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Barriers and enablers for upscaling coastal restoration

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ABSTRACT

Coastal restoration is often distrusted and, at best, implemented at small scales, which hampers its potential for coastal adaptation. Present technical, economic and management barriers stem from sectoral and poorly coordinated local interventions, which are insufficiently monitored and maintained, precluding the upscaling required to build up confidence in ecosystem restoration. The paper posits that there is enough knowledge, technology, financial and governance capabilities for increasing the pace and scale of restoration, before the onset of irreversible coastal degradation. We propose a systemic restoration, which integrates Nature based Solutions (NbS) building blocks, to provide climate-resilient ecosystem services and improved biodiversity to curb coastal degradation. The result should be a reduction of coastal risks from a decarbonised coastal protection, which at the same time increases coastal blue carbon. We discuss barriers and enablers for coastal adaptation-through-restoration plans, based on vulnerable coastal archetypes, such as deltas, estuaries, lagoons and coastal bays. These plans, based on connectivity and accommodation space, result in enhanced resilience and biodiversity under increasing climatic and human pressures. The paper concludes with a review of the interconnections between the technical, financial and governance dimensions of restoration, and discusses how to fill the present implementation gap.

1. Introduction

Coastal zones, concentrating high population densities, economic assets and cultural heritage, are urbanising more rapidly than inland regions [1], while coastal ecosystems provide highly productive and biodiverse environments, with an important and often underappreciated carbon storage potential [2,3]. The narrow coastal fringe, a dynamic ecotone comprising water and land zones with a fuzzy boundary [4], is experiencing progressive degradation and escalating risks [5], with deep uncertainties affecting how to restore sustainably [6,7]. Progressive geomorphic degradation and loss of biodiversity suggest that the protection of still relatively healthy coastal ecosystems is manifestly

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insufficient [8], which increases the restoration deficit. This deficit is linked to restoration interventions that are too small, too late or too sectoral to reverse these trends and increase the resilience of present coastal systems. The restoration deficit is projected to grow under accelerating climatic pressures, notably sea-level rise and population densities, expected to increase more than 50% by 2100 [9]. Sea-level-rise (SLR) acceleration due to global warming, will have effects on coastal risks and ecology, which will result in a reduction of coastal habitats and their biodiversity, degrading their health status, although requiring further data and analyses to understand the combined evolution details. The resulting decrease of ecosystem services (ESS) will aggravate the resilience deficit for vulnerable coastal systems, until they cross a threshold or tipping point, beyond which coastal ecosystems cannot be easily restored. Approaching this irreversible situation curtails the potential of ecosystems to adapt under new climate or management conditions.

The barriers (technical, financial, management or commitment limits) and enablers (biophysical knowledge, economic advances, favourable governance or social engagement) to coastal restoration are deeply interconnected. These barriers, summarized below (Table 1), are difficult to overcome without large enough interventions that demonstrate the potential of restoration for enhancing biodiversity and ecosystem service delivery. Coastal adaptation plans based on restoration can provide an excellent demonstration of how to control flooding and erosion risks [4,10], while contributing to natural capital stocks and climate mitigation through coastal blue carbon [11,12].

To deliver these ESS and preserve coastal biodiversity, restoration must be upscaled, increasing the implementation domains and pace of interventions, commensurate with the increase in climatic and human pressures. Coastal restoration must be also outscaled, exporting the approach to other regions and countries [87], because such an extension is needed to make a difference to global adaptation and mitigation. Restoration upscaling will enable a cumulative delivery of ecosystem services and improved biodiversity status that will support coastal adaptation under future scenarios, where such upscaling is particularly well suited to reduce risks in river-delta-coast systems [88]. Restoration outscaling should enable a global extension of decarbonised coastal protection and a significant contribution to climate mitigation through enhanced coastal blue carbon. Without enough up- and out-scaling, coastal restoration will keep on being distrusted since it will hardly perform as required by present coastal stakeholders, failing to demonstrate its potential and to build up trust due to insufficient funding and engagement [89]. Restoration and natural resource management are often characterized by public dissatisfaction, lack of public participation and distrust of government [84,85], reinforcing scepticism. Restricted restoration outcomes, commonly due to the lack of upscaled interventions embedded in complex social-ecological systems, make the building of such trust a complicated endeavour [86].

Restoration is hampered by technical, financial and governance barriers [23] that preclude a widespread implementation of large-scale interventions. The UN call to action, by declaring 2021-2030 as the “UN Decade on Ecosystem Restoration”, recognizes such hurdles and the need to accelerate the restoration of degraded ecosystems [24]. Coastal habitats, in particular, present the lowest proportion of ‘good status’ in conservation (Habitats Directive), ecological (Water Framework Directive) or environmental (Marine Strategy Framework Directive) terms, according to the nine European Union habitat groups analysed for sustainability [75].

In the following, we first review how and why current approaches to coastal restoration are too local to deliver the expected restoration outcomes, attributing the restoration deficit to technical, financial and governance barriers that hinder upscaling. Next, we discuss innovations to overcome present barriers, illustrating them for three coastal archetypes that represent vulnerability hotspots. This is supplemented by an analysis of outscaling to worldwide coasts, followed by a discussion on how upscaled coastal restoration may align adaptation with mitigation, if the implementation gap is efficiently filled by our generation.

Table 1
Summary of technical, financial and governance barriers to upscale coastal restoration interventions.

Coastal Restoration Barriers Technical limitations	Financial limitations	Governance limitations
■ Engineering expertise ■ Data and metrics for biodiversity and ESS ■ Monitoring and maintenance plans ■ Delayed performance ■ Room for adaptation	■ Benefit-cost ratios ■ Returns from investments ■ Business plans suited to local constraints ■ Short term and small scale bias ■ Long term support	■ Integrated approach ■ Coordinated decision making ■ Social perception and pervasive inertia ■ Short term policies ■ Convergence of stakeholder interests

2. Problem setting: need for a systemic coastal restoration

Risk reduction in coastal zones has been a traditional priority, favouring rigid interventions that do not define explicit tipping points (TP) as resilience thresholds associated to biodiversity or ecosystem services, [18]. Solutions that apply ecosystem services (ESS) to curb coastal risks and degradation need to define explicit TPs that must not be crossed to allow for the recovery of biodiversity or ESS [13]. Such TPs can be illustrated by minimum size of dunes and emerged beaches or minimum density and complementarity of species, where the threshold crossings are more apparent for engineered or sediment-starved coastlines. These vulnerable coastal systems feature limited accommodation space [20], threatened biodiversity and reduced ESS delivery [21], particularly under climate change [19]. Piecewise restoration [14], vested interests and lack of socioeconomic consensus [15] limit large scale restoration implementation, with few analyses tackling barriers and opportunities [22]. Present coastal restoration practice builds upon a fragmented governance framework that favours short-term interventions [16], leading to long-term losses of coastal biodiversity and socioeconomic assets [17].

Restoration performance is limited by combined barriers such as: (a) locally validated techniques with limited engineering experience and background on restoration ecology, which hamper an efficient roadmap to systemic restoration [25]; (b) scarce funding and limited long term commitment, preventing large-scale restoration with the full delivery of ESS [16], whose assessment still externalises many costs and impacts [26]; (c) governance fragmentation, which is not well suited to integrate all relevant coastal social-ecological dimensions nor to incorporate long term objectives [27].

Overcoming such barriers is essential for coastal systems characterized by imbalances in water/sediment/nutrient fluxes, scarcity of financial support, limited business plans for restoration interventions, and fragmented governance and decision making processes, with divergent stakeholder views and interests. These barriers require a transition in governance and policies to avoid undesired levels of coastal vulnerability and to generate the development of resilience from biophysical and socioeconomic standpoints. Such a decrease in resilience can be illustrated by sediment-starved deltas, where the limited sedimentary input and competing uses for water/sediment in the catchment basin and coastal zone result in enhanced subsidence and erosion. Subsidence hinders deltaic plain resilience by limiting vertical land levels, while erosion reduces the emerged coast and dune sand reserves, which may not be enough to counter storm impacts and may hamper the success of coastal restoration [90]. These biophysical barriers decrease coastal resilience and generate socioeconomic barriers that hinder upscaled restoration. The resulting restoration deficit will be aggravated under projected climatic and human pressures. since, for instance, an acceleration of sea-level-rise will require enhanced riverine solid discharges and coastal room to compensate for projected increases in flooding and erosion.

We posit that a successful coastal restoration should be systemic in: (a) spatial-temporal coverage; (b) ecosystem types; (c) governance systems; (d) financial instruments and (e) social engagement. Jointly addressing the problem roots and symptoms generates positive synergies for biodiversity and ESS, while minimizing disservices and coping with tradeoffs. These tradeoffs can be illustrated by the increasing scarcity of freshwater, sediment of suitable granulometry or the room needed by fluvial and marine dynamics to operate and increase natural resilience. A systemic restoration based on connectivity and natural processes, supported by recent advances in knowledge, tools and governance, should curb the present coastal degradation, which continues in spite of growing investments. Such restoration should be linked to a socio-economic transformation that applies innovation and education to tackle the inevitable tradeoffs and promote up- and out-scaling, for instance by enabling river basin erosion and downstream supply to ensure sufficient sediment supply to the downstream delta and coast.

We propose systemic large-scale restoration as the basis for coastal adaptation, structured by "adaptation-through-restoration" plans that upscale connectivity, along the river and across the coast, to enhance natural fluxes and dynamics for an improved biodiversity and ESS delivery. These plans, based on restored biodiversity and ESS, will sequence adaptation decisions and promote NbS building blocks [28] within a systemic restoration approach, illustrated by river and coastal by-passes that are redistributed by controlled fluvial discharges and coastal storms. Such an NbS approach, with regular monitoring and maintenance of wetlands, seagrass meadows and dune habitats. will result in a climate resilient adaptation that preserves coastal bio- and geo-diversity. Five main ESS are considered in many coastal restoration schemes (with other ESS included depending on site specific features): (a) reduction of flooding risks; (b) reduction of erosion risks; (c) preservation of water quality; (d) maintenance of fish/aquaculture stocks; and (e) sustained enhancement of coastal blue carbon (Fig. 1). The resulting increase in coastal resilience, associated with the natural capacity of coastal ecosystems to withstand climatic and human pressures, will lead to enhanced funding and socioeconomic commitment to upscale restoration.

Adaptation pathways, a sequenced roadmap to support structured decision making for a flexible resilience of coastal systems, can steer the proposed systemic restoration, aiming for an effective risk reduction with a reduced carbon footprint, when compared to conventional engineering works. The generated pathways [43,4] should align coastal adaptation with climate mitigation, through "decarbonised" coastal protection and enhancement of coastal blue carbon. The effectiveness of systemic restoration requires pairing restoration with monitoring and maintenance, to provide an evolving assessment of biodiversity and ESS delivery, with harmonized metrics that enable a comparison across restoration interventions.

Data-based metrics, with a consistent combination of climatic projections and meteo-oceanographic predictions, both associated to the prevailing local climate, can support a quantitative definition of warnings when approaching coastal TPs. Such early and climatic warnings, defined in terms of key oceanographic and morphological variables (significant wave height, emerged beach width, etc.) constitute a key requirement of the proposed systemic restoration, because they will provide advance information to take decisions for risk reduction and to assess restoration performance, both contributing to increase socio-economic engagement. The proposed adaptation-through-restoration plans should result in a transversal commitment (Fig. 1) of citizens (social engagement to coastal restoration), stakeholders (including management and funding) and policy makers (transformation in governance/policies).

3. Coastal restoration up- and out-scaling: current barriers

3.1. Current coastal restoration experiences

Depending on their deterioration level, degraded EU coastal systems require restoration or renovation to improve and sustain biodiversity and ESS delivery [29]. Although it is acknowledged that under accelerating climate change [30] restoration must be enhanced, coastal systems approaching an irreversible degradation or TP may require a renovation within properly designed upscaling plans. These plans should incorporate new technical and financial tools to comply with the post-2020 global biodiversity framework or the new EU 2030 Biodiversity Strategy. In these cases, current restoration is not enough to reverse biodiversity losses [8] by 2030, and coastal systems will fail to meet the target of achieving restored coastal ecosystems by 2050. Restoration benefits, both for coastal ecosystems and the societies they support, include enhanced biodiversity and resilience for vulnerability and biodiversity hotspots such as the selected pilot sites (Table 1). This can be illustrated by improved habitat health (submerged and emerged coast), reduced erosion and flooding (full coastal transect) and enhanced coastal blue carbon (sea grass meadows and wetlands).

We posit that without an increase in restoration pace and scale, as illustrated by a set of representative pilot cases (Table 2) presented with emphasis on the "enablers" developed (Section 4), coastal adaptation and biodiversity will continue to degrade under global warming. Without an upscaled restoration suited to increasing climate pressures, there will be increasing difficulties to meet EU and international natural policy targets, in particular for ecosystems with a high potential to capture/store carbon and to reduce disaster impacts [13].

Recent restoration experiences have favoured short-term and piecewise interventions, falling short of socio-economic expectations [79] that include the livelihoods [31] of more than 3 billion people globally. Although the ocean contribution to the world economy is expected to double by 2030 [32] and coastal ESS provide a key support for basic livelihoods and safety of a significant percentage of worldwide population, many coastal restoration assessments exclude ESS delivery [33], because they are not yet traded in formal markets. The valuation of ESS delivery stemming from restoration, still presents considerable uncertainties [10], with an error margin up to two orders of magnitude [34]. Such limitations have acted as a barrier towards upscaled coastal restoration plans, even though they are known to provide climate resilience [35] and enhance natural synergies [36,37].

Restoration techniques for coastal ecosystems are generally more expensive than those for terrestrial habitats, presenting larger uncertainties in investment returns and ESS delivery [91]. In spite of that, restored coastal ecosystems are known to lead to safe coastal trajectories that remain within sustainability thresholds [38], where the lack of harmonized metrics for biodiversity and ESS delivery has prevented more quantitative demonstrations. Technical barriers in the metrics for coastal biodiversity and ESS have exerted a negative effect on socio-economic engagement towards large-scale restoration. This is compounded by the wide range of scales for assessing restoration performance. As illustration, the establishment of some coastal vegetation may require months [39], while decades may be needed to achieve fully developed wetlands [40]. Further technical barriers are introduced by the effect of meteo-oceanographic extremes such as wave storms, whose impact is hard to predict on the mid- to long-term scales.

Because of these uncertainties, stakeholders tend to favour apparently more reliable rigid infrastructure (e.g. traditional coastal groynes or seawalls), in spite of well documented functional and environmental problems [76]. Current restorations are seldom supported by updated forecasting and projection techniques, and do not apply new financial instruments nor new governance possibilities [41,42,5,16,27]. Implementations are hard to upscale and compatibility with long term sustainability aims may be uncertain. The lack of objective ESS assessments, without an explicit definition of restoration goals, impede

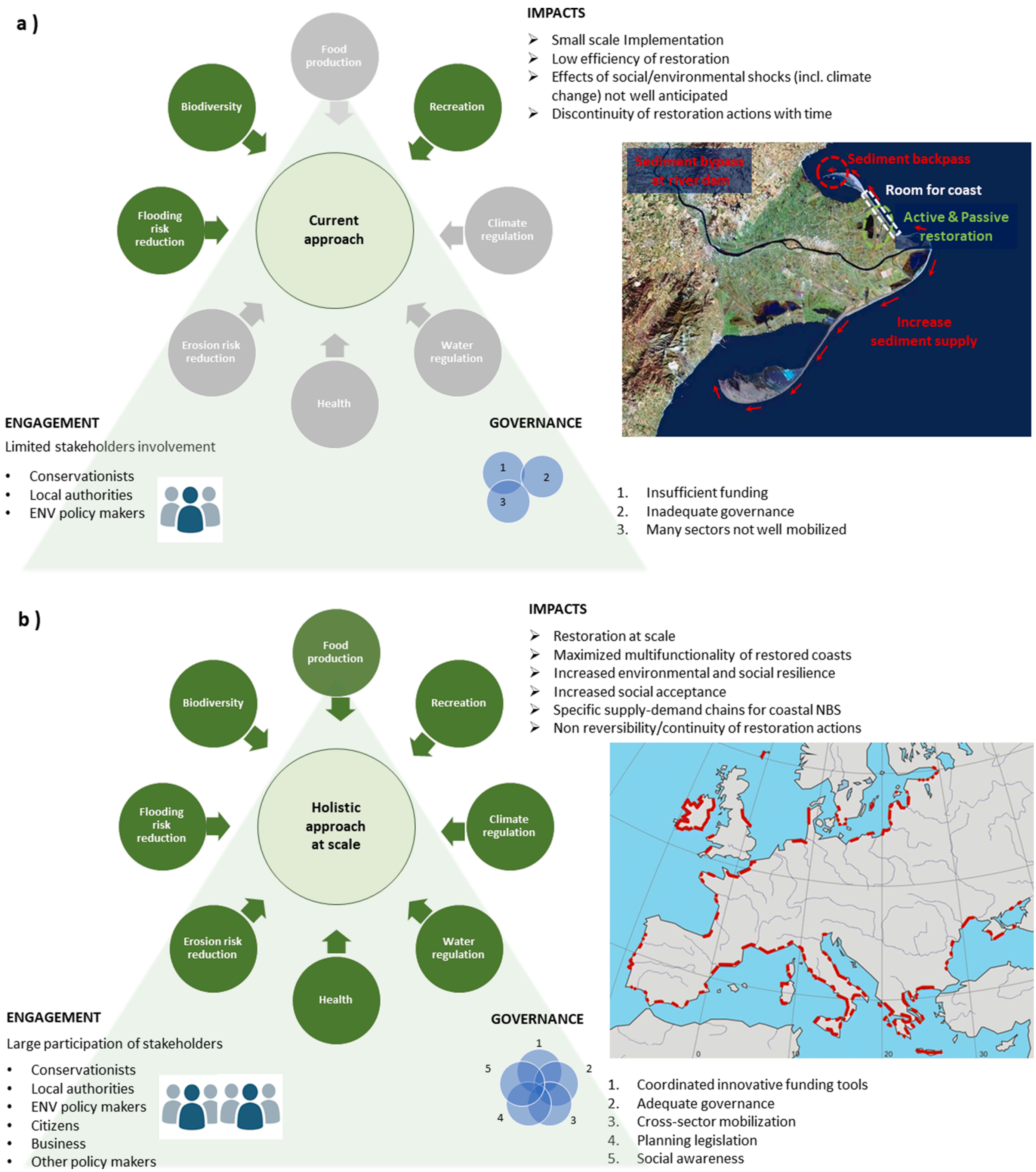

Fig. 1. I cannot see the full figure captio so I cannot check it is completeComparison between current local restoration approaches, based on sediment recycling for the Ebro river-delta-coast continuum (upper panel a), with potential upscaling holistic approaches along selected European coastal stretches with red dots indicating erosion hotspots (lower panel b). The comparison considers impact, engagement and governance aspects (three vertices of the shaded triangle) in the two approaches, indicating additional features that can enable a transformative shift for restoration upscaling (panel b). Grey circles (upper panel) indicate ecosystem services (ESS) often not included in local interventions (panel a) while green circles indicate key ESS (panel b) to be targeted by upscaled restoration (after [82]).

Table 2
Selection of pilot restoration cases representing coastal vulnerability hotspots in Europe, including for each pilot case: a) restoration demonstration plans; b) restoration targets for biodiversity and ESS: c) adaptation-though-restoration pathways; d) transformative governance and policies for upscaled restoration.

Coastal archetype	Restoration demo plans	Restoration targets (biodiversity and ESS)	Adaptation-through-restoration pathways	Transformative governance and policies (upscaled restoration)
Estuarine coastal archetype Wadden Sea North Sea cross-border case	- Estuarine connectivity - Coastal room for habitat dynamics - Circular use of sediments	- Restore saltmarshes & intertidal seagrass; migratory & breeding wetland bird species and migratory fish species - Reduction of flooding and erosion risks; improved water purification; increased climate regulation	- Scalable restoration interventions - NbS building blocks - Pathways with ESS and tipping points	- Coordinated governance shift in the three involved countries - Synergetic restoration policies across borders - Support to trilateral Wadden Sea cooperation (in terms of assessments, metrics…)
Deltaic coastal archetype Ebro Delta Western Mediterranean case	- River to coast connectivity, dam by-passes and controlled floods - Coastal room for sustainable buffer / filter - Along and across shore connectivity, removing barriers with new habitats for ESS	- Restoration of wetlands, seagrass, beaches & dunes; Annex I Bird species plus several species on Habitats Directive - Higher fish stock; reduction of flooding and erosion risks; improved water purification; increased climate regulation	- Living lab for adaptive restoration - Coordinated river/coast plans with Restoration Platform and Governmental coordination - Delta as green infrastructure with quantified services	- Co-designed governance shift with coordinated co-management tables - Restoration policies from relevant Government bodies that incorporate bottom up initiatives - Integration of stakeholders and researchers for explicit and sequential targets within a Restoration Revolution
Lagoon coastal archetype Venice / Arcachon Lagoons Adriatic and Mediterranean lagoon cases	- Protection of saltmarsh edges and halophytic vegetation using naturalistic engineering techniques - Refilling of wetlands using sediments dredged from the lagoon - Restoration of natural morphological structures of wetlands to favour migratory bird areas	- Restore wetlands and seagrass; 3 marine seagrasses & 4 fish sp. of EU importance; 12 bird sp. from the Birds Directive - Higher fish stock; reduction of flooding and erosion risks; improved water purification; increased climate regulation	- Living lab approach to adaptive restoration - Adaptation pathways that coordinate short to long term objectives, with restoration implementation to avoid TP crossings - Scoreboard for NbS and ESS to make explicit socioeconomic criteria and to generate engagement	- Public/private partnerships to finance restoration, building upon the existing administrative structure - New policies, implementing governance mechanisms that support restoration and promote its implementation - Decision support tool based on big data and machine learning

socio-economic engagement and hinder the consensus required to share restoration benefits or common TPs [43,44]. These TPs should consider transient conditions (e.g. in river discharge regulation), extreme events (e.g. combined surge and wave storms) and adaptation timing [92]. Otherwise TPs may fail to delineate sustainability thresholds, leading to cumulative impacts [45] that drive many coastal degradation cases.

3.2. Barriers to restoration up- and out-scaling

The transition from local restoration to large-scale implementation (Fig. 1), as required by increasing climatic and anthropic pressures, is hampered by a range of barriers [46,47] that can be structured into three main categories, as described below and summarized in Table 1.

- Technical barriers: due to limited engineering and ecological expertise, scarce accommodation space and demand for a rapid ESS delivery and biodiversity recovery. This is compounded by limited maintenance and data available [48,49].
- Financial barriers: due to limited funding, undervaluation of restoration benefits, insufficient mechanisms for capturing restoration value (i.e., converting the value into revenue streams that can fund restoration projects), and a lack of capacity to develop restoration business plans that are attractive to investors. [50].
- Governance barriers: due to fragmented structures, social inertia and stakeholder conflicting interests. This is aggravated by unsupportive policies, favouring short term objectives that hinder new governance arrangements [47].

These barriers will vary with coastal archetype, habitat considered, climate conditions, restoration scale and stakeholder history, as presented below.

a) **Technical barriers**
- **Acute degradation level and divergence in target state**, which may suggest renovation rather than restoration approaches [22], conditioned by available natural resources, environmental quality, meteo-oceanographic climate and applicable policies. These elements and their interactions result in technical barriers to restoration upscaling, as illustrated by sand availability in many deltas or limited accommodation space on urbanised coasts. The problem may be compounded by lack of data or accepted metrics and limited application of new tools, such as early warning systems, seldom applied to pre-condition the coast before storm impacts. Restoration upscaling requires the support of new data and models [77] to make explicit the range of target states and synergies or tradeoffs involved, as illustrated by restoration plans [52] that promote upstream erosion to enhance accretion for sediment-starved downstream coastal systems.
- **Insufficient restoration pace/scale with uncertain benefits and tradeoffs**, where the lack of metrics and limited knowledge on hydro-morpho-eco interactions limit the resilience and sustained delivery of ESS and biodiversity recovery from the interventions. For instance, seagrass beds increase coastal blue carbon but may reduce onshore sediment transport and, thus, may decrease vertical accretion in adjacent inshore wetlands [111], reducing their adaptation capacity under accelerated SLR. Moreover, outcomes for some targeted populations (e.g. Bird Directive species) and some ESS may become available only at a certain time after restoration (e.g. slow growth of submerged meadows under polluted waters) or require continuous maintenance (e.g. sediment bypassing). This might lead to insufficient restoration outcomes, including risk reduction rates which, unless restoration is upscaled, can increase stakeholder mistrust in restoration [53].
- **Poor sequencing and limited compatibility with existing infrastructure**, which constitute important requirements for stakeholders and financial commitment, but are rarely addressed in restoration plans. This is because upscaling plans introduce technical uncertainties due to more complex boundary conditions and interactions, as illustrated by changing water and sediment availability in different catchment basin sectors or by changing seawater temperatures in coastal seas and deltaic bays/lagoons, which may affect transplantation success [93]. These barriers to

restoration upscaling also include interactions with existing infrastructure, illustrated by dams or groynes, which may produce sedimentary deficits in lower river courses and along coasts [94, 95]. Recent restoration experiences provide limited data on the impact of infrastructure for future climate conditions. Overcoming these technical barriers requires new knowledge and models, which are now becoming available [77] to simulate what if scenarios for up- and out-scaling of climate-proof restoration.

b) **Financial barriers**

- **Limited public and private funding**, where public funding for restoration is generally limited, and any restoration activity needs to compete with other demands for public money (education, health care, security, etc.). In recent years, additional pressures were put on public budgets due to economic/financial crises and austerity policy [96]. Private funding can to some extent supplement public funding, in particular through environmental NGOs, nature foundations and philanthropists, but again, budgets are limited.
- **Undervaluation of the benefits of restoration**, which is one of the reasons why restoration projects may fail to compete with other public projects (e.g., grey infrastructure projects). This is because restoration activities provide a wide range of ESS and biodiversity gains which are seldom considered in project appraisals due to the difficulty in monetizing them [97]. Furthermore, restoration projects often have a large time-lag between implementation and delivery of full benefits (e.g., plants need to grow), and therefore have limited influence on economic decisions due to discounting [98]. Finally, the high option value of restoration, which refers to the value of restoration to self-adjust or be adjusted under changing conditions, is seldom included in project appraisals, leading to a bias for grey infrastructure solutions as these generally have low option values [43]
- **•Insufficient revenue generation,** since even when restoration projects deliver high benefits, this does not necessarily mean that they can attract (private) finance. A prerequisite for finance is that the values generated by restoration activities can be converted into revenues (i.e. cash flows), because only then can these revenues be used to repay the (private) investor. For restoration projects, however, benefits are difficult to convert into revenue streams, because benefits have public good characteristics, are dispersed across diverse beneficiaries, and some occur stochastically (e.g., the full benefits of flood protection only occur during extreme high-water level events). Furthermore, the benefits of restoration activities often have a higher variability and are more uncertain as compared to grey solutions [98]. For these reasons, revenues from restoration are often perceived to be risky and "light" by investors [99].
- **Lack of attractive business plans**, because even when the conditions for funding and financing are favourable, initiators of restoration projects often lack the expertise to put together business plans that are attractive to investors [99]. Specifically, initiators of restoration projects are usually not familiar with the finance terminology, and have often limited experience with investment planning.

c) **Governance and policy barriers**

- **Institutional inertia that may hinder restoration-supportive policies** and instead keep favouring conventional interventions, backed by decades of practice, often with unsatisfactory results [47]. The reluctance to adopt innovative restoration policies is compounded by tradeoffs and uncertainties in the expected benefits, which are often slow to realise. Short term socioeconomic interests may also discourage the development of restoration supportive policies, presenting analyses without an ethical error assessment [51] and casting doubts on the benefits of NbS. This may result in decisions that avoid political costs and favour do-nothing options over restoration.
- **Limited socioeconomic commitment to and confidence in NbS**, attributing the limited biodiversity outcomes and delivery of ESS to failing restoration and underestimating barriers and costs of small scale interventions [10,16]. Barriers arising from fragmented policies and limited legislative coordination are seldom considered, despite being a common cause of limited restoration success. Divergent views among different levels of governance and conflicting public and private interests, may further hinder socioeconomic engagement to restoration upscaling, justifying shorter term views and interests.
- **Lack of consensus adaptation pathways**, hampering the inclusion of long-term priorities and shared aims into current decisions and/or mid to long term planning. The lack of an agreed road map or target state for coastal adaptation-through-restoration, will affect coastal systems for present and future generations. Coastal adaptation barriers will be compounded by transient financial support and volatile, often not well coordinated, decisions and associated policies.

The barriers described above, commonly acting in combination, hamper restoration upscaling and undermine the restoration tenet, contributing to a progressive coastal degradation that we shall leave as an inheritance to the coming generations. The barriers to outscaling will aggravate the global coastal degradation, as many coastal systems are approaching irreversible losses, particularly in low-lying coastal environments [112]. These coastal tracts (e.g. deltas), are easier to urbanise but more threatened by relative SLR due to subsidence, demanding thus more urgent restoration. Overcoming these barriers to restoration up- and out-scaling requires a combination of technical advances and financial instruments, supported by a transition in governance with appropriate mechanisms. All of this should be attainable with a modicum of coastal "optimism", as discussed in what follows.

4. Enablers against restoration barriers: synergistic innovations

Innovation may help to overcome current barriers to restoration up- and out-scaling, applying recent developments in biophysical sciences and recovering knowledge from traditional expertise, such as re-establishing sediment laden river discharges (e.g. [83]), which was a traditional practice in deltaic areas. New techniques, enhanced funding, socio-economic engagement and a transformative shift in governance and policies can act as "enablers" that support such restoration up- and out-scaling and contribute to fill the present implementation gap. Innovation-based transformation should jointly consider short and long term social-ecological aims, supported by an objective assessment of biodiversity and ESS that, to ensure a sustained engagement, should be based on ethics and equity among social groups and generations [51, 54]. A focused summary of innovations, well suited for adaptation-through-restoration plans and apt for up- and out-scaling, is presented for vulnerable coastal archetypes in the following paragraphs. We advocate that a synergistic combination of NbS as building blocks, within a scalable adaptation-through-restoration plan, will increase the scale of coastal restoration and speed up the required implementation.

The innovations described below have been derived from a complementary set of pilot cases (Table 2) from the REST-COAST EU research project (https://rest-coast.eu/https://rest-coast.eu/) that illustrate how human pressures may alter biodiversity and decrease ESS delivery (Table 3). These pilot cases demonstrate the potential of restoring connectivity and natural dynamics to improve biodiversity and promote resilience based on a decarbonised coastal protection and enhanced blue carbon. Restoration targets natural values and socio-economic outcomes, going beyond the limits of traditional coastal engineering interventions (see e.g. [100–103] for the Venice lagoon case).

a) **Technical innovations**

Table 3
Common human pressures that, because of the limited size of restoration implementations, increase coastal vulnerability in the considered pilot sites. The vulnerability increase has been related to a reduction in biodiversity (BDV) and ESS delivery, from analyses performed in the pilot cases (Table 2). The main negative impacts of human pressures in these examples (see references from the pilot cases) are the following: reduction of biodiversity (termed BDV in the Table), impairment of food provisioning (termed FP), loss of climate regulation potential (termed CR), loss of water quality purification capacity (termed WP), increase of coastal flooding risk (RF), increase of coastal erosion risk (RE).

Human pressures (proposed restoration)	Impacts on BDV & ESS Bio-diversity BDV	Food Provisioning FP	Climate Regulation CR	Water Purification WP	Flood Risk Reduction RF	Erosion Risk Reduction RE
Disruption of coastal and river-coast connectivity (increasing water/sediment fluxes with by-passes and controlled flooding)	X	X		X	X	X
Degradation of coastal biodiversity (active/passive restoration of dune/beach, wetland and seagrass habitats)	X	X	X	X	X	X
Lack of accommodation space for coastal dynamics (increasing backbeach space and promoting geo-bio-diversity for resilience)	X		X	X	X	X
Loss of coastal habitats and quality (enhancing hydro-morpho-ecological synergies for a healthy coast)	X	X	X	X	X	X

- **Restored connectivity supported by advanced modelling.** Restored connectivity in river-delta-coast continuums will increase natural resilience and environmental quality with a low carbon footprint. Enhancing coastal accommodation space to connect coastal tracts, or dam sediment by-passes to connect river stretches, illustrate some of the possible interventions [34,38]. These should be supported by advanced monitoring and modelling. Available forecasting models, for instance, can inform coastal or river bypasses for sand-starved coasts, incorporating natural transport in downstream controlled floods, or performing coastal nourishments for incoming storms as rapid defence measures [4]. These technical "enablers", tested in a limited number of cases [55], can enhance sediment fluxes towards deltaic-coastal systems, supporting inorganic soil trapping and the development of vegetation for organic soil production, increasing thus coastal resilience and biodiversity under surges, waves and SLR.
- **Implementation within a safe operating space.** Planning interventions within such a safe space, defined in terms of key biophysical variables and their thresholds, will enhance the sustained recovery of biodiversity and delivery of ESS, with thresholds defined from advanced simulations and observations that characterise hydro-morpho-eco-logic interactions. This can be exemplified by limits in seabed mobility (vertical accretion-erosion) or nutrient concentrations, outside which seagrass vegetation cannot survive [56]. Restored seagrass meadows, with an enhanced extent and density, will contribute to coastal risk reduction and healthier habitats for fisheries and aquaculture, providing additional benefits to coastal stakeholders. The extent, shape and density of seagrass meadows and wetlands are, hence, key components to define the safe operating space thresholds for a resilient restoration [114].
- **Increased pace of restoration upscaling.** The pace and scale of restoration implementations should be adjusted to climatic and human pressures, considering existing infrastructures. The proposed adjustment should ensure biodiversity and a sustained ESS delivery under changing socioeconomic and climatic conditions. This can be illustrated by the implementation of dam by-passes or coastal back-passes, supported by natural power (e.g. flood events) to redistribute sediments. This flooding, marine or riverine, also presents tradeoffs such as damages to socioeconomic assets, salinization of farming soil, etc. [14,21]. The services and disservices of restoration upscaling should, thus, be ethically evaluated and presented with estimated uncertainties to coastal stakeholders, so that the rate and pace can be adjusted according to services (e.g. volume and rate of sediment reaching the coast) and tradeoffs (e.g. bypass of polluted sediments).
- **Proactive maintenance with performance indicators.** An advanced in-time maintenance, steered by harmonised metrics and data, will enable a sustained and controlled delivery of ESS in parallel to an improved biodiversity status, comparing the performance of restoration interventions. Such maintenance will ensure that coastal systems remain within the thresholds of the safe operating space, while enhancing synergies from relevant hydro-morpho-ecological interactions, such as polluted sediment that may hamper wetland or seagrass development if thresholds (TPs) are exceeded. The application of TPs to upscale restoration requires harmonised metrics, and the support of an early warning system that forecasts key hydro-morpho-eco variables, to anticipate additional protection for vulnerable coastal habitats under incoming storms. Such additional protection (e.g. trench/dune reshaping or sandbag barriers), should limit undesired impacts on coastal systems, while enabling natural adjustments. These adjustments are driven by available storm or flood energy, e.g. overwash in deltaic barrier beaches that enhance barrier width or improve lagoon or bay environmental quality [4,44].

b) **Financial innovations**

- **Increasing restoration funding.** This will be achieved by overcoming the undervaluation of biodiversity gains and ESS, leading to higher benefit-cost ratios based on the full gamut of mitigation and adaptation benefits [57] and the option value of restoration through methods such as real-option analysis [104]. Additional private funding should also be increased in the context of company corporate social responsibility, as well as from individuals via crowdfunding campaigns.
- **Innovative value capture instruments and business models,** able to capture the value delivered by restoration. Public value capture instruments are important, because about 75% of NbS across Europe are funded publicly [105]. Promising solutions include municipal finance vehicles such as public-private partnerships, regional resilience funds [106] and land value capture instruments such as coastal levies, surcharges [107] or land sale [108]. Restoration savings, from technological advances (Section 4a) or from a better distribution of risks and responsibilities (public and private actors involved in the implementation) should also be considered [109,110].
- **Improved capacity to develop business models and bankable plans.** These plans should provide guidance and training for restoration practitioners in business planning, and contribute to co-develop business plans with tailored funding and financing arrangements among practitioners and finance experts [97].

c) **Governance and policy innovations**

- **Multi-level governance mechanisms.** The mechanisms proposed, advancing in integration and supported by favourable policies, will contribute to consolidate a systemic approach to restoration. Systemic interventions must go together with a river-delta-estuary-coast integrated governance, supported by the proposed technical and financial innovations (Sections 4a and 4b). These governance mechanisms should result in enhanced natural resilience for river-coast continuums, integrating the concept into policies and decision making. This can be illustrated by river hydrologic plans [61] which explicitly consider coastal protection plans and jointly contribute to EU/National Directives (e.g. Water Framework, Floods, Habitats, Green Deal…).

- **Explicit accounting of coastal natural capital**. Coastal governance should account for the social-ecological benefits from ESS and prove the benefits of synergies among ecosystems for large scale restoration projects. A regular assessment of biodiversity and ESS delivery, considering the multiple time/space scales involved and the variety of actors benefitting from the targeted services, should be periodically presented to all relevant stakeholders. Such accounting for multiple ESS and dissemination of restoration outcomes will enable to overcome restoration barriers associated with present conflicts in degraded systems, such as sediment starved deltas [37] under present conditions and future SLR. Communication plans should present ethically and with estimated uncertainties, the multi-faceted outcomes of restoration for present and coming generations, particularly under changing climate scenarios.
- **New policies towards decarbonised coastal protection**. The proposed shift in policies should promote habitat restoration as an alternative to coastal rigidization, with interventions that can become more resilient under accelerated SLR. This approach to coastal protection will enable an adaptation that is aligned with mitigation, based on low carbon protection and enhanced coastal blue carbon from restored coastal habitats. These new policies require a convergence of stakeholders in a coordinated effort towards large-scale restoration, as illustrated by some deltas worldwide [66], whose sustainability pathways aggregate river hydrology and coastal protection plans. Such coordination will help to develop the exceptional potential of coastal blue carbon [58] and to promote an up- and out-scaled low carbon coastal protection. Expected benefits include territorial cohesion by shared risk reductions and compensation of carbon accounting, which may help to overcome some present conflicts, for instance, between upstream and downstream communities in river-coast systems.
- **New plans for a transition in governance**. The proposed shift in governance will lead to policies harmonised among regions and countries that are better aligned with higher level frames such as the EU Green Deal. Such a transition should be better suited to support restoration up- and out-scaling, contributing to fill the present implementation gap and to meet increasing socio-economic demands under changing climatic and human pressures. Upscaled restoration plans, complying with national, EU and international legislation, should proactively engage a broader range of stakeholders, sharing the benefits from enhanced biodiversity and risk reductions within a resilient coastal adaptation that is aligned with climate mitigation.
- **Continued training for deeper stakeholder involvement,** complying with local features and history for capacity building in a wide range of investors and funders. This training will be supported by Coastal Restoration Platforms, which are organised fora where public and private stakeholders meet regularly with scientists, investors, managers and policy makers. Restoration Platforms, under different names, exist or are being organised at all the pilot sites (Table 2), with participation of various level of Government, NGOs and conservation groups, scientists and relevant socioeconomic actors. Their work builds upon technical, financial and governance innovations, which can act as enablers for an increased socioeconomic commitment, based on the continuous training and new tools/knowledge provided.

5. Upscaled adaptation-through-restoration plans: illustrative pilot cases

Adaptation-through-restoration plans should be suited for up- and out-scaling, while complying with site-specific constraints and history (good and bad practices). Large scale restoration must consider local and regional climates, environmental and ecological conditions plus socio-economic characteristics and culture, to overcome the technical, financial and governance barriers. The upscaling approach for the pilot cases presented below, aims to achieve a resilient risk reduction and to prevent current barriers bogging down large-scale restoration. The three selected pilot cases represent vulnerability hotspots and correspond to lagoonal, deltaic and estuarine systems. The fourth case presented, tackling worldwide coastal restoration, aims to provide criteria for ranking global restoration implementations, in support of an out-scaling for the proposed approach.

a) Arcachon lagoon (France). Lagoon coastal archetype

The Arcachon Bay, with a submerged area that ranges from about 150 km^2 to 50 km^2 depending on tidal phase, represents the tidal coastal lagoon archetype, and is located on the SW Atlantic coast of France. It hosts the largest *Zostera noltii* seagrass meadow in Europe as well as several *Z. marina* beds in the subtidal area [59]. These *Z. noltii* meadows have lost 45% of their surface area in the last two decades, with a corresponding loss of *Z. marina* of about 90% [60]. This negative evolution results in a steady decrease of ESS, such as protection against flooding/erosion or loss of coastal blue carbon. The governance structure is complex, suited to the broad range of actors and users of the lagoon, including tourism, oyster farming and natural parks [59].

Limited achievements from zonal seagrass restoration measures have reduced socio-economic confidence in NbS, where technological, financial and governance barriers have hampered a larger scale implementation. A systemic restoration of the whole lagoon should consider all the relevant biophysical interactions with neighbouring coastal and land systems and socioeconomic interactions with local and national actors. Such a systemic approach will enhance funding and legislative support, enabling the upscaling required to restore the Zostera meadows and deliver ESS that can increase engagement and funding. Overcoming these social, institutional and financial barriers requires technically innovative solutions, which demonstrate the upscaling potential for seagrass recovery. Innovations are particularly required to protect meadows at the early development stages and under energetic hydrodynamic conditions, when high bed shear stresses disrupt plant growth. The proposed technical innovation to stimulate seagrass re-growth comprises a hybrid solution, combining grey infrastructure and NbS, based on a tide and current attenuation device called La Roselière (Fig. 2), already tested in local restoration interventions. This biomimetic device, structurally reproducing grass and algae sheltering effects, is made up of ropes of adjustable length, on which coconut wicks are fixed. The grey infrastructure part provides the hydro-morphodynamic damping required for seagrass to develop under a wider range of hydrodynamic conditions, including climatic or human modulations (e.g. SLR or enhanced tidal currents due to dredging). The seagrass development, NbS part of the intervention, allows further damping of hydrodynamic drivers and increases the resilience of the system to future disturbances expected to increase in coastal lagoons worldwide.

The amount of hydro-morpho-dynamic damping should preserve the natural variability of the lagoon system and be assessed for a wide enough range of meteo-oceanographic conditions. Recent results from local projects have shown how a device such as La Roselière may enable a significant increase in seagrass meadows and seabed structural

Fig. 2. Illustration of hydro-morphodynamic damping from La Roselière, a hybrid grey infrastructure/NbS approach for coastal restoration developed by EGIS-Seaboost and deployed at Arcachon bay, south Atlantic coast of France (credit: A. Musnier, Seaboost).

recovery in the lagoon, when compared to conditions without technically-enhanced restoration [60]. This type of approach, combining grey infrastructure and NbS, supplemented by increased funding and favourable governance and policies, should enable upscaled seagrass restoration. In large scale interventions biophysical fluxes within the lagoon should be proactively maintained within a safe operating space. Such maintenance, combining monitoring and simulations (e.g. additional damping when indicated by an early warning system) within an adaptation-through-restoration plan, requires enhanced funding and engagement for a proactive maintenance.

The proposed restoration plan should demonstrate how modulated lagoon fluxes and increased connectivity can enhance biodiversity and ESS delivery. The resulting improvement of *Z. noltii* beds should serve to attract further funding based on the achieved risk reduction and biodiversity gains. The application of harmonised metrics for biodiversity and ESS delivery will enable a comparison of restoration results versus negative evolution trends in other lagoon systems, supporting the outscaling to other restoration sites and contributing to fill the implementation gap in large-scale seagrass restoration projects.

a) **Ebro delta (Spain). Deltaic coastal archetype**

The Ebro delta, with an area of 320 km^2 and 40 km of coastline, is located on the Mediterranean NE coast of Spain and represents the microtidal sediment-starved deltaic archetype. This delta hosts a wide range of habitats with rich biodiversity, which provide important ESS, most of them "subsidized", as in other river-delta-coast continuums, by the Ebro river discharges [61]. The Ebro delta, supporting important rice fields and aquaculture activities, has experienced intense reshaping, subsidence and area losses since the turn of last century. This retreating evolution, with shoreline erosion exceeding 40 m/year [4,62] and relative SLR up to 5 mm/year is the result of progressive river regulation, with 187 dams and a reduction of solid fluvial discharges above 90% and close to 100% for the sand fraction [61].

Enhanced flooding and erosion have led to increasing risks for deltaic plain activities and infrastructures [63], which are projected to increase under future climate scenarios. The root of the problem is the reduction of riverine fluxes, which leads to an increasing sedimentary deficit and acceleration of relative SLR, combining subsidence and eustatic rise [112]. Any systemic restoration will require progressively larger volumes of sediment to compensate for SLR and subsidence, maintaining relative land-sea levels and thus deltaic sustainability. The sedimentary deficit, growing with time due to accelerated SLR and compounded by subsidence in deltas, cannot be overcome by traditional engineering at acceptable levels of energy use and carbon footprint. This is because seawalls, groynes or even artificial nourishment would have to be maintained and enlarged, to compensate for the enhanced erosion, flooding and salinization due to increasing relative SLR. The cost in terms of energy and the carbon footprint (including that of seawater pumping from increased polderdization) associated to these interventions would increase until a sustainability threshold is reached or the next generation decides to abandon these defences. The proposed adaptation-through-restoration plan is based on a hybrid approach that combines technological solutions and NbS: a) dam by-pass for inorganic sediments, transported downstream by controlled floods; b) damped coastal hydro-morphodynamics, by restored wetlands, dunes and seagrass meadows, facilitated by an increase in coastal accommodation space. Such restoration interventions, complying with river hydrological and coastal protection plans, should increase the resilience of both the deltaic plain and its coastal fringe, reducing risk levels and enhancing biodiversity. The riverine and marine NbS should be coordinated, looking for mutual synergies (e.g. avoiding rapid losses of the new sand arriving from the river to the coastal fringe) within adaptation pathways that restore natural processes and river-delta-coast connectivity to increase deltaic resilience. These pathways (Fig. 3) should be co-designed by relevant stakeholders, linking NbS building blocks within an adaptation strategy that complies with mitigation objectives and is regularly maintained to avoid adaptation tipping points (TP). Demonstrated risk reduction and improved biodiversity, together with new financial instruments and a governance shift, will support further restoration upscaling for similar deltaic systems, steered by adaptation pathways (Fig. 3). These pathways should include: (a) "business as usual" coastal trajectories (AP1 in Fig. 3), with small-scale reactive interventions, where tipping point A (TP A) represents significant losses of coastal area/resources; (b) reactive coastal trajectories (AP 2), with local re-alignment/re-naturalization and piecewise rigidization works, where TP B represents, as before, significant losses of area/resources; (c) rigidization coastal trajectories (AP 3), with large-scale conventional interventions to achieve a fixed (in the short term) coast line, where TP C represents economic/environmental limits associated to short-term impacts and costs; (d) medium-scale restoration trajectories (AP 4), with a proactive reconnection of coastal hydro-ecological fluxes, where TP D represents limits in socioeconomic acceptance associated to thresholds in costs or availability of natural resources (e.g. space or sand); (e) large-scale restoration trajectories (AP 5), with basin-scale reconnections and wholistic coastal restoration, looking for synergies to enhance

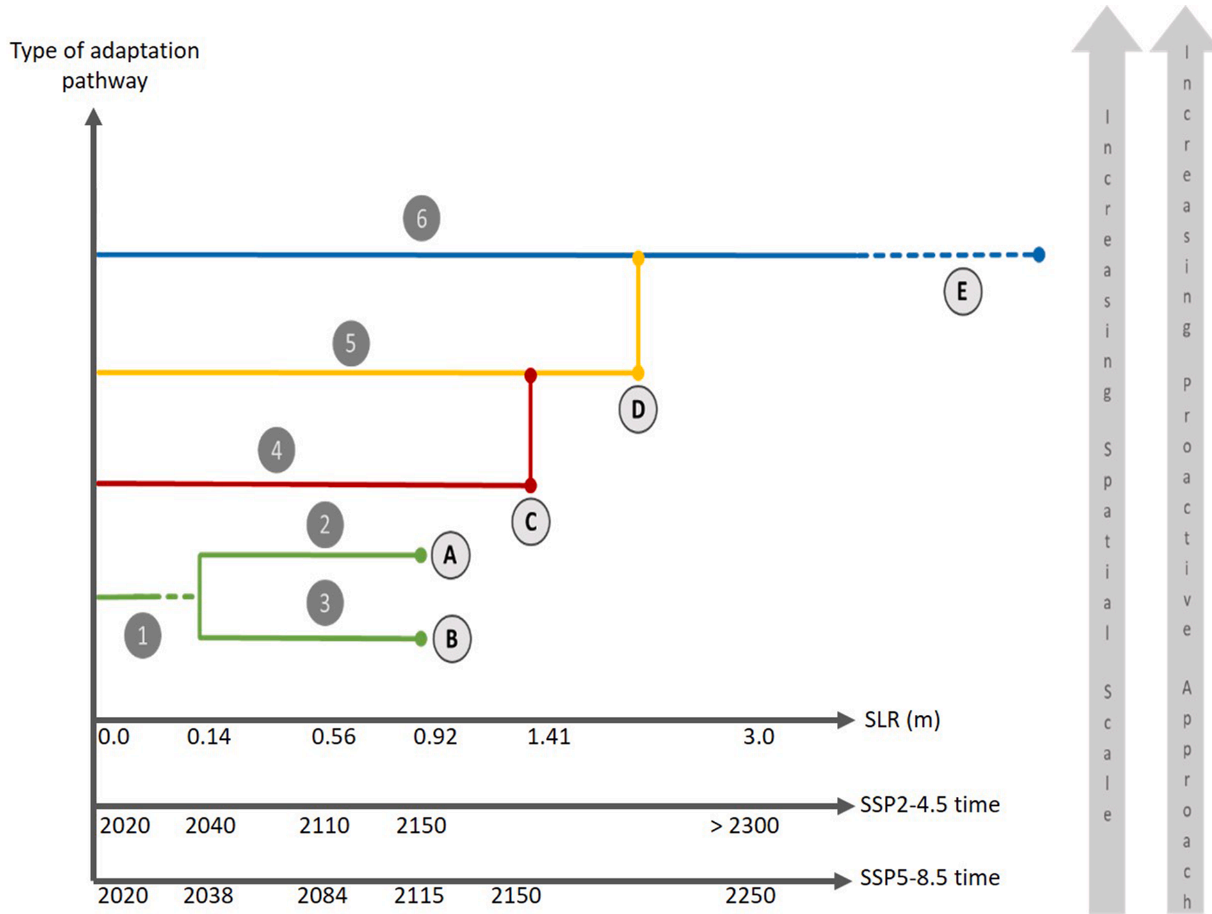

Fig. 3. Set of pathways for deltaic/estuarine adaptation-through-restoration plans. Horizontal axis indicates qualitatively SLR levels without subsidence for the Ebro pilot and approximate time horizons for an average (SSP2-4.5) and a pessimistic (SSP5-8.5) scenario from AR6 of IPCC [30]. Vertical axis represents types of possible adaptation pathways, with inner vertical lines indicating transitions from one pathway to another. The types of adaptation pathways considered are (see text for more details): (1) small-scale reactive interventions (business as usual, BAU); (2) mid-scale reactive interventions (moderately upscaled BAU); (3) large-scale rigidization (upscaled traditional engineering); (4) proactive medium scale restoration (moderately upscaled combination of NbS); 5) proactive large-scale restoration (upscaled combination of NbS); 6) systemic restoration plus adaptive management (upscaled restoration paired with monitoring and maintenance).

ESS delivery, where TP E represents a limit in available natural capital, in particular water/sediment resources; and f) systemic restoration trajectories (AP 6), with an adaptive management that includes the long-term maintenance of coastal connectivity and dynamics, where TP F represents socioeconomic commitment limits. The relative location of TPs along the time axis, although qualitative, is based on the expertise from previous studies on Mediterranean sediment-starved deltas [62, 63]. These proposed pathways should enable a proactive approach to restoration up- and out-scaling for deltaic and estuarine systems, contributing to fill the present implementation gap.

a) **Wadden Sea (transboundary). Estuarine coastal archetype**

The Wadden Sea, shared by The Netherlands, Germany and Denmark, is a UNESCO World Heritage site, hosting a rich biodiversity and wildlife in the largest temperate system in the world of intertidal sand/mud flats and salt marshes. The Wadden Sea represents the intertidal ecosystem archetype, with wetlands, estuaries, lagoons and islands under meso to macrotidal conditions. It is subject to important human pressures, features over 500 km of coast and a total area of 14,700 km^2, of which 11,208 km^2 are under protection status to preserve the largest intertidal seagrass area (more than 200 km^2) in Europe [64]. Wadden Sea estuaries, shaped by human intervention, have experienced dredging and eutrophication that, through interactions, can develop into severe threats to the ecological system. This is confirmed by the seagrass beds decline over the last decades in the Dutch and Lower Saxonian Wadden Sea, where the evolution trend may be compounded by climatic and human pressures. In these areas, seagrass meadows appear to be recovering due to measures that lower nutrient discharges and reduce eutrophication, reversing the mentioned declining trend [49].

Such a recovery is not apparent in the central and SW Wadden Sea, including vast estuaries such as Western Scheldt, Elbe, Ems and Weser, where human interventions have decreased ESS from seagrass meadows, oyster beds and salt marsh pioneer zones. Effects of human-induced changes in Wadden Sea morphology have been associated with a hyperturbid system and water quality degradation, where local restoration interventions have not been enough to reverse the decline in ESS delivery.

An upscaled adaptation-through-restoration plan that includes monitoring and maintenance, is considered the most sustainable strategy for reversing the loss of habitats and environmental quality. This is the goal of some present initiatives, such as the Trilateral Monitoring and Assessment Programme or TMAP [113]. Upscaled restoration should build upon available seagrass ecosystem management recommendations [66], based on an inland-sea connectivity (Fig. 4) that enables the recovery of tidal flats and salt marshes. This recovery and the enhanced delivery of ESS will result in improved water quality, reduced suspended sediment and modified nutrient cycling resulting in lower nitrogen loads, proving the shared benefits of upscaled restoration. By

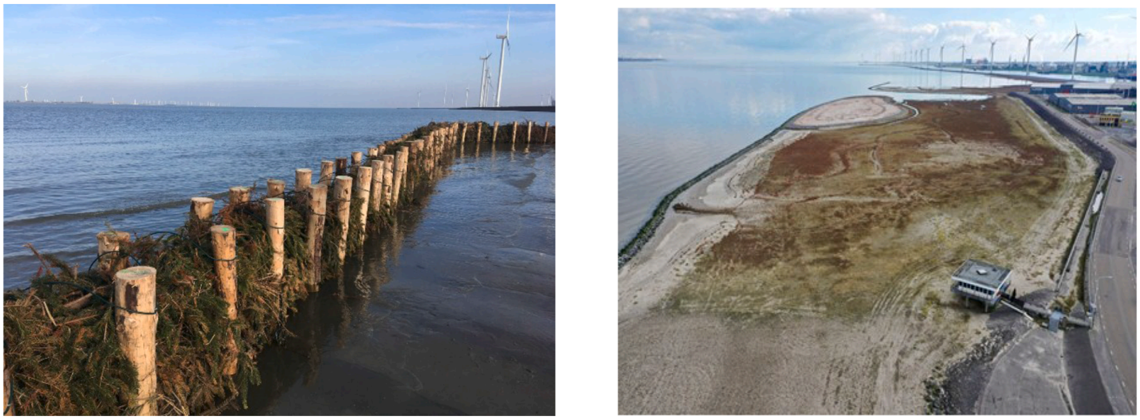

Fig. 4. Wave damping based on natural barriers to promote sediment accretion and salt marsh development (left) and large-scale salt marsh reconstruction (right) to reduce flooding risks with NbS near the city of Delfzijl (The Netherlands) in the Ems-Dollard estuary.

extending and creating new saltmarsh areas (e.g. Ems-Dollard estuary), further accretion and environmental quality improvements are expected [67], promoting the value of estuaries as habitats for birds and benthic/fish species [65]. These results support the out-scaling of the proposed approach, based on long-term ecological and economic benefits in spite of apparent short-term economic losses.

Large-scale adaptation-through-restoration plans for these systems enable sufficient conditions for habitats and ESS to keep pace with increasing climatic pressures and to revert long-term and large-scale morphodynamic imbalances. These imbalances, associated with existing diking, have resulted in losses of tidal flats [113], where the required restoration upscaling is prevented by divergent interests between conservation groups and different socio-economic sectors. These barriers, compounded by the complexity of monitoring and maintenance by three different EU countries, may be aggravated by shortcomings of EU and national laws for habitat protection and policy fragmentation in three countries, which together do not favour large intervention scales, hinder funding and limit social engagement.

Adaptation-through-restoration pathways, based on natural dynamics and connectivity, should be supported by modelled coastal trajectories that anticipate the results of various NbS and hybrid solutions operating at different scales, as a function of implementation sequences. Simulated trajectories and early plus climatic warnings should prove the potential of restoration, backed by a proactive management of water/sediment dynamics in the restored domain. This management, promoting a transboundary restoration of the entire North Sea, should promote synergies between coastal restoration, hinterland planning and land uses, so that restoration benefits become more clearly apparent and tradeoffs are kept under control. An innovative transboundary governance at basin scale can support a shift in policies, which can, in turn, enable further up- and out-scaling of restoration to fill the present implementation gap.

a) Out-scaling to worldwide coasts (global). Ranking and criteria

Worldwide restoration cannot be simultaneously implemented, and it will require a ranking of global coastal systems based on their vulnerability, the potential impacts on natural and socioeconomic assets [9], and the available coastal space, considering water/sediment quality [36]. Such a ranking can be used to build a plan for sequencing implementation, since the limitations in funding and governance differences would preclude a simultaneous approach. Any ranking for outscaling restoration must consider climate change drivers [68], land use socio-economic trends [69], ecological status and capacity to deliver ESS [44]. Recent advances in data and models can now enable such a global analysis, since it is at global scale where biodiversity and ESS, in particular coastal blue carbon [70], can demonstrate their cumulative benefit for a coastal adaptation aligned with mitigation.

By restoring coastal connectivity and accommodation space, ecosystem adaptive capacity will be enhanced [44], improving biodiversity status and increasing ESS delivery, while avoiding some negative tradeoffs of hard engineering, such as coastal squeeze [11]. Coastal squeeze potential can, therefore, be applied as a measure of the coastal adaptation deficit [68], which could be circumvented by the proposed adaptation-through-restoration plans. Simulated coastal trajectories with and without ESS, building upon recent modelling developments [44,9], can serve to assess up to what point restoration can be outscaled globally. A first illustration of this global analysis, based on wetland capacity to reduce erosion and flooding risks, has been prepared for worldwide coasts (Fig. 5), as a measure of their out-scaling potential. The analysis compares coastal evolution differences between: (a) present conditions, where wetland inland migration under SLR is prevented in coastal areas with population densities exceeding 5 people/km^2 and (b) future scenarios, mimicking the implementation of large-scale restoration, where wetland inland migration under SLR is prevented only in areas with population densities larger than 300 people/km^2 [36]. The obtained results point out the importance of reconnecting coastal accommodation space when implementing large-scale restoration, particularly when looking for an adaptation aligned with mitigation through coastal blue carbon and decarbonised protection.

An outscaling of the proposed harmonized metrics, supported by global satellite data and modelling capacities now available, would enable a sequenced approach to worldwide coastal restoration. This approach would overcome the inevitable limitations in global funding and the different levels of development of national policies. Local restoration results can inform national policies, where the technical and financial innovations proposed can help to fill the present implementation gap.

6. Conclusions

To address the current deficit in coastal restoration, particularly at large scales, NbS implementation should be made more attractive for investors and policy makers, engaging stakeholders towards a "restoration revolution". Such a peaceful revolution should align coastal adaptation with climate mitigation, pairing restoration with a maintenance steered by observations and simulations. Monitoring and predictions/projections, represent a minimal cost with respect to the recovery of biodiversity and delivered ESS, but can help to make explicit restoration benefits in front of coastal stakeholders. By providing new tools and data to such stakeholders, conveniently organised into Coastal Restoration Platforms, it should become easier to engage civil society and attract enhanced funding to increase restoration pace and scale.

Local restoration practice has demonstrated that restored

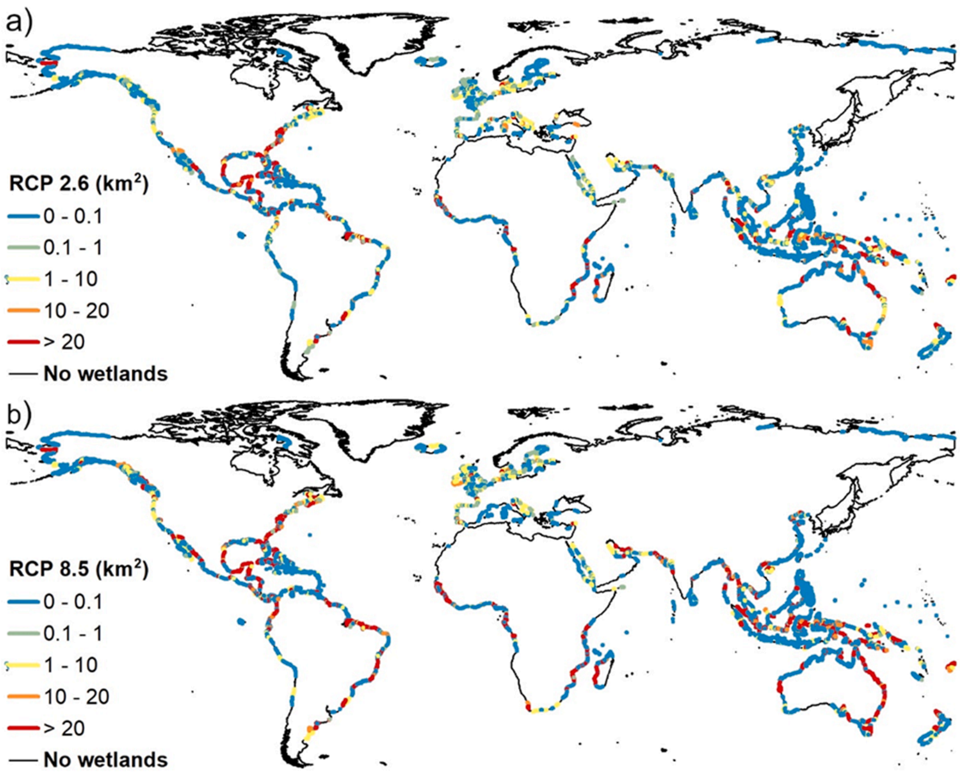

Fig. 5. Global coastal squeeze potential as a measure of the adaptation deficit, for tidal marshes/mangrove forests under climatic and anthropic pressures. Results based on modelled (2010 and 2100) differences in coastal wetland areas with/out inland migration (see text). Coastal squeeze potentials (km^2) are shown for: (a) lower boundary (RCP2.6, 5th percentile - global SLR average = 24.7 cm) and (b) upper boundary (RCP8.5, – 95th percentile - global SLR average = 88.8 cm) scenarios, based on data from [36].

biodiversity and ecosystems can reduce flooding and erosion risks, improve water quality and enhance productivity (aquaculture and fisheries), while increasing coastal blue carbon. These benefits go together with tradeoffs, illustrated by the increasing limitations in available riverine discharges (competing uses for scarce freshwater, curtailing catchment basin erosion while enhancing coastal subsidence and retreat, etc.). Here ESS may modulate the impact of extremes and balance the competing interests of different territories (e.g. upstream versus downstream communities), proving the need for a large scale restoration that reduces risks and improves biodiversity for the full river-delta-coast system. These ESS feature greater flexibility and self-adjustment capacity than traditional rigid engineering for most cases, one notable exception being urban coasts without hinterland for adaptation. The proposed upscaling in connectivity (river to coast and in the nearshore) and synergies (among wetlands, dunes and seagrass meadows and between riverine/coastal domains) should help to demonstrate the potential of upscaled restoration, contributing to fill the current implementation gap. Healthy ecosystems resulting from large-scale interventions, together with their ESS, should enable more resilient coastal trajectories under accelerated climatic pressures, promoting the values of out-scaling restoration as a key element in worldwide coastal adaptation.

Large-scale restoration, based on NbS building blocks, can be favourably compared to conventional engineering interventions or do-nothing options [72], in terms of coastal resilience [71] or stakeholder engagement [78]. Demonstrated restoration success stories will increase restoration funding, supported by the adaptation-through-restoration plans proposed to overcome present restoration barriers [73]. Adaptation pathways will help to sequence the proposed interventions, structuring them within a “restoration revolution” that enables informed stakeholder choices. Decisions on which habitats to be restored, technical approaches to be selected, intervention sequences to be preferred or biodiversity and ESS to be targeted, can then be considered for up- and out-scaling. The increase in restoration scale and pace will underpin the proposed restoration revolution, linking worldwide successful restoration implementations, such as for instance those from the Mississippi delta or saltmarshes in NW Europe [74,80,81]. These success stories, from pilot sites as the ones here presented, will help to overcome present barriers, improving the social bias towards rigid structures or economic analyses that do not internalise all environmental costs, particularly longer-term ones.

Adaptation-through-restoration plans that incorporate early warning systems and climatic projections, can contribute to bridge the gap between short- and long-term restoration goals. Such warnings will help to sequence interventions across time scales, aiming for biodiversity recovery and a cumulative ESS delivery, rather than mortgaging interventions or increasing tradeoffs. There will result a decarbonised coastal adaptation, curbing the current degradation of coastal systems and promoting natural resilience.

NBS Impacts and implications

Environmental concerns

Restoration upscaling for river-delta-coast systems will improve biodiversity status and curb present habitat losses due to water quality degradation and sediment starvation. The associated environmental concerns can be circumvented by an upscaled restoration that consists of NBS building blocks coordinated within a systemic approach.

Economic concerns

A holistic ecosystem service assessment, avoiding the common undervaluation in current analysis and giving the right weight to long-term benefits can help to overcome economic concerns for restoration. The incorporation of new financial instruments, including the tradeoffs required for restoration upscaling, will contribute to enhanced funding.

Social concerns

Combined technical, financial and management innovations can support a shift in governance and perception to enhance social engagement to restoration. The proposed adaptation-through restoration plans, with consensus tipping points, can overcome social concerns that hinder an upscaled coastal restoration, which will lead to risk reduction based on natural capital conservation.

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Declaration of Competing 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.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100032.

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