions and macroalgal blue carbon, reflecting more complete accounting of greenhouse-gas fluxes and cross-system connectivity (Yin et al., 2023; Lester, 2023).
Growing interdisciplinary integration, with ecosystem services, remote sensing and spatial planning emerging as key themes (Wang et al., 2024; Nuyts et al., 2024).
These trends frame restoration not only as a biodiversity or local management tool, but as a central strategy in national and sub-national climate policies.

**Sea-level rise and coastal risk science**

Sea-level rise (SLR) science has similarly expanded, with thousands of publications spanning physical drivers, impacts, adaptation and coastal ecosystems (Khojasteh et al., 2023). Bibliometric mapping identifies four major clusters: geological indicators, physical components of SLR, impacts and adaptation, and coastal ecosystems and habitats (Khojasteh et al., 2023).
Importantly, the relative emphasis is shifting from purely physical analyses to solution-focused topics, including high-end SLR scenarios, declining ecosystem services, flood hazards and coastal squeeze (Khojasteh et al., 2023; Arkema et al., 2024). This evolution underscores the role of coastal ecosystems and restoration as both vulnerable to SLR and central to adaptation strategies (Jones et al., 2024; Hagger et al., 2024; Sievers et al., 2023).

**Coastal material stocks and socio-metabolic risks**

A complementary strand examines how sea-level rise intersects with built infrastructure and material stocks in coastal regions. For example, analysis of material stocks in The Bahamas shows that a substantial share of buildings and transport infrastructure is exposed to 1–3 m SLR scenarios, with transport stocks particularly vulnerable (Martin del Campo et al., 2023). These studies highlight the need to integrate ecosystem-based adaptation and restoration with broader development, planning and rebuilding decisions to avoid lock-in of maladaptive investments (Martin del Campo et al., 2023; Arkema et al., 2024; Manea et al., 2023).

## METHODS

This review synthesizes peer-reviewed publications from 2020–2025, including bibliometric studies, ecological experiments, spatial modelling research, and governance analyses. Sources were selected from Scopus-indexed literature relevant to blue carbon, restoration ecology, seascape ecology, and MSP. Comparative and thematic synthesis methods were used to organise findings into ecological, spatial, and socio-governance dimensions.

## RESULT

**Coastal wetlands: tidal marshes, mangroves and supratidal forests**

Recent syntheses underline that restoration in tidal marshes, mangroves and coastal forests must account for their dynamic nature, connectivity and exposure to multi-dimensional stressors (He et al., 2025; Jones et al., 2024; Hagger et al., 2024). Coastal wetlands experience fluctuating salinity, inundation, storms, droughts and trophic interactions, which interact with land–sea connectivity and climate change (He et al., 2025). Restoration success therefore depends on matching interventions (e.g., hydrological reconnection, replanting, assisted succession) to spatiotemporal stress regimes and species interactions (He et al., 2025; Silliman et al., 2024).

In grazed tidal marshes, spatial prioritisation using Marxan indicates that fencing specific portions of collapsed marsh and future inundation zones can recover a large share of ecosystem services (carbon and nitrogen sequestration, fisheries enhancement, coastal hazard mitigation) with limited area and cost, but trade-offs among services must be explicitly considered (Araya-López et al., 2025). Similarly, Australian case studies demonstrate that economically viable blue carbon projects often hinge on stacking carbon credits with co-benefits and recognising the aspirations and rights of Traditional Custodians (Hagger et al., 2024).

In China, ecosystem-based marine comprehensive zoning demonstrates how ecological zones, control zones, development zones and reserve zones can be delineated to balance ecological protection and marine development, with Marxan-based optimisation improving compactness, protection outcomes and economic benefits (Chen et al., 2025; Li et al., 2024). Compatible marine utilisation models further differentiate between development sequencing, spatial coexistence and functional synergy, providing frameworks for managing multi-use seas under MSP (Li et al., 2024).

**Seagrass ecosystems**

Seagrass beds are critical for biodiversity, carbon storage, fisheries and coastal protection (McHenry et al., 2023; Sievers et al., 2023). Yet they are declining globally due to poor water quality, coastal development and climate stress.

Spatial modelling reveals complex spatial patterns of seagrass ecosystem services: hotspots of nursery habitat, blue carbon, recreation and coastal protection often do not fully overlap, creating co-benefits and trade-offs (McHenry et al., 2023). Biodiversity is not a reliable proxy for other services, underscoring the need for direct, service-specific assessments when prioritising conservation and restoration (McHenry et al., 2023; Sievers et al., 2023).

Suitability modelling and climate forecasting can identify seagrass restoration sites that remain viable under future scenarios. In Western Port (Australia), random forest models suggest that climate change could substantially reduce the area and quality of suitable sites by 2030 and 2090, even among locations currently considered suitable (Dalby et al., 2025). These findings emphasise the importance of incorporating future environmental conditions into restoration planning, and of avoiding "risky" sites that may quickly become unsuitable.

At the local scale, seagrass-assisted recovery in Malaysia highlights the value of long-term monitoring and species complementarity. Seedling-based rehabilitation using a stabiliser species plus cover species achieved high survival and extensive coverage, with mixed-species assemblages enhancing sediment stabilisation and recovery trajectories (Zakaria et al., 2025). Such case studies complement modelling work by providing empirical evidence of effective methods and time scales.

Connectivity-informed approaches to seagrass conservation further show that identifying dispersal sinks and source–sink linkages can guide where to prioritise protection and restoration to support regional persistence (Pastor et al., 2023). In the NW Mediterranean, dispersal modelling and graph theory reveal key seagrass nodes and corridors among islands and bays, implying that restoration in highly connected sinks may generate disproportionate benefits (Pastor et al., 2023).

**Oyster reefs and shellfish habitats**

Oyster reefs function as blue carbon sinks and biodiversity hotspots while providing coastal protection and water filtration (Shi et al., 2024; Hart et al., 2024; Howie et al., 2024). Assessment of oyster reefs in Hainan Island shows substantial carbon pools and sensitivity of carbon storage to temperature and aquaculture pressures; natural oyster reefs there remain at risk of anthropogenic disturbance, prompting calls for protective policies and artificial enhancement (Shi et al., 2024).

Experimental oyster reefs in estuaries reveal that habitat setting strongly influences macroinvertebrate communities, while predation pressure, especially by large fish, can severely limit juvenile oyster survival (Hart et al., 2024). Practitioners can leverage these insights by placing reefs adjacent to specific neighbouring habitats to shape community composition and by employing caging or complex substrates in high-predation environments (Hart et al., 2024; Silliman et al., 2024).

Site selection for oyster reef restoration illustrates how traditional habitat suitability models can be enriched with social data. In Sydney Harbour, integrating conflicting estuarine uses, connectivity and participatory mapping into GIS-based models dramatically reduces the area deemed suitable compared to biophysical-only models, but yields more realistic, socially supported options (Howie et al., 2024). This underscores that stakeholder support is a critical determinant of suitability, not a secondary consideration.

## Coral reefs, kelp forests, sandy shores and biogenic reefs

Coastal restoration extends beyond vegetated BCEs to coral reefs, kelp forests, sandy shores and biogenic worm reefs. For coral reefs, nutrient enrichment linked to seabirds can modulate recovery potential: in atoll systems recovering from rat eradication, seabird-vectored nutrients interact with seascape configuration, especially seafloor curvature and depth, to create hotspots of nutrient enrichment and potential resilience (Stuart et al., 2025).

Kelp forests, targeted by ambitious restoration goals, increasingly rely on environmental niche tools that integrate global observations and biophysical datasets to map species-specific environmental envelopes and identify suitable regions for restoration and protection (Eger et al., 2025). Such tools support evidence-based site selection and can be updated as new data emerge.

Biogenic worm reefs in sandy coastal systems, such as Sabellaria spinulosa reefs in the Adriatic, represent fragile habitats of conservation concern that contribute to coastal protection and biodiversity (Gabbianelli et al., 2025). Preliminary mapping using geophysical surveys and diver observations provides baselines for geoconservation and informs MSP and marine protected area designation (Gabbianelli et al., 2025).

Sandy shores more broadly are recognised as highly dynamic, vulnerable social–ecological systems shaped by sand, waves and tides and strongly affected by human activities (Cecilia Carcedo et al., 2025). Restoration and conservation here require integrated understanding of physical drivers, biological communities across dunes–beach–surf compartments, and intensifying anthropogenic pressures (Cecilia Carcedo et al., 2025; Velázquez-Ochoa & Enríquez, 2023).

## Marxan and MSP for restoration and conservation

Marxan remains a central tool in conservation planning and increasingly in restoration prioritisation, especially when combined with MSP (Chen et al., 2025; Araya-López et al., 2025; Baker-Médard et al., 2024; Manea et al., 2023). In coastal wetlands and grazing lands, Marxan can optimise site selection for restoring marshes to recover multiple ecosystem services while minimising fencing and management costs (Araya-López et al., 2025).

At the scale of marine spatial planning, Marxan-based ecological zoning can delineate ecological preservation, control, development and reserve zones, balancing ecological and socio-economic objectives (Chen et al., 2025). Compatibility-based MSP frameworks further allow simultaneous or sequenced uses of marine space, where compatible marine uses are evaluated along dimensions such as quantity, spatial conflict

and impacts on natural attributes (Li et al., 2024).
In Europe, reviews of MSP plans reveal that addressing underwater noise is still emerging, with considerable potential for MSP to manage noise-producing activities in an ecosystem-based manner and to coordinate with the Marine Strategy Framework Directive (Bosi et al., 2023). This illustrates how MSP can be expanded to integrate new environmental pressures and cross-border issues.

**Table 1. Coastal and marine ecosystem types, key services and restoration challenges**

| **Ecosystem type** | **Dominant ecosystem services** | **Typical restoration or management approaches** | **Key challenges and risks** | **Ref.** |
|---|---|---|---|---|
| Mangroves & tidal marshes | Carbon sequestration, coastal protection, nursery habitat, water quality | Tidal reconnection, managed realignment, planting, assisted succession | Sea-level rise, subsidence, land-use conflicts, methane emissions, tenure and rights | Jones et al., 2024; He et al., 2025; Hagger et al., 2024 |
| Seagrass meadows | Nursery habitat, blue carbon, coastal protection, recreation | Seed-based and vegetative transplantation, water quality improvement, protection of hotspots | Light limitation, eutrophication, climate-driven regime shifts, fragmented services | McHenry et al., 2023; Dalby et al., 2025; Zakaria et al., 2025 |
| Oyster reefs & shellfish | Habitat provision, carbon storage, water filtration, coastal protection | Reef construction, substrate enhancement, stock augmentation, fishing restrictions | Predation, disease, water quality, stakeholder conflicts and site suitability | Shi et al., 2024; Hart et al., 2024; Howie et al., 2024 |
| Coral reefs and lagoon systems | Biodiversity, fisheries, tourism, coastal protection | Active coral restoration, water quality management, land-based pollution control | Eutrophication, Sargassum influx, warming, local nutrient loading | Stuart et al., 2025; Velázquez-Ochoa & Enríquez, 2023 |
| Kelp forests | Biodiversity, fisheries, blue carbon, cultural values | Harvest controls, outplanting, niche-based site selection, invasive species control | Warming, marine heatwaves, grazing, socio-economic constraints | Eger et al., 2025; Sievers et al., 2023 |
| Sandy shores & biogenic reefs | Coastal protection, biodiversity, recreation | Dune and beach restoration, geoconservation, access and development management | Rapid morphodynamics, tourism pressure, infrastructure encroachment | Cecilia Carcedo et al., 2025; Gabbianelli et al., 2025 |

## Decision support tools for blue carbon and seagrass restoration

GIS-based decision-support tools are proliferating to identify suitable restoration sites for blue carbon and seagrass ecosystems (Nuyts et al., 2024; Dalby et al., 2025). For blue carbon ecosystems along Victoria's coastline, multi-criteria tools integrate BCE distribution, geomorphology, hydrodynamics and land tenure to map passive and active restoration suitability, revealing extensive opportunities primarily on public land (Nuyts et al., 2024). These tools distinguish between restoration pathways, support regional planning and highlight the need to integrate socio-economic factors and stakeholder engagement (Nuyts et al., 2024; Hagger et al., 2024).
For seagrasses, forecasted suitability models combine machine-learning algorithms with climate projections and local stressor scenarios (e.g., light reduction) to identify resilient restoration areas and avoid risky sites (Dalby et al., 2025). Such approaches demonstrate that restoration planning must be explicitly climate-informed rather than solely based on current conditions.
Environmental niche exploration tools for kelp forests generalise this logic at global

scales, synthesising niche characteristics across species and ecoregions to support site selection for restoration and protection (Eger et al., 2025). Together, these tools exemplify the increasing integration of big data, remote sensing and modelling with restoration decision-making.

### Connectivity and co-benefits in spatial planning

Seascape connectivity is increasingly recognised as a determinant of restoration benefits, not just of biodiversity and resilience (Wedding et al., 2025; Rummell et al., 2023; Pastor et al., 2023; Sievers et al., 2023). Long-term monitoring of a restoring coastal wetland shows that biodiversity, fisheries benefits and functional diversity increase over time at restoration sites but not at controls, and that co-benefits are positively linked to connectivity, mangrove extent and salinity (Rummell et al., 2023). This supports tighter integration of connectivity metrics in restoration spatial planning.

Global analyses of mangrove biodiversity, carbon stocks, fish and invertebrate production, and coastal protection show that hotspots of single services and multi-service co-occurrence vary widely across regions (Sievers et al., 2023). Some nations may benefit from targeting multi-service hotspots, while others require complementary portfolios of sites focused on different services (Sievers et al., 2023). These insights underscore that restoration strategies should be context-specific and multi-objective.

Resnagging log structures in estuaries further illustrates how spatial patterns in connectivity and habitat condition shape fish assemblages and restoration potential (Goodridge Gaines et al., 2024). Strategic placement of log snags in relation to estuary mouths, urban structures, depth and algae cover can maximise benefits for fish and fisheries, offering an alternative or complement to more abiotic-sensitive restoration methods like seagrass or shellfish restoration (Goodridge Gaines et al., 2024).

**Table 2. Selected decision-support tools and planning frameworks for coastal restoration**

| Tool / framework | Primary application | Key data inputs | Main strengths | Ref. |
|---|---|---|---|---|
| Marxan-based ecological zoning | Ecological zone designation, reserve design, restoration targeting | Habitat maps, biodiversity, costs, threats, land/sea use | Transparent optimisation, scenario testing, multi-objective planning | Chen et al., 2025; Araya-López et al., 2025; Baker-Médard et al., 2024 |
| Compatibility-based MSP models | Managing multi-use seas and compatible marine utilisation | Functional zones, use types, conflict indicators, legal frameworks | Addresses overlapping uses, supports sequencing and synergy | Li et al., 2024; Manea et al., 2023 |
| GIS multi-criteria DST for BCEs | Blue carbon restoration site selection | BCE distribution, geomorphology, hydrodynamics, land tenure | Differentiates passive vs active restoration; transferable | Nuyts et al., 2024; Hagger et al., 2024 |
| Forecasted seagrass suitability models | Climate-resilient seagrass restoration planning | Environmental variables, climate projections, water quality | Identifies resilient sites, avoids future-unsuitable areas | Dalby et al., 2025 |
| Environmental niche tools for kelp | Global kelp restoration and conservation planning | Species occurrences, oceanographic variables | Quantitative niche characterisation, global coverage | Eger et al., 2025 |
| Socialscape-informed Marxan | Conservation planning with social processes | Human activity, access rights, social costs, climate change | Spatialises social processes, addresses justice and feasibility | Baker-Médard et al., 2024; Howie et al., 2024 |

## Social, legal and governance dimensions

### Law, policy and governance for upscaling restoration

Upscaling marine and coastal restoration requires transformation in legal and governance systems, not just ecological or technical innovation. Legal and governance analyses identify multiple barriers to scaling, including inadequate permitting frameworks, tenure issues, risk and liability concerns, lack of overarching restoration targets and fragmented governance (Bell-James et al., 2025; Manea et al., 2023; Saunders et al., 2024).

Global "bright spots" demonstrate solutions such as fit-for-purpose permitting, clear restoration targets, integrated governance frameworks and legal recognition of nature-based solutions (Bell-James et al., 2025). National-scale engagements with stakeholders in Australia, for example, distilled ten guiding principles for large-scale coastal and marine restoration, ranging from co-design and fit-for-purpose governance to no-gap funding, robust monitoring and knowledge sharing (Saunders et al., 2024).

Ecosystem-based MSP frameworks that explicitly integrate restoration alongside conservation and sustainable use can help align spatial planning with restoration needs (Manea et al., 2023; Chen et al., 2025; Li et al., 2024). Linking MSP with restoration can, in principle, scale interventions and support implementation of global commitments like the Kunming–Montreal Global Biodiversity Framework (Manea et al., 2023; He et al., 2025; Bell-James et al., 2025).

### Social data, participatory mapping and socialscapes

Despite widespread recognition that stakeholder support is crucial, social data often remain a "missing layer" in restoration planning (Howie et al., 2024; Baker-Médard et al., 2024). Participatory mapping and stakeholder engagement can reveal conflicts, preferences and local knowledge that profoundly affect feasibility and legitimacy (Howie et al., 2024; Baker-Médard et al., 2024; Saunders et al., 2024).

In oyster reef restoration planning, integrating conflicting uses (e.g., shipping, recreation) and participatory mapping into suitability models sharply reduces candidate sites but increases the likelihood of successful implementation and long-term support (Howie et al., 2024). Socialscape ecology encourages planners to represent not only the spatial distribution of human activities but also underlying drivers, rights, access and involvement of resource users in decision-making (Baker-Médard et al., 2024).

Digital literacy and collaborative technology integration in higher education and workforce development may indirectly support restoration by building capacity for data analysis, modelling and participatory tools (Nelms, 2025; Musendekwa, 2025). Strengthening collaboration between academic institutions, practitioners and communities is central to co-designed, equitable restoration (Saunders et al., 2024; Bell-James et al., 2025).

### Equity, cultural values and Traditional Custodians

Case studies in Australia highlight the importance of engaging Traditional Custodians in blue carbon projects, recognising cultural benefits and rights, and aligning restoration with Indigenous leadership and knowledge systems (Hagger et al., 2024; Saunders et al., 2024). These dimensions affect site eligibility, governance arrangements and project outcomes, and must be addressed through context-specific processes, not generic blue carbon frameworks.

More broadly, spatial prioritisation of ecosystem services often reveals mismatches between ecological and social priorities; for example, focusing solely on coastal hazard mitigation may deliver poor outcomes for other ecosystem services (Araya-López et al., 2025; McHenry et al., 2023; Sievers et al., 2023). Equity-sensitive planning should therefore explicitly consider who benefits from which services, where and at what cost.

**Table 3. Social and governance dimensions influencing coastal restoration outcomes**

| Dimension | Key issues for restoration | Illustrative examples | Implications for planning and practice | Ref. |
|---|---|---|---|---|
| Legal & permitting frameworks | Fit-for-purpose permits, clarity on liability and risk | Restoration bright spots with tailored permitting systems | Reduce administrative barriers, clarify responsibilities | Bell-James et al., 2025; Saunders et al., 2024 |
| Tenure and rights | Land/sea tenure, Native Title, access rights | Traditional Custodians' leadership in blue carbon projects | Shape eligibility, benefit-sharing and governance | Hagger et al., 2024; Saunders et al., 2024 |
| Social data & participatory mapping | Stakeholder support, conflicts, local knowledge | Oyster reef planning with participatory GIS | Avoid conflict, increase legitimacy and feasibility | Howie et al., 2024; Baker-Médard et al., 2024 |
| Governance integration | Fragmented institutions, cross-scale coordination | National roadmap for coastal restoration | Provide overarching principles and multi-level coordination | Saunders et al., 2024; Manea et al., 2023 |
| Capacity and digital literacy | Skills for modelling, data use, co-production | IHE–workforce collaboration on digital literacy | Enable uptake of spatial tools and participatory methods | Nelms, 2025; Musendekwa, 2025 |
| Policy targets and incentives | Clear restoration targets, carbon markets, co-benefits | Blue carbon projects linked to carbon markets and co-benefits | Align finance with ecological and social priorities | Hagger et al., 2024; Lester, 2023; Jones et al., 2024 |

## Carbon sequestration, co-benefits and trade-offs

Blue carbon restoration is rarely justified by carbon alone; co-benefits for biodiversity, fisheries, water quality, coastal protection and cultural values are often central to project design and community acceptance (Hagger et al., 2024; Jones et al., 2024; Sievers et al., 2023; McHenry et al., 2023). Global assessments of mangrove ecosystems show substantial co-occurrence of biodiversity, carbon storage, coastal protection and fish/invertebrate production, but with highly heterogeneous spatial patterns and varying correlations among services at national scales (Sievers et al., 2023).

Coastal wetland restoration can increase carbon sequestration only under specific conditions of additionality, feasibility and permanence, and when methane emissions and system-wide carbon exchanges are considered (Jones et al., 2024; Yin et al., 2023). Natural climate solution frameworks emphasise that climate benefits should be evaluated over management-relevant decadal timescales and at system scales that capture cross-habitat carbon flows (Jones et al., 2024; Lester, 2023; Yin et al., 2023).

Restoration can also entail trade-offs: prioritising a single service, such as coastal hazard mitigation, may undermine other services if not carefully balanced (Araya-López et al., 2025; McHenry et al., 2023; Sievers et al., 2023). Spatial analyses of seagrass services show that hotspots of biodiversity, blue carbon, recreation and protection are only partially overlapping, indicating that portfolios of sites may be needed to achieve multi-service objectives (McHenry et al., 2023).

Bibliometric analyses highlight emerging research frontiers around methane emissions, lateral carbon exchange and carbonate burial in BCEs, underscoring that restoration interventions must be evaluated with these processes in mind (Yin et al., 2023; Lester, 2023; Wang et al., 2024).

**Table 4. Blue carbon and ecosystem service insights across vegetated coastal ecosystems**

| Ecosystem | Key carbon cycling processes | Emerging research frontiers | Co-benefits and trade-offs | Ref. |
|---|---|---|---|---|
| Mangroves | Sedimentation, biomass accumulation, lateral export | Restoration impacts on methane, encroachment, biomass estimation | Strong blue carbon and protection; trade-offs with land use and tenure | Yin et al., 2023; Jones et al., 2024; Hagger et al., 2024 |
| Salt marshes | Organic matter burial, lateral exchange | Methane emissions, impacts of mangrove encroachment | High carbon and biodiversity; sensitive to SLR and management | Yin et al., 2023; He et al., 2025; Araya-López et al., 2025 |
| Seagrasses | Belowground carbon storage, carbonate cycling | Ocean acidification, restoration impacts, macroalgal carbon | Co-benefits for fisheries and recreation; services vary spatially | Yin et al., 2023; McHenry et al., 2023; Dalby et al., 2025; Zakaria et al., 2025 |
| Supratidal & coastal forests | Aboveground biomass, soil carbon | Integration into blue carbon schemes, fire–carbon interactions | Cultural and biodiversity values, trade-offs with agriculture | Hagger et al., 2024; Sievers et al., 2023 |
| Oyster reefs | Calcification, shell and sediment carbon | Quantifying net carbon effects under disturbance | Habitat, fisheries and protection; sensitive to disturbance | Shi et al., 2024; Hart et al., 2024 |
| Integrated seascapes | Cross-habitat carbon fluxes | System-wide accounting, co-benefit optimisation | Managing portfolios of sites for multiple services | Sievers et al., 2023; Jones et al., 2024; Rummell et al., 2023 |

## DISCUSSION

The integration of ecological theory, spatial planning, and social–legal governance is essential for effective and scalable marine restoration. Ecological insights reveal that foundation species and positive interactions improve restoration success. MSP tools and spatial modelling support climate-resilient site selection, while socio-governance frameworks ensure long-term feasibility, justice, and stakeholder support. Cross-cutting barriers include insufficient system-wide carbon accounting, limited climate scenario integration, fragmented governance, and underrepresentation of social data in modelling. Long-term monitoring and co-designed restoration involving local and Indigenous communities are critical.

## CONCLUSIONS

Recent literature on blue carbon, coastal wetlands, seagrasses, oyster reefs, coral and sandy systems paints a picture of both escalating risk and unprecedented opportunity. Coastal and marine restoration is no longer an isolated ecological activity: it operates at the nexus of climate mitigation, adaptation, biodiversity conservation, development planning and social justice (Jones et al., 2024; Hagger et al., 2024; Saunders et al., 2024; Bell-James et al., 2025).

Key shifts include the rise of system-wide, co-benefit-focused approaches; the integration of seascape and socialscape ecology into planning; and the proliferation of spatial decision-support tools capable of guiding restoration in complex, multi-use environments (Wedding et al., 2025; Nuyts et al., 2024; Dalby et al., 2025; Baker-Médard et al., 2024). At the same time, bibliometric analyses reveal a strong trajectory toward solution-focused research, especially around restoration, ecosystem services and climate adaptation (Khojasteh et al., 2023; Yin et al., 2023; Wang et al., 2024). Realising the potential of coastal and marine restoration as a regenerative, climate-resilient strategy will require deep integration of ecological theory, spatial planning, social data, legal frameworks and economic instruments. It will also demand co-design with Indigenous peoples and local communities, and recognition of the material, cultural and justice dimensions of coastal change (Hagger et al., 2024; Saunders et al., 2024; Baker-Médard et al., 2024).

By synthesising recent advances across these domains, this review provides a conceptual and practical foundation for designing restoration programmes that not only rebuild ecosystems but also enhance resilience, equity and well-being across coastal seascapes.

### *Declaration by Authors*

**Acknowledgement:** None
**Source of Funding:** None
**Conflict of Interest:** No conflicts of interest declared.

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How to cite this article: Nasruddin, Dewi Wahyuni K Baderan, Sukirman Rahim, Asda Rauf, Marni Susanti Hamidun. Toward regenerative coastal seascapes: integrating blue carbon, restoration ecology, and spatial planning across marine and coastal ecosystems. *International Journal of Research and Review*. 2025; 12(12): 401-416. DOI: *https://doi.org/10.52403/ijrr.20251245*

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