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Inclusion of condition in natural capital assessments is critical to the implementation of marine nature-based solutions

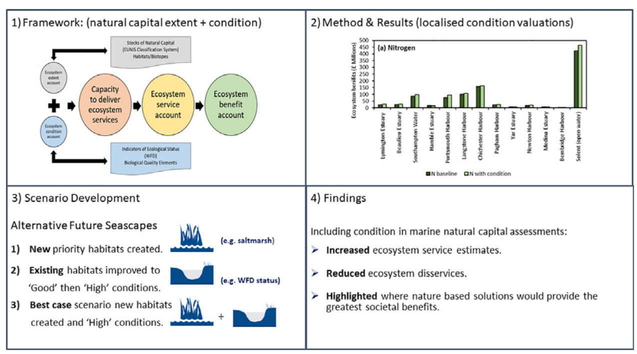
Stephen C.L. Watson [a,b,*], Gordon J. Watson [a], Nicola J. Beaumont [b], Joanne Preston [a]

[a] Institute of Marine Sciences, School of Biological Sciences, University of Portsmouth, Ferry Road, Portsmouth PO49LY, UK
[b] Plymouth Marine Laboratory, The Hoe Plymouth, Prospect Place, Devon PL13DH, UK

HIGHLIGHTS

- Natural capital (NC) condition accounts are assessed using nature-based solution (NbS) scenarios.
- Links between habitat condition (ecological status) and ecosystem services supply are explored.
- Integrating habitat condition indices improved ecosystem service (ES) benefits by 11–67%.
- Not including condition in NC or NbS assessments could lead to undervaluation of ES benefits.
- Restoring existing and creating new NbS habitats in Solent could yield £1.218 billion per year.

GRAPHICAL ABSTRACT



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ABSTRACT

Current approaches to measure ecosystem services (ES) within natural capital (NC) and nature-based solutions (NbS) assessments are generally coarse, often using a single figure for ecosystem services (e.g., nutrient remediation or blue carbon sequestration) applied to the local or national habitat stock, which fails to take account of local ecosystem conditions and regional variability. As such, there is a need for improved understanding of the link between habitat condition and ES provision, using comparable indicators in order to take more informed management decisions. Here the UK, Solent Marine Sites (SEMS) is used as a case study system to demonstrate how Water Framework Directive (WFD) 'ecological status' and other indicators of ecosystem condition (state or quality) can be coupled with habitat extent information to deliver a more precise locally-tailored NC approach for active coastal and marine habitat restoration. Habitat extent and condition data are collected for seven NbS relevant coastal habitats (littoral sediment, mat-forming green macroalgae, subtidal sediment, saltmarsh, seagrass, reedbeds and native oyster beds). The workflow includes: 1) biophysical assessment of regulatory ES; 2) monetary valuation; and 3) compilation of future scenarios of habitat restoration and creation. The results indicate that incorporating classifications by condition indices into local NC extent accounts improved ES benefits by 11–67%. This suggests that omitting condition from NC assessments could lead to undervaluation of ES benefits. Future scenarios of restoration in the SEMS also show that the additional regulatory benefits of reaching 'Good' ecological status are £376 million annually, but could be as much as £1.218 billion if 'High'status and all habitat creation targets were met. This evidence of the potential value of restoration and importance of including condition indices in assessments is highly relevant to consider when investing in water ecosystems conservation and restoration as called for by the UN Decade on Ecosystem Restoration (2021 – 2030), and more generally in global nutrient neutrality and blue carbon policy strategies.

* Corresponding author at: Institute of Marine Sciences, School of Biological Sciences, University of Portsmouth, Ferry Road, Portsmouth PO49LY, UK.
E-mail address: stw@pml.ac.uk (S.C.L. Watson).

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1. Introduction

Natural capital (NC) accounting frameworks are increasingly being used to measure the capacity of ecosystems to provide flows of ecosystem services (ES), which can be defined as "*the contributions of ecosystems to benefits used in economic and other human activity*" (SEEA and United Nations, 2021). NC accounts do this by tracking the extent (or quantity) and condition (or quality) of natural resource stocks (e.g., species, habitats, ecological communities) relative to societal targets using existing regulatory limits and policy commitments (Mace et al., 2015). The majority of NC related studies to date have examined the relationship between habitat extent and ES supply (e.g., de Groot et al., 2012; Costanza et al., 2014; Xie et al., 2017), often linked to developing global or National Ecosystem Assessments (NEAs). An advantage of extent data is that it is relatively easy to measure (e.g., via remote sensing, GIS based habitat mapping assessments, biodiversity inventories, ecological models), the information is readily accessible (e.g., through data repositories such as EUNIS (European nature information system) or OBIS (Ocean Biodiversity Information System)), and it is regularly updated. These attributes mean that extent data is highly applicable for NC accounting purposes, provided that uncertainty is well addressed when comparing extent areas over different points in time. A substantial drawback of using only extent data is that this data does not entirely capture the dynamics or condition of ecosystems and their relative ability (or capacity) to provide ES (Hooper et al., 2021; Keith et al., 2020). Although condition is commonly recognised as important in many NC or ES studies, it is rarely considered in depth and these linkages are also rarely quantified (Rees et al., 2022; Makowska et al., 2022). As such, it is proposed that a critical evidence gap remains around the link between ecosystem conditions and the delivery of ES at local to national scales (e.g., Grizzetti et al., 2019).

The absence of condition from NC assessments also risks providing inaccurate evidence and driving ineffective decision making. Research linking marine or coastal NC asset condition to the capacity of ecosystems to generate ES (ES supply) and the actual use of these service (ES flow) is however still nascent (Hooper et al., 2019), partly due to different approaches used to assess the condition of habitats and with different interpretations of what is meant by the condition of an ecosystem asset. At the international level, the UN United Nations (UN) Sustainable Development Goals (United Nations, 2015) include a broad range of indicators that can be used to determine condition of the marine environment. In the UK and the European Union, ecosystem condition includes the legal concept of "*status*" measured over time and is often compared to agreed environmental directive targets, such as the Water Framework Directive 2000/60/EC (WFD) and the Marine Strategy Framework Directive 1992/43/EEC (MSFD). Under both directives, "*ecological or environmental status*" is a measure of the abundance and composition of different organisms in a food web or habitat and represents an integrative measure of the condition of the waterbody. This concept is commonly used as a synonym for 'ecosystem state' which can be defined as "*the physical, chemical and biological condition of an ecosystem at a specific point in time*" (Maes et al., 2018). Changes in ecosystem state or condition are tightly linked to changes in ES supply. It has generally been correlated that healthy ecosystems can provide a set of essential services which in turn deliver benefits and increase wellbeing (Beaumont et al., 2007; Díaz et al., 2015; Potschin and Haines-Young, 2013), while degraded aquatic ecosystems can lose their capacity to provide services (Culhane et al., 2019).

Supplies of ES relating to ecosystem condition have recently been conceptually correlated with ecological status classifications in terrestrial and freshwater ecosystems (Grizzetti et al., 2016; Maes et al., 2018). Expanding this framework to better understand the relationship between marine and coastal conditions and services would aid in design measures to protect and enhance the ecological and environmental status of marine ecosystems. There is also a need for long-term monitoring of the condition of all types of ecosystem assets using comparable indicators (Broszeit et al., 2017). In particular, limited data are often available to assess the condition of assets involved in providing regulating and supporting services (e.g., Watson et al., 2020) and there is an overwhelming lack of historical data on the state of biodiversity in many marine regions of the world (Tolochko and Vadrot, 2021). In many locations statutory monitoring assessments such as the WFD or MSFD could be the most time and cost-effective source of data on the state of biodiversity or habitat condition; these data can serve as suitable reference levels for NC condition assessments.

To address these evidence gaps, the primary objective of this study was to explore how indices of routinely collected habitat condition data can be incorporated into a marine and coastal NC accounting framework to effectively and efficiently address the issue of including condition in NC assessments. The secondary objective of the study was to use scenario analysis to determine how future habitat restoration approaches might influence the provision of ES and NC. A recent entry to this discourse is 'Nature-Based Solutions' (NbS), defined by IUCN as "*actions to protect, sustainably manage, and restore natural or modified ecosystems*" (Cohen-Shacham et al., 2016), which have a prerequisite that: functioning ecosystems are required to ensure the delivery of ES (Nesshöver et al., 2017). However, the potential of NbS to provide the intended benefits has not been rigorously assessed and there are concerns over their reliability and cost-effectiveness compared to engineered alternatives (Seddon et al., 2020).

A case study of the coastal and estuarine habitats of the Solent Marine Sites (SEMS) situated on the south coast of England UK was selected to provide focus for these two objectives. The SEMS is centre-stage to several important new NbS habitat restoration initiatives (e.g., Harding et al., 2016; RHCP, 2020; ReMEDIES, 2021), which aim to find ways to create and restore the condition of nationally important habitats, such as saltmarsh, seagrass meadows and the threatened and declining native oyster species and habitat (*Ostrea edulis*) (Beck et al., 2011; Helmer et al., 2019), thus it is an exemplar case study to test the transferability of such approaches to other regions. This assessment focused on a biophysical and economic valuation of reactive nitrogen (N), phosphorus (P) and carbon (C) sequestered and stored in benthic habitats, due to increasing NbS policy ambitions of achieving net zero release of these compounds into the marine environment (e.g., blue carbon and nutrient neutrality goals). Blue carbon refers to organic carbon that is captured and stored by the oceans and coastal ecosystems, particularly by vegetated coastal habitats (see Lovelock and Duarte, 2019) and is an increasing imported facet of achieving global net zero targets. Proposals to achieve nutrient neutrality or the net zero release of (N and P) to the marine environment is a relatively recent concept (see Leip et al., 2014), but has wide relevance globally. In the SEMS region, as there are high levels of both N and P input to this water environment with evidence that these nutrients are causing eutrophication at this designated site (RHCP, 2020).

To achieve the primary objective, this study specifically aimed to 1) evaluate the extent and condition of seven key NbS relevant coastal habitats; littoral sediment, mat-forming green macroalgae, subtidal sediment, saltmarsh, seagrass, reedbeds and native oyster beds; 2) examine the biophysical and monetary benefits (or potentially disservices) of adding local condition information to NC accounting assessments; and 3) explore four hypothetical scenarios for existing habitat restoration and new habitat creation to find out how different ES would be enhanced (or degraded) based on different designs of the restoration action. The change in production of specific regulatory ecosystem benefits (i.e., economic cost savings of improved water quality or damages avoided via climate regulation) was then quantified by factoring in proposed new SEMS habitat restoration sites. It is important to notice that this study does not aim to quantify the relationships between the biological condition indices and ES, but instead identifies potential relationships based on existing scientific evidence.

2. Materials and methods

2.1. Background and Solent marine sites condition indicators

Assessment of ecosystem condition can be derived from comparative indicators of 'ecological status' and other such information through routine national assessment methods, e.g., marine habitat quality assessments, bathing water directives, Ecological or Environmental Status (WFD & MSFD), conservation status and trends of species in Marine Protected Areas (MPAs). Here we used the most relevant policy targets related directly to indicators of condition status, for example EU WFD ecological status classes, which describe the condition of the SEMS coastal waters out to one nautical mile. Appendix 1 Table S1 provides a summary of the relative ecological condition criteria used in this study based on WFD ecological status (EQR) data. To represent the local condition of different habitats in the SEMS (see map in Fig. S1) we used the 2016 WFD (cycle 2) summary condition assessments for thirteen waterbody catchments, together with their qualifying sub-feature assessments (Table 1). Six habitats, including littoral sediment, subtidal sediment, saltmarsh, seagrass beds, reedbeds and native oyster (*Ostrea edulis*) beds, were selected based on previously mapped data for the region by Watson et al. (2020) and were *a priori* established using the European Nature Information System (EUNIS) habitat classification system. Green macroalgal mat sediment systems generally dominated by *Ulva, Enteromorpha* and *Chaetomorpha* spp. were also disaggregated from littoral sediment EUNIS classifications and were considered as a separate habitat (see Watson et al., 2020 for methodology). The ecological condition of the seven habitats were then assessed using a range of proxies. WFD classification data for benthic invertebrates in transitional and coastal waters were used as a proxy to represent the ecological status of EUNIS littoral sediment (A2.3, A2.4) and subtidal sediment (A5.2, A5.3, A5.4) habitat condition (Table S1). Similarly, WFD angiosperm biological condition elements were used to represent the status of EUNIS saltmarsh (A2.5) and seagrass communities (A2.61, A5.53, A5.545), while the status of littoral sediment overlain with macroalgal mats was defined using the WFD macroalgae classification blooming tool (Table S1). Common reedbeds (C3.2, C32.1 *Phragmites australis*) fall under the WFD primarily as a feature of water-dependent protected areas, but are often not formally monitored as part of the surface water monitoring programmes. As WFD information was not available for the SEMS we used UK Natural England (NE) maritime SAC (Special Areas of Conservation) condition assessment data (Table S1) as a proxy for EUNIS reedbed habitat condition.

Native oyster bed (A5.435) conditions were calculated based on the percentage of historical (1974) to current (2017) abundance of oyster beds remaining in each WFD catchment. Categories of condition were assigned based on the methodology developed by Beck et al. (2011) as follows: <20% lost ('High'), <50% lost ('Good'), 50% to 89% lost ('Moderate'), 90% to 99% lost ('Poor'), >99% lost ('Bad' or 'functionally extinct') see Table S1. A summary of the calculations used to represent oyster condition in each catchment are given in Appendix 1 (Table S2). The contemporary ecological condition of native oyster beds in the SEMS is 'Bad' (Table 1) or functionally extinct, given that they remain at <1% of prior abundances in all catchments assessed, although individual oysters are still present in most places at densities <1 individual per m^2.

2.2. Assessing habitat condition, natural capital and ecosystem services

Potentially, the achievement of a 'Good' or 'High' ecological status of habitats should mean safeguarding the ecological integrity of marine systems and thereby preserving their capacity to provide ES to humans. In particular, there is increasing evidence that 'Good' ecological status can be related with the delivery of a broad spectrum of ES, particularly regulating services (e.g., Tolonen et al., 2014; Maes et al., 2016; Vidal-Abarca et al., 2016a; Broszeit et al., 2017). This inference is based on recent scientific understanding that the relationship between ecological condition and regulating ES is generally linear in nature and is expected to have a positive relation with the ecological status (e.g., Smith et al., 2017; Grizzetti et al., 2019). Based on this evidence, we applied a conceptual framework (Fig. 1) to assess the capacity of the biological condition indices used in the SEMS to evaluate the ability of coastal and transitional habitats to deliver regulatory ES. In this framework, changes in ecosystem extent and condition have the potential to affect the capacity of systems to deliver ES and benefits. Ecosystem service and benefit accounts (physical and

Table 1
Relative assessment of ecological condition across the SEMS. Based on WFD ecological status data, Natural England condition assessment data and Beck et al. (2011) protocols. Ecological condition is assigned on a scale of 'High', 'Good', 'Moderate', 'Poor' or 'Bad'. *The Hamble Estuary is not a WFD waterbody, therefore the values used here reflect its status within the larger Southampton Water complex. (N/A) no data available (Unfavourable: Unknown Condition), (−) habitat not present. Native Oyster beds under WFD ('Class A', 'Long-term B', 'Class B', 'Class C' and 'Prohibited').

Assessment Unit (EUNIS Code)	Littoral sediments (A2.3, A2.4)	Littoral Sediments (With Macroalgae) (−)	Sublittoral Sediments) (A5.2, A5.3, A5.4)	Saltmarsh (A2.5)	Seagrass (A2.61, A5.53, A5.545)	Reedbed (C3.2, C32.1)	Native Oyster (*Ostrea edulis*) (A5.435)
Total Habitat Extent (ha)	6204	1616	19,486	1261	698	273	2839
Assessment Classification	WFD (2016)	WFD (2016)	WFD (2016)	WFD (2016)	WFD (2016)	NE (2018)	Beck et al. (2011)
Condition Indicator	Invertebrates	Macroalgal mats	Invertebrates	Angiosperms (Saltmarsh)	Angiosperms (Seagrass)	Angiosperms (Reedbed)	Native oysters
Lymington Estuary	High	Good	High	Moderate	(N/A)	Unfavourable - Recovering	–
Beaulieu Estuary	Good	Good	Good	Moderate	(N/A)	Favourable	(N/A)
Southampton Water	Good	Good	Good	Good	Good	Unfavourable - Recovering	(Prohibited) Bad
Hamble Estuary*	Good	Good	Good	Good	Good	Unfavourable - Recovering	(Prohibited) Bad
Portsmouth Harbour	High	Moderate	High	Moderate	Moderate	(N/A)	(Fail) Bad
Langstone Harbour	Good	Good	Good	Moderate	(N/A)	(N/A)	(Prohibited) Bad
Chichester Harbour	Moderate	Moderate	Moderate	Moderate	(N/A)	Unfavourable Recovering	(Prohibited) Bad
Pagham Harbour	Good	Good	Good	Moderate	Moderate	(N/A)	–
Yar Estuary	Moderate	Moderate	Moderate	Moderate	(N/A)	(N/A)	–
Newton Harbour	Good	Moderate	Good	Moderate	(N/A)	(N/A)	–
Medina Estuary	Moderate	Moderate	Moderate	Moderate	(N/A)	(N/A)	(N/A)
Bembridge Harbour	High	Moderate	High	Moderate	(N/A)	(N/A)	–
Solent Channel (Open Water)	Good	Good	Good	Moderate	Moderate	(N/A)	(Prohibited) Bad

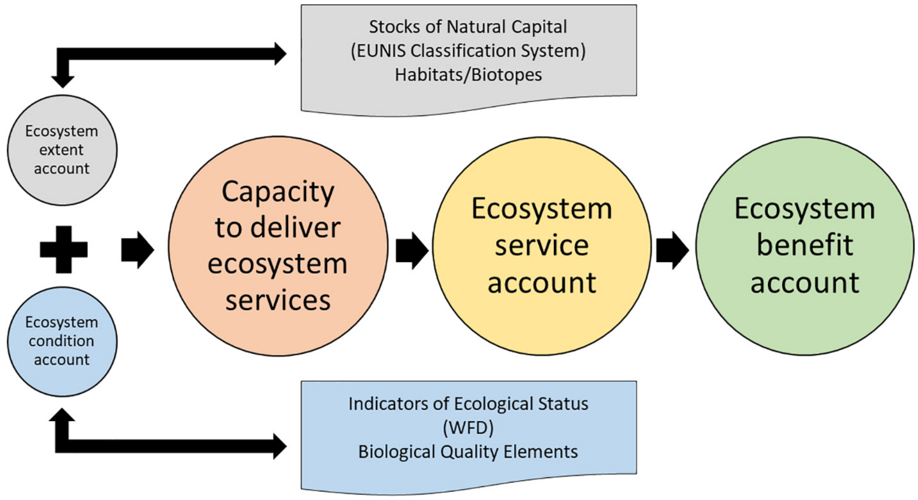

Fig. 1. The conceptual framework used in this study to explore the place of ecosystem condition indices in a natural capital accounting framework. Ecosystem extent and ecosystem condition define the total capacity to deliver ecosystem services. This in turn generates a flow of ecosystem services and subsequent benefits.

monetary) record the supply of ES by ecosystem assets and record information on several final ES, including waste (nutrient) remediation (e.g., Watson et al., 2016) and climate regulation (Beaumont et al., 2014) which are the ES of focus in this study. Data on the biophysical rates for these ES were extracted from previous studies and literature reviews of SEMS habitats following the statistical approaches presented in Watson et al. (2020) using either the median, sample range (minimum and maximum) or interquartile range (75th and 25th percentiles) (see Appendix 1 Table S3).

A five-point scale of biophysical rates for N removal through denitrification and nutrient (N, P and C) sequestration, as a function of nutrient burial in sediments, was then used to describe how ecosystem functions and supplies of regulatory ES relate to different scales of condition (see Table 2). Using this scale, the level of provision made by each respective habitat was adjusted in a hierarchical process using data based on the reference condition of each habitat. As a pragmatic choice of reference site condition, the arithmetic median-(Q2)-biophysical values (i.e., assuming all habitats are in 'Moderate' condition) can be used as a suitable reference level to test if adding habitat condition information effects, the overall supply of ES. The total extent (area) of benthic habitats is fixed in both reference condition (e.g., extent with 'median' conditions) and adjusted modelled reference condition scenarios (e.g., extent with sub-catchment condition information). This framework and procedure is in line with UK (ONS & Defra, 2017) and international (Bateman and Mace, 2020; SEEA and United Nations, 2021) guidance and implicitly involves local qualitative or quantitative adjustments of the initial NC stock. In the case of some angiosperm habitats (e.g., seagrass and reedbed) where there was no WFD regional data and the NE condition data was Unfavourable (Unknown Condition); it is assumed that they are providing an arithmetic median (Q2) level of ES. In the case of littoral sediments covered with macroalgal mats, movement towards achieving 'Good' or 'High' status for this habitat indicates a reduction in the algal mat biomass (Table 2) and therefore a reduction in its nutrient removal potential. The separation and reversal of macroalgal mats regulatory ES delivery vs condition in Table 2 is therefore an artefact of how its ecological status is determined using WFD assessment measures.

The total value of ecosystem benefits for each catchment was estimated using localised replacement costs for removing a kilogram of N or P and UK non-traded carbon prices based on the marginal abatement cost method. Watson et al. (2020) reviewed the annual costs of removing N and P from a wide range of sources in the SEMS, and concluded that average costs ranged from 295 [£/kg] for N and 282 [£/kg] for P. Also following Watson et al. (2020), average abatement costs of reducing CO_2 are estimated as 60 [£/tonnes] per year (DECC, 2011). Combining the previously calculated biophysical rates with N and P replacement costs (£/kg/yr^{-1}) and the CO_2 marginal abatement costs (£/tonnes/yr^{-1}), estimates can be made for the value of these ES.

2.3. Predicting future benefits of habitat creation and restoration

In the last phase of this research, a targeted potentiality analysis was conducted to extend the previous reference condition biophysical estimates, with forecasts of the potential uplifts in ES supply provided if the overall waterbody sub-feature assessments (i.e., individual habitats) transitioned to better ('Good' or 'High') status conditions, reflecting a spectrum of potential changes in water quality and NC asset condition. Four possible future scenarios for habitat restoration in the SEMS were then identified. The scenarios are 1) new NbS priority habitats created; 2) all existing catchment habitats are restored to "Good" ecological status; 3) all existing catchment habitats are restored to "High" ecological status; and 4) a 'best case'

Table 2
Theorised level of regulatory ecosystem service (e.g., nitrogen, phosphorous and carbon burial or sequestration) provided by habitats in various condition states.

Water framework directive ecological status, Natural England and Beck et al. (2011)	Natural England condition assessment	Level of regulatory ecosystem service (all other habitats)	Level of regulatory ecosystem service (Littoral sediments overlain with macroalgal mats)
High	Favourable	Max	Minimum
Good	Unfavourable Recovering	75th percentile (Q3)	25th percentile (Q1)
Moderate	Unfavourable No Change (or Unknown Condition)	Median (Q2)	Median (Q2)
Poor	Unfavourable Declining	25th percentile (Q1)	75th percentile (Q3)
Bad	Partially Destroyed	Minimum	Maximum

scenario with a combination of new NbS habitats created and all existing habitats restored to "High" ecological status.

The aim was to categorise how N, P and C related ES would be enhanced (or degraded) based on different designs of the restoration or habitat creation action. To generate the future scenarios of new NbS habitat creation, we used Regional Habitat Compensation targets calculated for the SEMS area (RHCP, 2020), which has identified the amount of habitat creation required to offset the adverse impacts to the marine designated sites due to coastal squeeze impacts (Table S4). The RHCP is currently focused on creating new saltmarsh habitat, as approximately 392 ha of this habitat type could be lost over the next century due to sea level rise. RHCP targets also suggest that 32 ha of littoral sediment and 17 ha of reedbed will need to be created via the managed realignment activities. To estimate future creation efforts for seagrass beds and native oyster habitats, GIS data layers created by the UK Marine Management Organisation (MMO, 2019) were used which show SEMS sites with theoretical potential for future seagrass and native oyster habitat creation, based on historical extent information. Potential habitat creation targets for seagrass and native oyster beds were calculated to be 8160 and 1458 ha respectively (Table S4). To represent N, P and C provisioning under new and restored habitat conditions, we used the previously calculated median (Table S3) biophysical reference condition values respectively. To represent N, P and C provisioning under new and restored habitat conditions, the previously calculated Q3 and maximum (Table S3) biophysical values were used respectively. The potential gain in ecosystem benefits from creating and restoring habitats were then derived using the same replacement costs and mid UK non-traded carbon prices outlined above in Section 2.2. In the case of newly created habitats, it should be noted that this is not the true net value, as to calculate this it would be necessary to know what the coastal habitat was converted into when it was lost. However, as many of the intertidal habitats (e.g., saltmarsh, reedbed and intertidal sediment) will likely be created on uninhabited agricultural land, this is not expected to be a major source of error.

3. Results

3.1. Factoring condition into the capacity of habitats to provide ecosystem service flows

The level of regulatory ES, nutrient remediation and carbon sequestration (as represented by N, P and C removal) that would be expected if local habitat condition classification data were combined with the extent (area) data is presented in Table 3. These levels are placed in the context of the reference condition levels ('Moderate' conditions) to reflect on potential regional improvements or deteriorations in biophysical supplies of ES. When all available data were combined among sub-catchments (now including condition alongside extent), we estimate there would be an 10.7% (349 t yr^{-1}) increase in N removal, an 27.6% increase in P removal (176 t yr^{-1}) and an 67.7% increase in C removal (16,300 t^{-1}). The greatest improvements in N, P and C removal were recorded across littoral sediments, subtidal sediments, saltmarsh and reedbed habitats (these increases ranged between 29 — 559%; Table 3). Seagrass habitats maintained similar ES sequestration and storage rates, while the contribution of macroalgal mats to N, P and C removal declined. The largest declines in ES supplies were recorded for native oyster beds (−37 — -905%; Table 3), reflecting the adjustment from the 'Moderate' state of this habitat to 'Bad' across all SEMS catchments. Based on the average replacement and abatement costs, total N, P and C removal by habitats are estimated to be worth in the region of £1.14 billion yr^1. More refined estimates factoring in the condition of the habitats would estimate the economic value of the N, P and C regulatory ES to be considerably higher at just under £1.29 billion yr^{-1} (an increase of £145.05 million yr^{-1}).

These valuations can also be disaggregated to provide nutrient reduction or sequestration values (£) at the catchment level (see Appendix A Fig. S2). The open water catchment of the SEMS had the highest economic value for N, P and C removal when factoring in habitat condition. The

Table 3
Relationship between the indicators of the ecosystem services analysed in this study and the proxy of the ecological status for SEMS habitats. Biophysical estimates presented in the table have been rounded to the nearest whole (tonne yr^{-1}). Negative values indicate net loss of the nutrient from the habitat. To ensure greater accuracy, economic calculations were based on biophysical estimates to four decimal places.

		Biophysical changes			Economic value captured	
Ecosystem service	EUNIS habitat	Reference (Median) conditions tonnes (yr^{-1})	Modelled localised condition scenarios tonnes (yr^{-1})	Direction of change (%)	Reference (Median) conditions £ (yr^{-1})	Modelled localised reference condition scenarios £ (yr^{-1})
Waste (nitrogen) remediation	Littoral sediments	827	1119	+35.3	£243.97 M	£330.04 M
	Littoral sediments (with macroalgal mats)	403	386	−4.2	£118.89 M	£114.01 M
	Sublittoral sediments	1292	1374	+6.3	£381.12 M	£405.26 M
	Saltmarsh	475	497	+4.6	£139.98 M	£139.99 M
	Seagrass	127	127	0	£37.41 M	£37.41 M
	Reedbeds	17	33	+94.1	£5.15 M	£9.71 M
	Native oyster beds	123	77	−37.4	£37.44 M	£22.72 M
	Sub Total	3264	3613	+10.7	£963.96 M	£1059.14 M
Waste (phosphorous) remediation	Littoral sediments	34	55	+61.7	£9.65 M	£15.57 M
	Littoral sediments (with macroalgal mats)	479	383	−20	£135.09 M	£108.06 M
	Sublittoral sediments	47	310	+559.5	£13.17 M	£87.43 M
	Saltmarsh	62	66	+6.4	£17.39 M	£17.40 M
	Seagrass	−30	−30	0	−£8.53 M	−£8.53 M
	Reedbeds	21	29	+38.1	£5.84 M	£8.29 M
	Native oyster beds	24	0.13	−99.4	£6.77 M	£0.04 M
	Sub Total	637	813	+27.6	£179.38 M	£228.26 M
Carbon sequestration and storage	Littoral sediments	8138	12,424	+52.6	£0.49 M	£0.75 M
	Littoral sediments (with macroalgal mats)	5031	4215	−16.2	£0.30 M	£0.25 M
	Sublittoral sediments	6820	19,613	+187.5	£0.41 M	£1.18 M
	Saltmarsh	1758	3834	+118.0	£0.11 M	£0.23 M
	Seagrass	768	768	0	£0.05 M	£0.05 M
	Reedbeds	1322	1437	+8.7	£0.08 M	£0.09 M
	Native oyster beds	238	−1916	−905	£0.01 M	−£0.11 M
	Sub Total	24,075	40,375	+67.7	£1.45 M	£2.44 M
				Total	**£1144.79 M**	**£1289.84 M**

largest increase in ES values also occurred in this region, particularly in relation to P and C removal, with increases of 230% and 117% respectively. Ten of the thirteen catchments increased in N equivalent economic value (e.g., replacement costs) when factoring in condition, five catchments had greater economic value associated with removing P and eight catchments had relatively higher C sequestration potentials. The Medina and Yar estuaries were not associated with changes in ES flows (see Appendix A Fig. S2). In summary, the results suggest that factoring in the relative local condition of the SEMS habitats would generally improve the total N, P and C removal estimates, but across several catchments there would be reductions in P removal value, owing to reduced macroalgal mat biomass and downgraded estimates of native oyster habitat conditions.

3.2. Potential future benefits of habitat creation and restoration

The potentiality analysis results obtained help to highlight that future native oyster bed restorations would bring some of the largest benefits in terms of N removal (Fig. 2a), while simultaneously there are large risks associated with littoral and sublittoral sediments transitioning to "Poor" or Bad" conditions in terms of P release (Fig. 2b). Similarly, the biophysical evidence indicates that restoring oyster conditions from 'Bad' to at least 'Moderate' would change the level of the C sequestration ES from a negative to a positive sequestration and storage capacity (Fig. 2c).

Available evidence also suggests that if future habitat condition were improved in the SEMS to the gradation that all habitats were in 'Good' or 'High' conditions (Scenario, 2 & 3 Table 4), then the additional ecosystem benefits of increased N, P & C sequestration and burial could be as high as £376 million or £830 million per yr^{-1} respectively. These estimates are indicative of catchment areas where an increase in nutrient remediation and carbon sequestration services due to improving habitat condition could improve local water quality. The relatively small increase in regulatory value between 'Moderate' and 'Good' scenario conditions is a result of several habitats already having achieved 'Good' (e.g., littoral sediments or sub littoral sediments) condition status in some catchments. Large environmental net gains could however be made by targeting habitats in 'Poor' or 'Bad' conditions. The only habitat in 'Bad' condition in the SEMS is the entirety of the native oyster seabed sites. Accordingly, the greatest gains were recorded for this habitat increasing in value by £508 million or £601 million per year respectively (Table 4).

Future SEMS habitat creation targets (Scenario 1 Table 4) show that approximately £49 million per year could be realised in terms of water treatment costs and avoided climate change damages if habitat creation targets were achieved for littoral sediment, saltmarsh and reedbed habitats in the SEMS (Table 4). Additionally, if seagrass and native oyster beds were restored to previous historical extents than an additional £339 million per year could be gained in regulatory ES value. This is would equate to total annual savings of £388 million (Table 4).

As new habitat creation and existing habitat restoration are likely to be conducted simultaneously, we also considered what the additional regulatory benefits value might be under a 'best case' scenario (Scenario 4 Table 4). If all potential habitat creation sites were realised and all existing habitats were improved to 'High' conditions, then we estimate the regulatory benefits provided by SEMS habitats would increase by approximately £1218.64 million. If this additional benefit flow is then added to our previously predicted £1289.84 million per year (under current conditions), then the regulatory value of future habitats would essentially be worth almost double their current value at £2508.48 million per year.

4. Discussion

4.1. Accounting for ecosystem condition

Across the globe, there is increasing evidence that huge areas of key estuarine and coastal habitats are being lost or degraded at accelerating rates, leading to growing concern because they have recognised ecological and economic values (Duarte et al., 2020; Worm et al., 2006). Active habitat restoration and creation via policy related mechanisms such as 'nature-based solutions' (NbS) will help to recover NC assets, enhance marine biodiversity and achieve global no net loss targets (Gómez Martín et al., 2020). Examination of the SEMS marine and coastal habitats with regard to their capacity to deliver key nutrient and carbon related ES indicates that many habitats in the SEMS were delivering at a much higher (e.g., littoral sediments and reedbeds) capacity than if we had only assumed 'average' or 'Moderate' levels of ES provisioning. This suggests that factoring in the relative local condition of the SEMS habitats would generally increase the total N, P and C removal estimates by 11–67%. This is an important consideration, as condition assessments are often omitted when creating ES or NC accounts (e.g., ONS, 2021) potentially leading to an undervaluation of regulatory ES. In the case of the SEMS, this undervaluation was estimated at £145.05 million yr^{-1} in terms of additional value. At the highest level, the results evidence the importance of including condition indices in NC assessments. However, the results also demonstrate that there is considerable variability within the condition of the sub-catchments. Spatial heterogeneity in the condition of ES across sub-catchments is clearly illustrated in the littoral and subtidal sediments assessments, with large differences in condition ('Moderate' to 'High') between several of the catchments. However, when aggregated, the combined assessments highlighted that several ecosystem assets are in-between 'Moderate' to 'Good' conditions, with the exception of those provided by native oyster beds which were all in 'Bad' condition.

These results have several implications. Firstly, it is clear that ES flow responses based on mean or 'average' values alone would be inaccurate; instead, ES capacity responses should be considered at the finest scale appropriate and should include a measure of habitat condition. In this case, and at this scale, the inclusion of condition caused the overall value of regulatory ES to increase. However, if we had used a different scale or area, it is equally possible that the inclusion of condition could have caused the value of the ES to decrease. Second, by displaying the intermediate values for the condition of all ecosystem assets and the ES they provide it is possible to see where the greatest gains in interventions to improve habitat condition can be made, informing effective and efficient decision making. Third, assessments that span a range of condition states, can help highlight where the change in the level of ES could be switched from a negative (disservice) effect to a positive ES supply. For instance, in the case of native oysters in the SEMS there are marginal gains to be made in terms of N and P remediation by improving oyster condition anywhere up to 'Moderate' conditions. The greatest benefits actually occur when transitioning from 'Moderate to 'Good' conditions, thus this should be the target of local management restoration efforts. This approach is relevant not just to the SEMS, but also more widely in other temperate coastal systems. Similarly, the biophysical evidence indicates that restoring oyster conditions from 'Bad' to at least 'Moderate' would change the level of the carbon sequestration ES from a negative to a positive ES supply. Other examples of where NbS restoration interventions could reduce the negative supply of services, were found in littoral and sublittoral sediments in 'Bad' to 'Poor' conditions. Yet, as there were no sediment habitats in these condition states in the SEMS, this information serves only as a precautionary degradation threshold for habitats in locations with 'Moderate' conditions e.g., Chichester Harbour and the Medina Estuary. While the quantification of disservices and the mechanisms that cause them in sediment systems and oyster beds needs further research (Schaubroeck, 2017; Blanco et al., 2019), understanding where NbS management actions can be implemented to reduce ecosystem disservices by improving habitat condition will ultimately improve human well-being.

4.2. Nature-based solutions to optimize marine ecosystems

Evidencing the link between good ecosystem conditions and higher provision of ES justifies the effort and the cost of maintaining ecosystems in good conditions or restoring them (Grizzetti et al., 2019). The SEMS has an abundance of mudflat, wetland and shellfish ecosystems which have traditionally played a central role in its society and economy (Foster

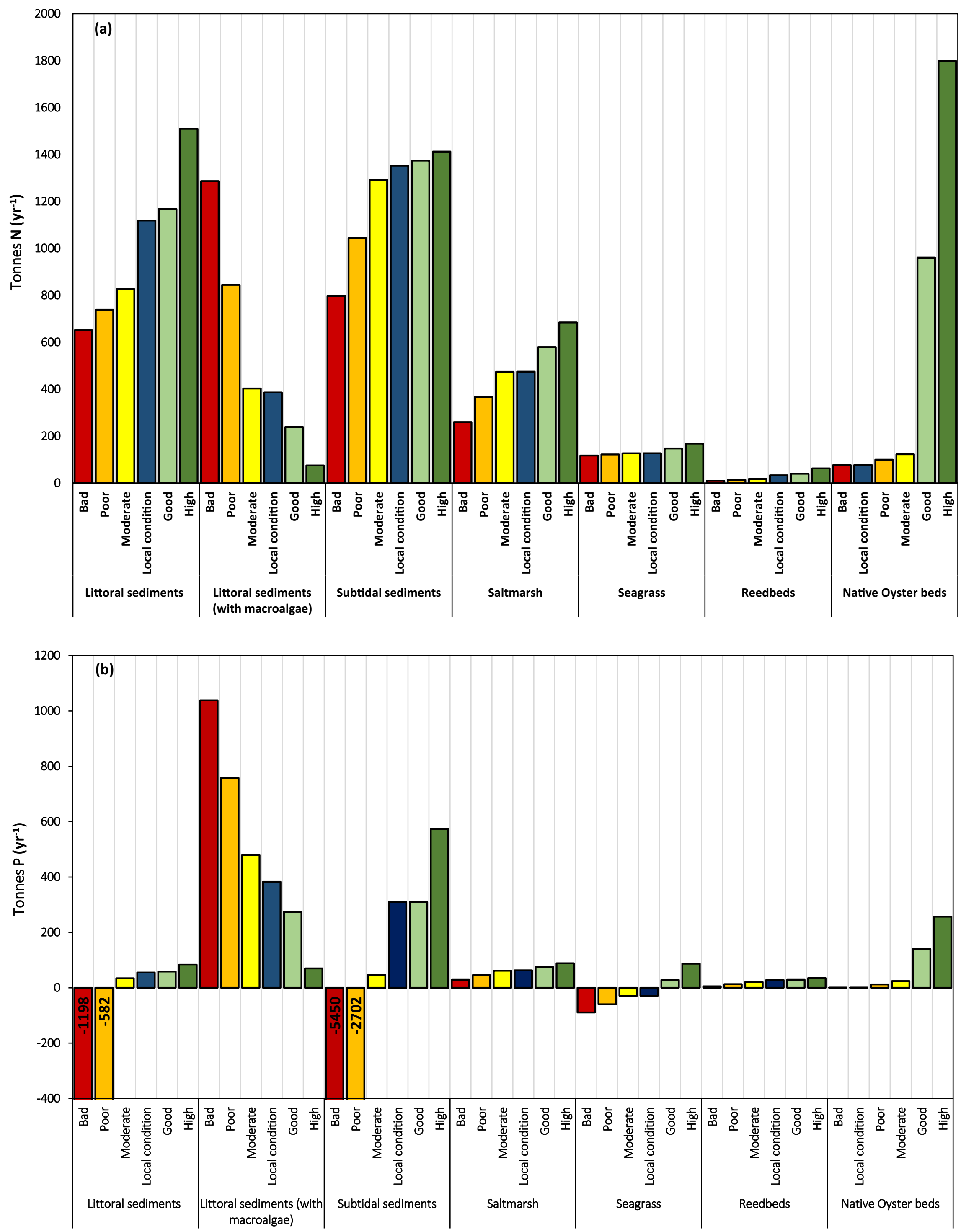

Fig. 2. Comparison of the total estimated regulatory service (tonnes yr^{-1}) provided by SEMS habitats under the full spectrum of condition states (a) Nitrogen, (b) Phosphorous and (c) Carbon.

et al., 2014; Helmer et al., 2019; Watson et al., 2017). Despite saltmarsh and seagrass being legally protected at UK state level, the SEMS is estimated to have lost hundreds of hectares of these habitats over the past few decades (Green et al., 2021; Watson et al., 2020). Likewise, a lack of enforcement and effective environmental management practices have resulted in severe deterioration of *Ostrea edulis* across the UK including the SEMS, described in detail by Key and Davidson (1981a) and Helmer et al. (2019). Therefore, characterising the current environmental situation for the SEMS and providing a quantitative evaluation on the future of key ES proved by restoring or creating new NbS habitats can spark a better-informed discussion about the benefits of restoration options including potential non-market values.

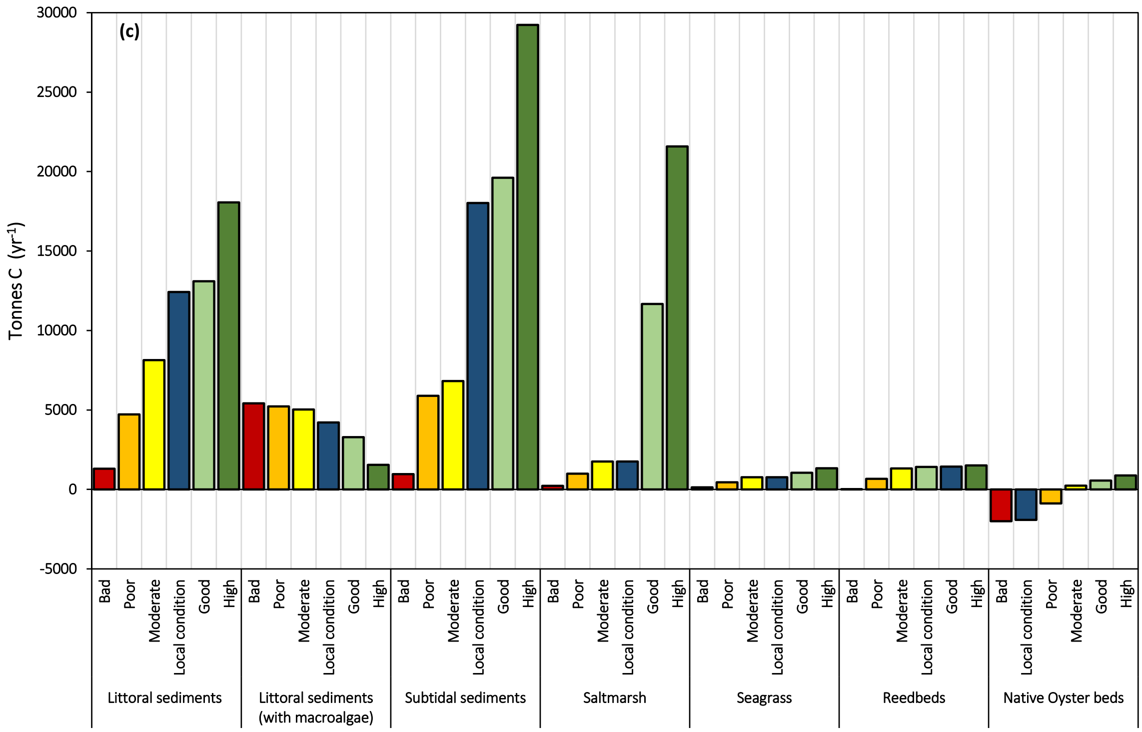

Fig. 2 (*continued*).

The future habitat restoration scenarios presented here for the SEMS generated compensating regulatory ES surpluses ranging between £376 and £830 million per annum respectively, highlighting clearly the large benefits that could be associated with improving the condition of existing habitats. The results shown here are presented at a regional scale, but could readily be applied at a larger national scale, enabling evidence-based decision making for policy decisions regarding the benefits of achieving WFD 'Good' ecological status by 2027. Given the large value associated with N, P & C sequestered and stored in coastal habitats, it also seems increasingly relevant to include the often considered 'ancillary' value provided by regulatory ES into mainstream policies such as UK's Nationally Determined Contributions (NDC) to reach net zero carbon emissions by 2050 (Paris Agreement 2015). Although blue carbon is not currently included in the UK's NDC inventory, we estimated substantial annual uplifts in future blue carbon (and nutrient sequestration) storage benefits (£388 million per annum) if new SEMS habitat creation targets were met. This offers early insight into the role that NbS could have in the restoration and recovery of degraded marine ecosystems as well as opportunities for increased economic and societal benefits.

4.3. Trade-offs and benefits of NbS habitat restoration and creation

While it is perhaps contrary to compare habitat restoration and creation goals, as both are likely needed simultaneously (Gann et al., 2019), our analysis does reveal that management efforts may be better placed on improving the condition of existing sediment (littoral and sub-littoral), saltmarsh and reedbed habitats, rather than creating new habitats. Conversely, creating new areas of seagrass beds may lead to greater

Table 4
Additional regulatory ES benefits (£ yr^{-1}) that would be realised if new priority habitats were created or if existing habitat condition were improved (to 'Good' or 'High' conditions) *Assumes new habitats are providing ES at 'Moderate' levels of condition.

Habitat	Ecosystem service	Creating new habitats* (Scenario 1)	Transition to 'Good' conditions, all existing habitats (Scenario 2)	Transition to 'High' conditions, all existing habitats (Scenario 3)	Creating new habitats* and transition to 'High' condition. (Scenario 4)
Littoral sediment	N	£1.20 M	£14.47 M	£115.23 M	£116.43 M
	P	£0.05 M	£1.06 M	£7.99 M	£8.04 M
	C	£0.002 M	£0.04 M	£0.34 M	£0.342 M
Saltmarsh	N	£41.63 M	£30.86 M	£61.86 M	£103.49 M
	P	£5.42 M	£3.41 M	£7.18 M	£12.6 M
	C	£0.03 M	£0.59 M	£1.19 M	£1.22 M
Reedbed	N	£0.31 M	£2.06 M	£8.70 M	£9.01 M
	P	£0.36 M	£0.96 M	£1.95 M	£2.31 M
	C	£0.005 M	£0.001 M	£0.01 M	£0.015 M
Seagrass	N	£418.11 M	£6.08 M	£12.22 M	£430.33 M
	P	−£99.87 M	£16.47 M	£33.03 M	−£66.84 M
	C	£0.54 M	£0.02 M	£0.03 M	£0.57 M
Native oyster beds	N	£17.80 M	£260.70 M	£507.84 M	£525.64 M
	P	£2.88 M	£39.58 M	£72.42 M	£75.3 M
	C	£0.001 M	£0.15 M	£0.17 M	£0.171 M
	Total	£388.48 M	£376.46 M	£830.16 M	£1218.64 M

regularly ES benefits — at least in the long term — compared with improvements to the condition of existing seagrass beds. Improvements in the condition of shellfish waters would also mean many aquaculture areas of the SEMS could be re-opened and harvested leading to further increases in total economic activity and associated ES benefits. These additional factors have recently been modelled for the Solent by Williams and Davies (2018) & Williams et al. (2018), who report that even a modest improvement in SEMS native oyster bed conditions from WFD class 'Prohibited' or 'Bad' to Class 'C' or 'Poor', could lead to substantial benefits (£555,806 per annum) in terms of additional provisioning ES flows. Still, as no costs for the respective necessary management interventions area are currently available, it is impossible to present the findings as a cost-benefit ratio. Also, while generalised costs to create new marine and coastal habitat are now becoming increasingly available (e.g., Bayraktarov et al., 2015) the myriad of costs involved with improving the ecological status of a habitat or an entire catchment are less attainable, largely due to the many different ways this process can be achieved. We recommend that future research could build on the findings presented here, including more detailed assessments of the costs involved in creating and restoring the habitats. A future challenge will also be to better understand how different conditions effect other ES provided by coastal and marine habitats, including examples of provisioning (e.g., aquaculture) and cultural services (tourism and recreation values).

4.4. Study limitations

The measurement of ecosystem condition following the concepts in an ecosystem accounting model is a complex and subjective task due to the need to consider multiple biotic characteristics including, vegetation and species density, canopy cover, biomass, habitat structure, productivity and decomposition processes. Thus, the biophysical estimates presented here are dependent on the indicators and indices of condition used to develop these accounts and that future adjustments to the analysis to reflect different indicators of condition would be a useful exercise (e.g., Czúcz et al., 2020, 2021a). For instance, integrative multi-metric indices such as the AZTI Marine Biotic Index (AMBI), benthic quality index (BQI) and the biotic index (BENTIX) are examples of benthic indices that have been widely applied and tested, particularly throughout Europe (Borja et al., 2019; Simboura and Zenetos, 2002). The MSFD 'Good Environmental Status' requirements have also been suggested as a starting point for the development of condition indicators in NC accounts (e.g., Rees et al., 2019; Judd and Lonsdale, 2021), although this is mainly in offshore marine areas away from the WFD coastal zone. Therefore, pending further testing of different condition indicators, we suggest that over time the biophysical accounts developed here could be broadened in scope and sensitivity tested with a larger range of condition indicators. Additionally, long term burial and denitrification estimates in this study have been estimated from extrapolation of sedimentation rates and N, P and C content of established habitat sediments (see Watson et al., 2020) to give an indication of the potential level of nutrient or carbon "stock" over a yearly cycle. While nutrients and carbon removed via denitrification are likely permanent, the biophysical values associated with the long-term stability and permanence of stocks stored in the sediment could be refined. In particular, long term seasonal measurements of dissolved organic nutrient production generated by macroalgal mat and other angiosperm biotopes, could further increase the global significance of the sequestration fluxes we estimate. Nevertheless, in this study, algal mat habitats are present all year round at the vast majority of the SEMS case study sites, so may capture some of these seasonal cycle variations. Likewise, the monetary values associated with newly created habitats have been estimated, these values fall short of true net values. This is because many of the new habitats were generally implemented on uninhabited agricultural land or other areas of seabed without significant existing nature conservation designations. Ideally, the areas of these new habitats would be calculated to determine the overall net change of N, P and C sequestered and stored.

5. Conclusion

This study demonstrates that not including condition accounts in NC or NbS restoration assessments could: 1) potentially lead to undervaluation of ES benefits, and 2) unintentionally overlook negative 'ecosystem disservices' in a seascape. In large MPAs, like the SEMS, recovery from 'Moderate' to 'Good' or 'High' ecological status could bring large, uncalculated regulatory ES benefits in a time-span relevant to achieving legislative environmental objectives (i.e., WFD targets aim to achieve 'Good' status in all UK catchments by 2027). This evidence is globally relevant when investing in water ecosystems conservation and restoration, as called for by the UN Decade on Ecosystem Restoration (2021–2030), and more generally in global nutrient reduction and blue carbon emission targets (e.g., global net-zero targets). Assessing how pressures might be reduced and the cumulative impacts of pressures on habitat condition (e.g., from abrasion from fishing gears, effects of sea level rise or direct effects of elevated nutrients) and timescales of recovery/change was outside the scope of this study. However, applying the existing reference condition stock and accumulation levels provided in this study to environmental, management or climate pressure considerations would be of merit in future (e.g., Rees et al., 2022). In particular, improved understanding of the impacts of trawling (Rijnsdorp et al., 2018), and other activities, could give useful insights to stock accumulation or degradation, timescales of change (including recoverability) and help inform management actions including MPA designs other NbS, or natural climate solutions.

CRediT authorship contribution statement

S Watson: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing - Original draft preparation, Writing - Reviewing and Editing, **G Watson**: Conceptualization, Visualization, Supervision, Writing - Reviewing and Editing, Funding acquisition, **N Beaumont:** Visualization, Validation, Writing - Reviewing and Editing,. **J Preston:** Conceptualization, Visualization, Supervision, Writing - Reviewing and Editing, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156026.

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