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Accounting for ocean impacts nearly doubles the social cost of carbon

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Check for updates

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Oceans provide essential benefits to people and the economy, underpinned by the extent and condition of marine ecosystems and infrastructure—or 'blue' capital. However, the impacts of climate change on blue capital have been largely overlooked in influential indicators such as the social cost of carbon (SCC). Here we integrate the latest ocean science and economics into a climate-economy model, capturing climate change impacts on corals, mangroves, seaports, fisheries and mariculture to estimate their welfare repercussions at a global scale. Conceptually, this ocean-based SCC (blue SCC) represents a component of the total SCC currently omitted in standard estimates. We estimate the 2020 blue SCC to be US$48 per tCO_2 (US$38–70, 25th–75th percentile) with baseline discounting, representing an almost doubling of the SCC estimate from the same model without considering ocean-related impacts. The blue SCC increases to US$168 for a discount rate of 2%.

The ocean is key to a thriving society. It provides a range of benefits that support market economies and sustain livelihoods and wellbeing[1–4]. Some economic benefits derived from the marine environment, such as seafood and maritime transportation, are traded in markets, and their value is observable in market prices. Others are not traded in markets, and their economic values are not directly observable (for example, coastal protection, recreational activities and the values that people place on the existence of marine biodiversity). In response, a growing body of academic and policy-oriented literature on the multifaceted concept of the 'blue economy' is highlighting the need for comprehensive frameworks that reflect the critical interdependence of the oceans, people and the economy[1,2,5].

Examples of 'blue capital' include fish biomass, living coral coverage, mangrove coverage, and seaports (although considered a human-made capital, they enable the ocean-based benefit of navigable waters; Fig. 1a). Such examples provide country-level benefits, as given by equations (2) and (3) (shown in the scatterplot of Fig. 1b as a percentage of gross domestic product (GDP)). The magnitude and composition of blue capital is distributed across geographies and socioeconomic groups, but the importance of blue capital, as a share of GDP, to the economy tends to be highest in low-income countries (larger markers in Fig. 1b occurring at lower GDP per capita).

Anthropogenic greenhouse gas emissions are changing the ocean's chemistry and physical conditions. Elevated greenhouse gas

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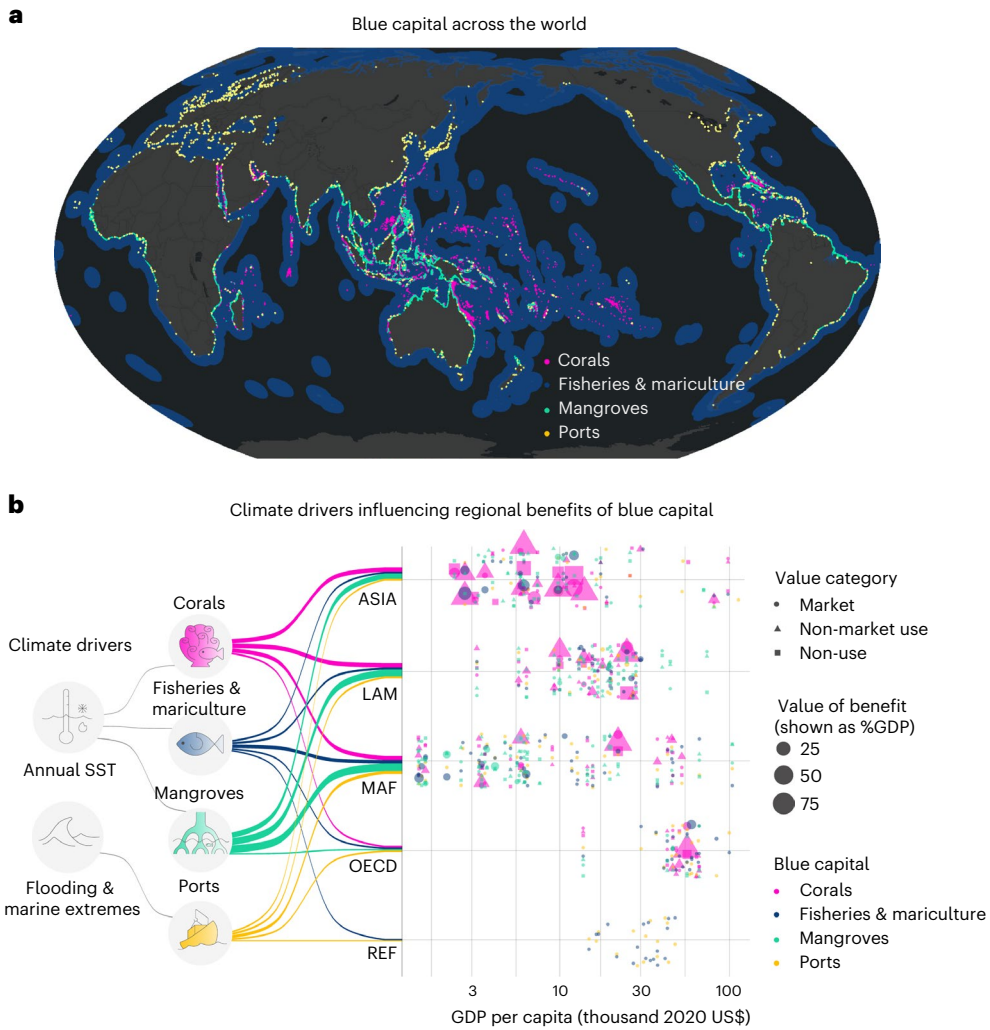


Fig. 1 | Blue capital and its values (in 2020 or the most recent year for which data are available). a, Geographical distribution of the four types of blue capital considered in this study: corals, mangroves, fisheries and mariculture, and seaports. **b**, Flow diagram (read from left to right). The leftmost set of icons represents the climate drivers through which climate change acts on blue capital in this study. The grey lines indicate the impact pathways through which climate change affects blue capital, as identified in the literature. The coloured lines show the distribution of blue capital across socioeconomic regions, and line width indicates the proportion of countries within each region that have such blue capital. The five regions are as follows: ASIA, Asian countries except the Middle East, Japan and the former Soviet Union states; LAM, Latin America and the Caribbean; MAF, the Middle East and Africa; OECD, the OECD countries and the EU member states and candidates; REF, the reforming economies of Eastern Europe and the former Soviet Union. In the rightmost scatterplot, the annual flows of blue capital values at the country level, as computed by equations (1) and (2), are shown by country as a percentage of GDP, ordered by GDP per capita. Basemap from Natural Earth (https://www.naturalearthdata.com/)[44] with data from refs. 45–48.

concentrations in the atmosphere lead to higher ocean temperatures[6], reduce the ocean's ability to hold oxygen[7], cause ocean acidification[8], increase the severity of extreme weather events[9] and contribute to sea-level rise. These changes to the ocean are driving widespread alterations in species distributions, phenologies, body sizes and ecosystem structures and functions, as well as leading to the mass mortalities of organisms. Some of the critical habitats for biodiversity and ecosystem services are particularly vulnerable to climate change, examples including the large-scale bleaching of coral reefs and the loss of seagrass beds and kelp forests. These changes in the ocean directly affect the benefits we derive from it and should be factored into the tools and frameworks that support climate policy and regulatory efforts.

The social cost of carbon (SCC), a well-known metric in climate policy and regulatory analysis, is an estimate of the total economic impact on humanity from the release of an additional tonne of CO_2 into the atmosphere. It should encompass all known climate-related damages to people and the biosphere. Integrated assessment models (IAMs) to calculate the SCC typically include an ocean carbon module for the physical regulation of CO_2, but the economic damages to marine ecosystems and ocean-dependent activities have been absent from these calculations. Recent analyses and systematic reviews acknowledge the omission of known climate-related ocean damages and call for their integration[10–13]. For instance, a systematic review by the US National Academy of Sciences[10] emphasized the need for a more accurate representation of climate-related damages, including impacts on marine fisheries, coral-based recreation, and tourism services, which are not represented in existing models. Similarly, the US Environmental Protection Agency's 2023 technical report conducts a thorough review of the SCC calculation, pointing out the absence of any representation of marine ecosystem services and fisheries damages[12]. Including ocean impacts in the SCC is essential for designing environmental policies that accurately reflect the economic value of greenhouse gas emissions. In this Article we present a calculation of an ocean-based SCC (hereafter 'blue SCC').

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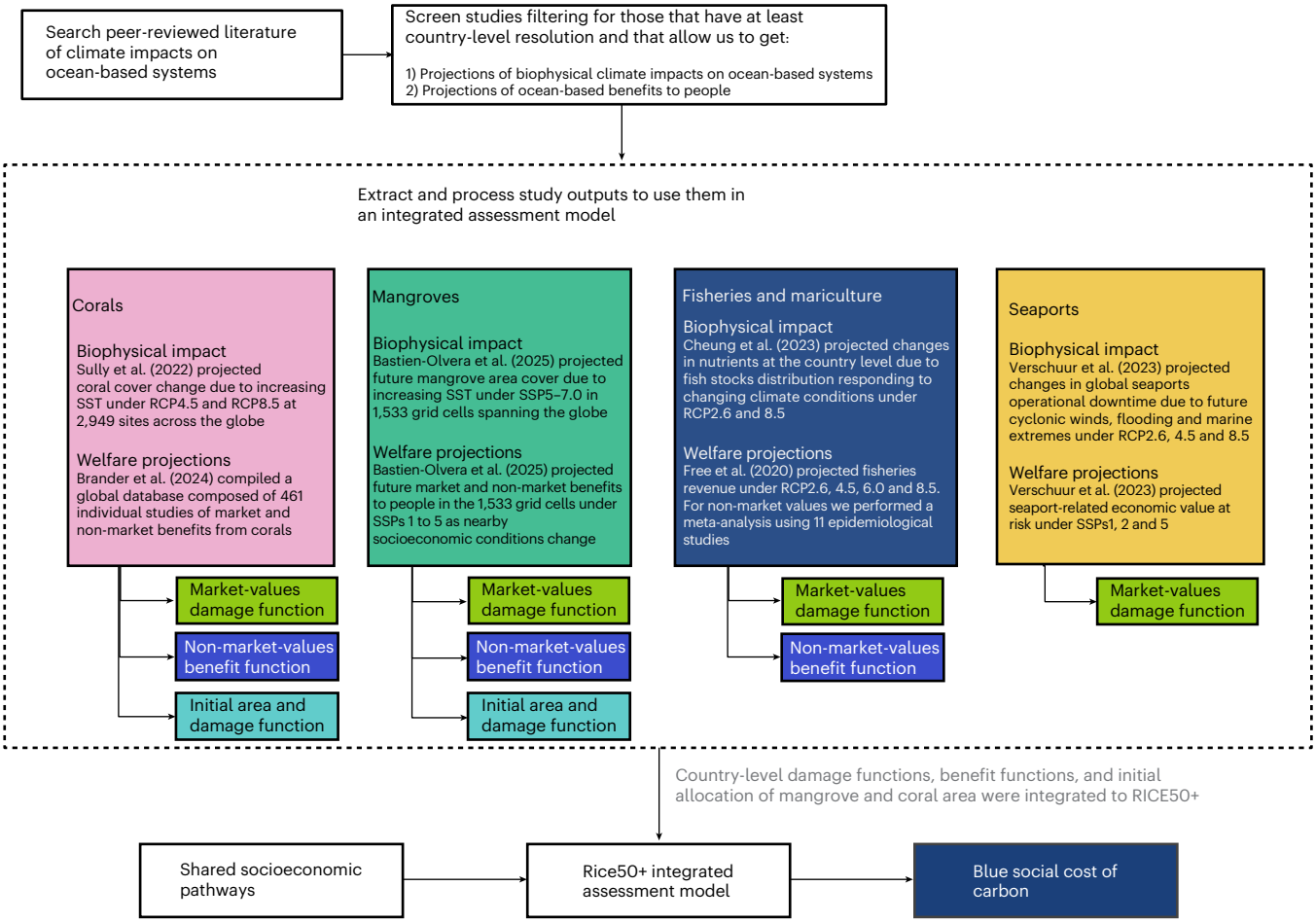


Fig. 2 | Analytical framework for estimating the ocean-based social cost of carbon. This diagram presents the structured analytical framework developed to quantify the blue SCC by integrating biophysical and economic valuation functions. The process starts with a literature search—screening studies that quantify climate-induced impacts on ocean-based assets or marine ecosystems. An in-depth analysis follows, focusing on the four types of blue capital identified: corals, mangroves, fisheries and mariculture, and seaports. Within each capital block, the diagram briefly presents the underlying biophysical and economic valuation studies that were selected. Each block highlights the types of value accounted for: market values, non-market use values and non-use values, as applicable. The processed values from each block are aggregated at the country level and subsequently integrated into the RICE50+ IAM. In the model, users can select the desired SSP to project the blue social cost of carbon under different climate and socioeconomic scenarios.

Approach

Our analysis integrates findings from the climate change impacts literature on corals, mangroves, seaports, and fisheries and mariculture—four sectors for which economic impact assessment studies have been conducted at a sufficiently detailed spatial scale to estimate country-level or subnational impacts. Our process harmonizes information from six main disparate studies into a framework that enables the quantification of the ocean-based economic damages associated with incremental warming, a necessary requirement to estimate the SCC (Fig. 2). In these sectoral impact studies, climate variables such as sea surface temperatures (annual mean and during the warmest month), maritime extreme events, and coastal flooding are empirically linked to impacts on blue capital and statistically linked to global mean temperature.

Our valuation of climate-induced damages to blue natural capital encompasses impacts on human wellbeing that are directly and indirectly reflected in markets. Market values are relatively straightforward, encompassing monetary losses such as decreased fisheries revenue or diminished trade. Non-market values include human health and nutrition from fisheries, coastal protection, recreational opportunities, as well as non-use values, generally termed existence value, that reflect the inherent worth that humans ascribe to ecosystems and biodiversity. We translate the projected changes in all blue capital categories under various climate change scenarios into welfare losses, and quantify these into monetary equivalents, allowing for a comprehensive analysis of ocean climate damages.

To account for market-related damages within our framework, we adopt a damage function approach commonly used in IAMs. This method uses stylized functions that relate the projections of country-level market loss to increases in global mean surface temperature relative to pre-industrial levels. Non-market values are incorporated from a natural capital perspective, meaning the climate-induced impacts on the stock of blue natural capital in each country (measured as mangroves and coral area coverage) are assigned a monetary value equivalent to the welfare benefits provided. We use 'benefit function' to describe the relationship that maps ecosystem stock into a flow of benefits. These two pathways—the damage function and the natural capital approach—were integrated into RICE50+[14], a computational model that simulates the dynamics of countries' economies under the influence of climate change. This integration resulted in a new version of the model, referred to as the 'blue' RICE50+ model, which specifically incorporates blue capital and is capable of calculating the SCC for the oceans. Details are provided in the Methods.

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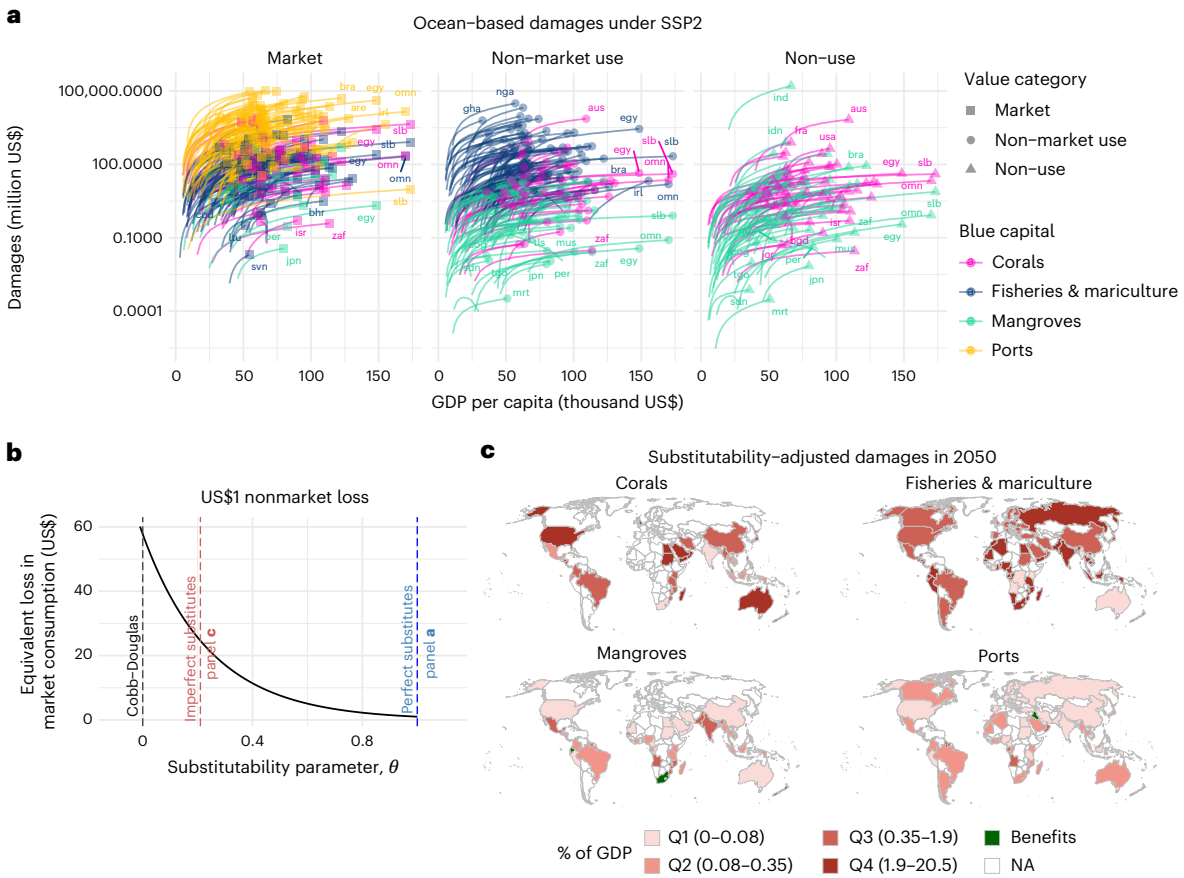


Fig. 3 | Climate damages on ocean-based values. This figure presents the projected economic damages resulting from climate change impacts on blue capital. **a**, Country-level damage trajectories in billions of US$ (log-scale) for each country across different types of value, from 2020 to 2100. These values have been obtained by simply monetizing physical impacts using their estimated economic monetary values and are not welfare-based. Each country's path is a plain line starting at 2020 (unmarked end) and ending at 2100, which is indicated by a terminal marker—square for market, circle for non-market use, triangle for non-use. **b**, Effect of the substitutability parameter on the market consumption-equivalent of losing US$1 of non-market value. The values shown are given by using Australia's market consumption levels and the non-market coral benefits in 2025 as an example. Note that θ can also be negative, representing various levels of complementarity; as θ approaches negative infinity, the value of one non-market dollar tends toward infinity, corresponding to the case of perfect complements. This illustrative example is not tied to a specific nesting level within the utility function; it serves to build intuition about how substitutability affects welfare valuation (further intuition is provided in the Supplementary Information). **c**, Total welfare-equivalent monetary climate damages in 2050 aggregated across the four types of blue capital shown in quantile groups relative to national GDPs. Basemaps in **c** from Natural Earth (https://www.naturalearthdata.com/)[44].

The economic damages of climate change to the oceans

We present the impacts on ocean-based welfare under a scenario representing a middle-of-the-road socioeconomic development path (SSP2) that, under a no-policy scenario, leads to an average temperature increase of ~3.6 °C by the end of the century over pre-industrial levels. Emissions and temperatures are determined endogenously by RICE50+, rather than by pairing SSP2 with an exogenous forcing pathway (for example, Representative Concentration Pathway (RCP) 4.5). We explore alternative socioeconomic and climate scenarios in the Supplementary Information and Extended Data Fig. 1.

The annual country-level damage trajectories from 2020 to 2100 (Fig. 3a) vary across market use, non-market use and non-use values. Damages increase over time as temperatures increase and the size of economies grows. Overall, market use damages are the largest in absolute terms, totalling global annual losses of US$1.66 trillion in 2100, followed by damages in non-use values amounting to US$224 billion and non-market use values adding up to $182 billion in annual losses.

Non-market damages are primarily driven by the health impacts of reduced nutrition availability from fisheries and mariculture, access to which substantially impacts mortality and morbidity, especially in lower-income countries. Non-market use value losses from corals and mangroves, which provide important coastal protection services, are also large. The largest share of damages in non-use values comes from the loss of mangroves in India, where the impact on mangroves is substantial, and the local population benefiting from these non-use values is also substantial.

One unit of loss in market-equivalent value is not equivalent to one unit of loss in non-market benefits, because market and non-market values are not perfect substitutes (Fig. 3b). In terms of the substitutability parameter (θ), we use a conservative elasticity of $\theta = 0.21$ based on recent literature[15]. This is a very important parameter, as shown in the uncertainty analysis.

The relative magnitudes of welfare-equivalent monetary damages are substantially different from those in absolute terms (Fig. 3c for the year 2050; also Supplementary Fig. 26). Each type of capital—corals, seaports, fisheries and mariculture, and mangroves—is associated with market, non-market use and non-use damages, where applicable. Ports have only market damages, whereas other capitals (such as mangroves and corals) include all the three value types (Table 1). The highest welfare-adjusted damages are for fisheries and mariculture,

Table 1 | Inclusion mechanisms for blue capital values in RICE50+

	Market values	Non-market use values	Non-use values
Corals	Damage function linking global mean surface temperature with decrease in market consumption	Damage function links global mean surface temperature with decrease in coral area Meta-regression using an ecosystem services database links area of ecosystem to value of non-market use benefits	Damage function links global mean surface temperature with decrease in coral area Meta-regression using an ecosystem services database links area of ecosystem to value of non-use values
Mangroves	Damage function linking global mean surface temperature with decrease in market consumption	Damage function links global mean surface temperature with decrease in mangrove area Meta-regression using an ecosystem services database links area of ecosystem to value of non-market use benefits	Damage function links global mean surface temperature with decrease in mangrove area Meta-regression using an ecosystem services database links area of ecosystem to value of non-use values
Fisheries and mariculture	Damage function linking global mean surface temperature with decrease in market consumption	Non-market-value benefit function represents the change in nutritional value from fisheries as global mean surface temperature increases	Insufficient data
Ports	Damage function linking global mean surface temperature with decrease in market consumption	Insufficient data	No theoretical basis

and welfare-adjusted damages associated with ports are generally the lowest. A few countries have expected net benefits.

The blue Social Cost of Carbon

To calculate the blue SCC, we first run the model under a reference scenario with climate impacts and then a second time with an additional megatonne pulse of CO_2 in 2020. We aggregate the different impacts and combine the economic and welfare effects through a utility function with decreasing marginal utility with income. We normalize the results per tonne of CO_2, computing the net present value of future impact streams using an endogenous discount factor (Methods). We keep the baseline model parameters as the central specification, and explore different values as sensitivity (Supplementary Table 6).

We find that the 2020 blue SCC is US$48 per tonne of CO_2 (Fig. 4a) (global average, without equity weights). For a pulse of CO_2 in 2030, the blue SCC is US$72 (all values are expressed in 2020 US dollars). Roughly half of the blue SCC can be attributed to non-market-related losses from fisheries and mariculture (namely their health costs), with the other half stemming from corals and mangroves. Notably, the welfare impacts from changes to the market use values of ports are small. This does not imply that the accumulated damages from these sources are insignificant, but rather reflects the essential welfare role of oceans' non-market use and non-use services given their limited substitutability (Fig. 3) as well as their typology and geographical distribution. For example, health impacts are the largest component of the blue SCC because they have a high economic value, monetized using a globally uniform 'value of a statistical life' (VSL).

To quantify uncertainty, we use a Monte Carlo approach to calculate blue SCC, with 10,000 combinations of parameter values (Extended Data Fig. 2). This allows us to quantify and partition uncertainty associated with the damage functions, ecosystem services benefit functions, the degree of substitutability between market, non-market use and non-use values, as well as climate sensitivity, the pure rate of time preference, and the elasticity of the marginal utility of consumption. Overall, the interquartile range (25th to 75th percentile) of the blue SCC is estimated to be between US$38 and US$70 per tCO_2. The most important driver of uncertainty in the blue SCC is the elasticity of substitution between market and non-market values in the utility function (Extended Data Fig. 2). The SCC is also very sensitive to parameters governing the non-use value of corals and the non-market use value of fisheries. We also compute the blue SCC across different SSPs, finding a skewed range between US$37 (SSP5) and US$77 (SSP3) per tCO_2 (Supplementary Fig. 25).

The blue SCC is comparable to other major sector-specific 2020-SCC estimates (for example, US$84 for agriculture, US$9 for energy, US$90 for mortality (as given by the Greenhouse Gas Impact Value Estimator (GIVE) model[16]) or US$4 for agriculture, −US$3 for energy, US$39 for labour, US$3 for coastal damages due to sea-level rise and US$146 for mortality as given by the Data-driven Spatial Climate Impact Model (DSCIM)[17–19], both used by the 2023 US Environmental Protection Agency (EPA) report[11]), recognizing differences in model structure, socioeconomic scenarios and preference parameters. To be able to compare our SCC values, we recalibrate the pure rate of time preference and elasticity of marginal utility of consumption to be consistent with near-term consumption discount rates of 1.5%, 2%, 2.5% and 3%, ensuring comparability with the GIVE model[16]. The resulting estimates are US$305, US$168, US$96 and US$64 (US_{2020}) per tCO_2, respectively (Extended Data Fig. 3). For a rate of 2% per year, the consensus value among experts[20], the blue SCC would imply an increase of GIVE SCC for SSP2 (US$158 ($US_{2020}$) per tCO_2) by ~106%.

Discussion and conclusions

There has been a long-standing need to integrate marine ecological responses to climate change into economic metrics that inform policymaking. Although existing IAMs typically simulate ocean carbon uptake dynamics, they do not explicitly model damages to ocean ecosystems or ocean-based sectors. Some work has explored climate damages linked to ocean dynamics (for example, Atlantic Meridional Overturning Circulation (AMOC) slowdown[21,22]). However, this is the first estimate that comprehensively integrates climate damages to a range of ocean-based ecological and economic systems into the SCC framework. Moreover, although recent econometric work implicitly captures climate impacts on market sectors in regional GDP projections, our approach disentangles sector-specific pathways by explicitly modelling market damages from blue capital degradation. The distribution of ocean-based welfare impacts is highly unequal across the world, with islands and small economies being disproportionately affected, a pattern also observed for terrestrial-based ecosystems[23].

The blue SCC presented here implies a substantial increase relative to the SCC obtained when running the standard RICE50+ model without ocean-based damages. Specifically, our results indicate that including ocean-based welfare would almost double the standard SCC derived from the same IAM (US$51 per tCO_2, in the central case; Extended Data Fig. 3). When we calibrate our model to the near-term 2% discount rate used in recent SCC estimates from the US EPA (applied in US policy as of 2024[11]) our result (US$168) represents a 106% increase in GIVE's SCC under SSP2. However, this comparison should be interpreted with caution (Supplementary Information). This increase is also consistent with trends in SCC estimates, which have historically risen as new scientific knowledge is incorporated[24]. The blue SCC responds

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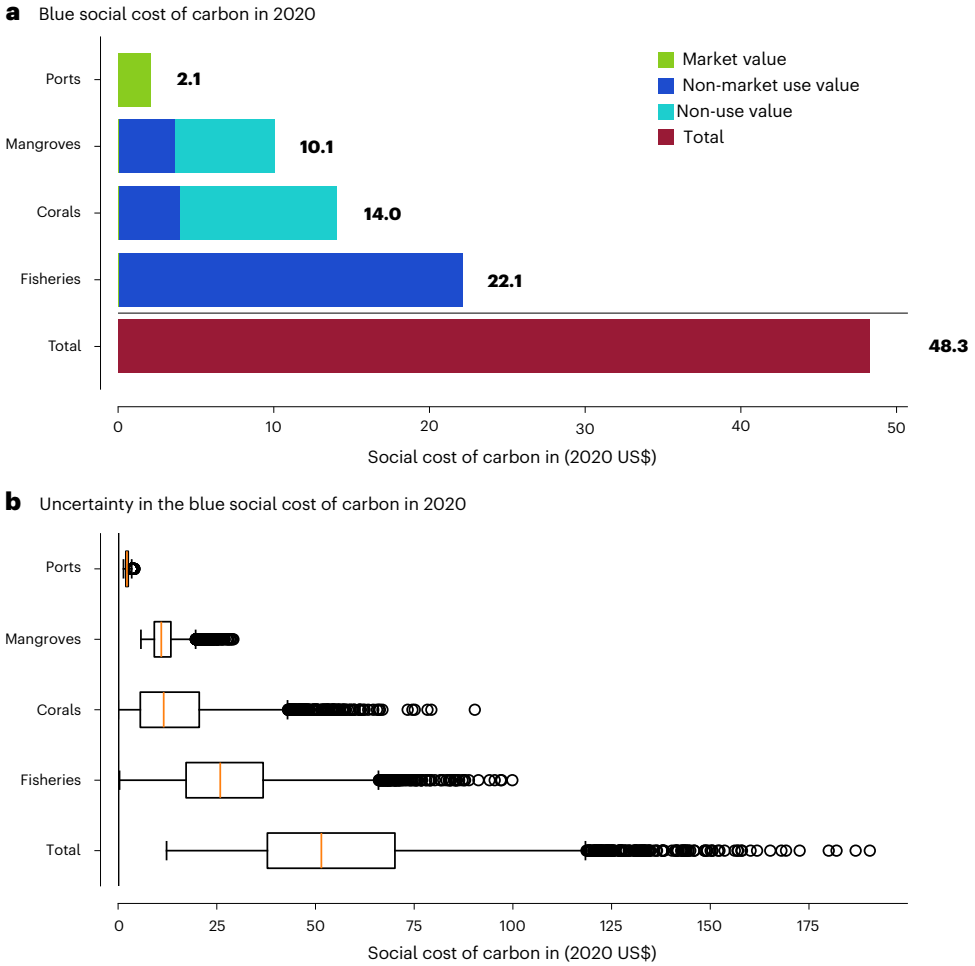


Fig. 4 | Blue SCC and its uncertainty. This figure presents the breakdown of the blue SCC and the sensitivity of the results to input parameters. **a**, Blue SCC is disaggregated by sector (rows), with each row corresponding to a different sector of blue capital (corals, mangroves, seaports, fisheries and mariculture), and each colour within the rows represents a different value type (market use, non-market use, non-use). The total SCC is displayed at the bottom as an aggregate of all components. **b**, Sensitivity analysis, showing the distribution of blue SCC estimates resulting from 10,000 simulations using a Monte Carlo approach. Boxes span the interquartile range (from the first quartile (Q1) to the third quartile (Q3)), with the orange line representing the median. The mean value of US$48 per tCO_2 is not shown in the graph. Whiskers extend to the farthest data points within 1.5 times the interquartile range from the box, and circles indicate outliers. Values of the blue SCC for different discount rates are discussed in the Supplementary Information.

to numerous calls to update the scientific foundations underlying current SCC estimates[25,26], many of which explicitly call for more comprehensive ocean-based assessments[10,11,13,23]. Our estimate expands on the existing estimates by incorporating several ocean-based damages that the US EPA acknowledges as important but has not yet included in SCC calculations, such as impacts on fisheries and mariculture, tourism, recreation and aesthetic values. The latest SCC report from the US National Academy of Sciences recommended the inclusion of an ocean chemistry module, a step toward accounting for ocean-based damages driven by indicators that are not closely coupled with temperature. Our analytical framework can be expanded to meet this goal. Blue SCC should be conceptually understood as a component of the total SCC, which includes all climate damages. However, because most current estimates omit ocean-based damages entirely, our results can be interpreted as the degree to which existing SCC estimates may be underestimating the true social cost of carbon emissions.

Diverse climate drivers underlie the biophysical impacts on each type of blue capital analysed in this study. We standardize these impacts by rescaling them to global mean surface temperature for ease of implementation in IAMs, including RICE50+, but the underlying science is far more complex. For coral reefs, the estimates are driven by localized changes in sea surface temperature[27]; for mangroves, the key driver is the sea surface temperature of the hottest month[28]. Seaport infrastructure is influenced by a combination of pluvial, riverine and coastal flooding, as well as cyclones and other extreme weather events[29]. In the case of fisheries and mariculture, our approach relies on a process-based model of marine ecosystems—specifically, the dynamic bioclimate envelope model—which incorporates sea surface temperature, sea bottom temperature, coastal upwelling, salinity and other environmental factors[30,31]. Future implementations can retain these sector-specific local drivers and link them to IAMs via spatial patterns; the GMST rescaling used here serves as a common baseline.

Although based on the best global knowledge, our analysis could be further refined to disentangle ocean drivers. For instance, increases in sea surface temperature contribute to coral bleaching by disrupting the symbiotic relationship between corals and algae. Simultaneously, ocean acidification impacts them by reducing their ability to form and maintain their structures[32]. These two drivers are often correlated in climate projections[33], but disentangling their specific effects could be valuable for exploring alternative scenarios where mitigation policies might target one but not the other. For example, solar radiation management could reduce sea surface temperature without addressing acidification.

The role of ecosystem services in supporting society and the economy has recently gained recognition as fundamental for

policymaking[15]. Using the latest empirical evidence on substitution elasticities—which captures the limited potential to replace natural services with human-made alternatives[34]—and employing welfare functions consistent with dual discounting[20,35] and previous IAMs[36,37], we find that the non-market use and non-use values of ocean-based ecosystems are the largest determinants of welfare losses from climate change, as reflected in the blue SCC. This metric can also strengthen complementary efforts to assess ocean wealth. For example, Bertram and colleagues[38] estimate ocean value by applying existing SCCs to the carbon sequestration of coastal ecosystems; incorporating a blue SCC would capture both carbon-storage benefits and climate damages to marine ecosystems, yielding a more complete ocean valuation.

Future work should broaden blue capital coverage and benefit types. For instance, our fisheries values currently include only economic revenue and nutrition. However, for many communities, being 'people of the sea' and practising traditional fishing methods is central to their cultural identity—something that cannot be captured by the utility approach alone[39,40]. Moreover, future estimates should incorporate additional types of blue capital, such as deep-sea ecosystems, which provide both use and non-use values[41]. These contributions are largely unaccounted for in the SCC and, as a result, are often overlooked in regulatory analyses that determine climate outcomes.

As the ocean takes a central role in climate policy, from carbon sequestration to broader interventions[42,43], it is crucial to address both the impacts of policy actions and the direct effects of climate change on ocean ecosystems. Only by integrating these perspectives can we fully understand the challenges and opportunities of preserving, and where possible restoring, our blue capital—a critical step towards achieving sustainable ocean stewardship during the United Nations Decade of Ocean Science for Sustainable Development. With its potential for practical applications in regulatory analysis around the globe, an estimate of a blue SCC is one tool for synthesizing the global consequences detailed in the extensive literature on climate change impacts on the ocean. It also aids in designing environmental policies that account for the economic value of marine ecosystems.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-025-02533-5.

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Methods

Analytical framework

To quantify the blue SCC, we have developed an analytical framework designed to systematically integrate projections from biophysical and economic valuation studies available in the peer-reviewed literature. We conducted a structured literature search focused broadly on studies quantifying climate-induced impacts on ocean-based assets or marine ecosystems, with explicit consideration for those that provided corresponding economic welfare valuations—either directly or through supplementary economic assessments or meta-analyses. Our search resulted in four sufficiently developed sectors—corals, mangroves, fisheries and mariculture, and seaports—that fulfilled two key criteria: (1) availability of geographically explicit biophysical projections at the national or subnational scale and (2) associated economic valuations, enabling welfare impact estimation at comparable spatial resolutions.

Our integrative approach required matching two distinct methodological components: the biophysical impact functions and the economic valuation functions. The biophysical component captures climate-driven changes in asset availability (for example, mangrove coverage, coral reef health, fisheries productivity, port functionality) derived from peer-reviewed climate impact modelling studies. The economic component translates these biophysical changes into welfare impacts using valuation methods appropriate for different categories of value: market use, non-market use and non-use. For studies already encompassing integrated biophysical and economic results, such as fisheries revenue impacts due to climate change or economic value-at-risk resulting from increased seaport downtime, we directly processed these datasets to generate reduced-form damage functions linking global mean surface temperature changes to country-level economic welfare impacts. For asset–value combinations requiring integration from multiple studies, we first constructed biophysical damage functions linking global temperature to physical impacts such as coral and mangrove area reductions. Subsequently, we developed simplified benefit functions directly relating these biophysical changes (for example, ecosystem area) to welfare benefits, adjusting for projected increases in income.

The resulting damage functions facilitate integration into the modified IAM, RICE50+. This compatibility enables consistent and flexible scenario analysis under various SSPs, supporting robust exploration of future climate-economic outcomes.

An essential feature of our analytical framework is its explicit consideration of the multiple dimensions of welfare impacts from ocean-based climate damages. We distinguish among three value types:

- Market values, where welfare impacts correspond directly to observable market prices, such as fishery revenues and maritime trade through ports;
- Non-market use values, representing benefits from direct ecosystem service use without explicit market pricing, such as nutritional health derived from fisheries or coastal protection from mangroves;
- Non-use values, reflecting welfare impacts stemming from the intrinsic existence of ecosystems independent of direct human use, such as biodiversity preservation in coral reefs.

Not all ocean-based assets exhibit all value categories due to either theoretical constraints or data limitations. For instance, non-use values are conceptually irrelevant for seaports, and non-use values for fisheries, although theoretically plausible, lack sufficient empirical quantification at the required spatial resolution. A detailed overview on how the valuation categories were implemented in RICE50+ for each sector is provided in Table 1, which clearly delineates the mechanism of inclusion.

RICE50+ model structure

To calculate the social cost of carbon for ocean-based welfare, we use an IAM that links the increase of a marginal tonne of CO_2 emissions to a series of interconnected systems. The approach begins with a carbon cycle model that describes the atmospheric response to additional emissions. The resulting changes are fed into a climate model (an implementation of the FaIR model[49]), which simulates the corresponding temperature effects. Finally, these climatic changes are assessed for their impacts on ocean-based welfare, capturing the socioeconomic consequences of alterations in corals, mangroves, fisheries and ports.

For this analysis, we utilize the RICE50+ model (v2.6.0)[14], an open-source coupled climate-economy model that extends the well-known Regional Integrated Climate-Economy (RICE) model[50]. RICE50+ represents a dynamic framework that divides the world into more than 50 regions (58 in its standard version; here we run it at the country level with 155 countries), allowing for region-specific assessments of the costs and benefits of carbon emissions. The impact of climate change on natural capital from changes in terrestrial vegetation cover has been quantified recently with this model[23]. We have enhanced this model to include the latest ecological and economic findings on the impacts of climate change on blue capital—the natural and human-made assets related to the ocean—as shown in Supplementary Fig. 1.

We modified the utility function (which, in the standard version, depends only on the level of consumption $C_{c,t}$ in country c at year t) to account for use and non-use values of four different ocean-based systems: corals, mangroves, seaports, and fisheries and mariculture. We modified the utility function to take the following form (for simplicity, we omit the population here, but all values are expressed in per capita terms of a representative agent in each country):

$$\text{Utility}_{c,t} = \frac{1}{1-\eta}\left(s_{1,1} \times \text{Use}_{c,t}^{\theta_2} + s_{1,2} \times \text{Nonuse}_{c,t}^{\theta_2}\right)^{\frac{1-\eta}{\theta_2}} \quad (1)$$

where θ_2 is the substitutability parameter between use- and non-use values[34,51], $s_{1,1}$ and $s_{1,2}$ are the share parameters, and η is the degree of relative risk aversion. The non-use value in equation (1) is given by

$$\text{Nonuse}_{c,t} = \sum_{b=\text{mangroves, coral}} V_{c,t}^{b,\text{nonuse}} \quad (2)$$

where V represents the annual flow of non-use value associated with blue capital b (for example, mangroves or corals) in each country. Although non-use values in principle could be associated with ecosystems across countries, in our approach we assign each country's non-use value based solely on the area of ecosystems within its own territory and a corresponding shadow price, without transferring ecosystem values across countries. We further divided the use values into those that are exchanged in the market economy and those that are not, also acknowledging that these use values are imperfect substitutes, captured by the elasticity of substitution θ_1:

$$\text{Use}_{c,t} = \left(s_{2,1} \times C_{c,t}^{\theta_1} + s_{2,2} \times \left(\sum_{b=\text{mangroves,coral,fisheries}} V_{c,t}^{b,\text{nonmarketuse}}\right)^{\theta_1}\right)^{\frac{1}{\theta_1}} \quad (3)$$

Following the structure introduced by Hoel and Sterner[52], we retained the share parameters $s_{1,1}$, $s_{2,1}$, $s_{1,2}$ and $s_{2,2}$ in the utility function for consistency, but set them to 1, as we explicitly calibrate the non-market components using empirical valuation data rather than rescaling through arbitrary shares. The elasticities of substitution θ_1 and θ_2 are set to 0.21. The consumption C of all market goods and services is given by

$$\begin{aligned} C_{c,t} = \tilde{C}_{c,t} \times ((1 + \lambda_{1,c}^{\text{coral}} + \lambda_{1,c}^{\text{mangroves}} + \lambda_{1,c}^{\text{fisheries}} + \lambda_{1,c}^{\text{ports}}) \\ \times \Delta T_t + (1 + \lambda_{2,c}^{\text{mangroves}}) \times \Delta T_t^2) \end{aligned} \quad (4)$$

where $\tilde{C}_{c,t}$ represents the consumption level in the absence of climate change, and the coefficients $\lambda_{n,c}^{b}$, $n \in \{1, 2\}$, capture the relationship between temperature and market damages resulting from goods and

services provided by corals, mangroves, fisheries and ports. ΔT_t is the change in global mean surface temperature with respect to pre-industrial levels.

Model parameterization

The value estimates that go into the utility function come from different approaches. For corals and mangroves, we first simulate the change in country-level cover area $A^b_{c,t}$ and then multiply it by their shadow price $p^{b,\upsilon}_{c,t}$, with b = {corals, mangroves} and υ = {non-use, non-market use}. Coral area cover changes as a linear function of temperature, based on ref. 27, and the mangrove cover changes as a quadratic function of temperature, based on ref. 28. The shadow price is obtained from the updated ecosystem services valuation database (ESVD) as presented in ref. 53. Following ref. 15, the value of corals market use and non-use values increases over time with the rate of growth of GDP per capita, as

$$p^{\text{corals},\upsilon}_{c,t+1} = p^{\text{corals},\upsilon}_{c,t}(1 + \gamma^{\upsilon} \times g_{c,t}) \tag{5}$$

where γ^{υ} is the income elasticity estimated from a regression model using ESVD studies for market use and non-use values. For mangroves, $\log(p^{\text{mangroves},\upsilon}_{c,t}) = a^{\upsilon}_c + b^{\upsilon}_c \log(\text{GDP}pc_{c,t})$, where parameters a^{υ}_c and b^{υ}_c rescale the high-resolution findings from ref. 28 to the average country-level value of mangroves using country-level GDP per capita. Therefore, the impact of climate change in these non-market values is only through reduced area, which would remain constant at today's values if temperature did not change. Although, in theory, the marginal value of ecosystems may also rise as they become scarcer, we do not incorporate this effect here due to data limitations.

The market damage parameters $\lambda^b_{n,c}$ for corals and mangroves are estimated by running two sets of simulations. First, we calculate the GDP contribution of corals and mangroves by multiplying their shadow price $p^{b,\upsilon}_{c,t}$ by the area, and assuming no climate-induced damages to their areas. We then calculate the contribution under a scenario with climate damages. The difference between these two scenarios, as a percentage of GDP, is fitted to the global mean surface temperature using a linear function for corals, and a quadratic function for mangroves, following the functional forms in their respective studies of origin. This $\lambda^b_{n,c}$ represents a real market output loss as used in the IAM's damage function—not a theoretical correction to GDP. Although our method uses shadow prices and is conceptually related to wealth-accounting frameworks, we do not compute net present values or deduct capital loss from national income. Instead, we keep ecosystem stocks in physical terms over time and compute their evolving contribution to market, non-market and non-use values each year.

The non-market use values from fisheries and mariculture were derived from the analysis by Cheung and colleagues[31] of the impacts of climate change on nutrient availability from fisheries and mariculture at the country level. We combine these projections with epidemiological studies on the dose–response relationships between several health outcomes and the intake of omega-3, calcium, iron and protein—the same nutrients analysed in ref. 31. With that, we project changes in mortality rates for each country based on climate impacts on these nutrients, considering each country's level of dependence on fisheries, while allowing for a conservative assumption that a substantial portion of fish-derived nutrients can be replaced by other sources. Our preferred specification is to monetize these impacts using a globally uniform VSL. This is derived from the US EPA estimate of US$7.4 million, rescaled from US to global GDP per capita, for a 2020 value of US$2.15 million, to reflect the average global GDP per capita level[54]. Over time, the VSL grows with the global average GDP per capita growth rate.

The coefficients $\lambda^{\text{fisheries}}_{1,c}$, which represent the market value losses from fisheries, are obtained from a bioeconomic model by Free and colleagues[55], which quantifies catch and profit levels at the country level for 60% of global fisheries under different management practices and climate impact scenarios. To provide a conservative estimate, we assume a full adaptation scenario in which maximum sustainable yield is maintained, allowing us to explore how profits under alternative climate scenarios diverge from those under the less climate-impacted RCP 2.6 scenario. The revenue loss at the regional level is then adjusted by a multiplier obtained from ref. 56, which reflects the broader economic impact of fisheries losses on related activities and income.

Finally, coefficients $\lambda^{\text{ports}}_{1,c}$, which account for market impacts from climate damages to ports, were obtained from an analysis performed by Verschuur and colleagues[29], which estimated potential damages to ports due to cyclonic winds, different types of flooding (coastal, fluvial and pluvial) and marine extremes (extreme waves, overtopping, heat and non-cyclonic wind) under climate change scenarios. The damages include direct physical damage to port infrastructure, representing a financial loss due to the costs of rebuilding or repairing these infrastructures; operational downtime caused by such damages, leading to a decrease in revenue for port operators; and the impact on maritime trade activities for countries reliant on these ports. The damage estimates are obtained by fitting a linear regression to the change in damages to ports (as a percentage of GDP) as a function of global mean surface temperature.

Details on all these components are provided in the Supplementary Information.

Model simulations to estimate the blue SCC

Based on the blue RICE50+ model output, we compute the SCC from oceans and separate it according to the different categories and types of ocean services $V^{b,\upsilon}_{c,t}$, using the nested utility function (equation (1)) and a country-level intertemporal welfare (W_c) function for each country as discounted utility summed over the population, which is the objective function for each region in the RICE50+ model:

$$W_c = \sum_{t=2020}^{2300} \text{pop}_{c,t} \times (1+\delta)^{-(t-2020)} \times \text{Utility}_{c,t} \tag{6}$$

where $\text{pop}_{c,t}$ represents the population in country c at time t, and δ is the pure rate of time preference. Note that in the RICE50+ framework, the model can be run in a global cooperative or non-cooperative mode. Here we use the latter, running each country separately under the different scenarios. Because, here, we do not implement global optimization scenarios, there is no issue of inequality considerations between countries, and we also do not apply explicit equity weighting[57] to take into account global differences in income levels. This allows for a uniform and unique global value for the SCC without adding further value judgements, notably on inequity aversion between countries[57]. Accordingly, we aggregate population-weighted country utilities converted into monetary terms and apply discounting as described in equation (9).

We ran the model once (all variables of this run are denoted without a hat) and then a second time adding one additional pulse of one megatonne of CO_2 of emissions in 2020 (variables denoted by a hat). The pulse was added upon a future emissions pathway result of running the model under socioeconomic variables consistent with SSP2 and a no-policy scenario where the global mean temperature increase reaches 3.5 °C by the end of the century, equivalent to 6.8 W m^{-2} of forcing). We first computed the monetary-equivalent per capita utility impact at any time t and in country c by computing for each combination of b and υ, that is, the difference in utility due to a change only due to impacts on $V^{b,\upsilon}_{c,t}$, whereas all other variables are kept at levels of the model run without emission pulse:

$$\Delta\text{Utility}^{b,\upsilon}_{c,t} = \text{Utility}_{b,\upsilon,c,t} - \widehat{\text{Utility}}_{b,\upsilon,c,t} \tag{7}$$

Here, $\widehat{\text{Utility}}$ is the utility result without the pulse and Utility is the utility with the emission pulse. This utility change was then converted into its monetary value at time t by the marginal utility of one unit of consumption $\frac{\partial \text{Utility}_{c,t}}{\partial c_{c,t}}$ in country c at time t. Finally, we used the endogenous

global Ramsey discount factor, as in ref. 16, to convert these values into today's monetary values. The discount factor is computed as:

$$\mathrm{DF}_t = (1+\delta)^{-(t-2020)} \frac{\left(\sum_c \frac{\mathrm{pop}_{c,t}}{\sum_{c'} \mathrm{pop}_{c',t}} c_{c,t}\right)^{-\eta}}{\left(\sum_c \frac{\mathrm{pop}_{c,2020}}{\sum_{c'} pop_{c',2020}} c_{c,2020}\right)^{-\eta}} \quad (8)$$

where $c_{c,t}$ represents consumption per capita (in US$_{2005}$), the pure rate of time preference is set at $\delta = 0.015$, and the elasticity of marginal utility of consumption is set at 1.45. Finally, we aggregate all impacts across the population to obtain the global value; that is, we compute the SCC for 2020 in US$_{2020}$ (note that the RICE50+ base currency is US$_{2005}$, so we convert the output in 2020 dollars using the International Monetary Fund's US$ deflator between 2005 and 2020, multiplying all values by 1.298763) based on the sum of the disaggregated impacts due to one tonne of CO_2, as

$$\mathrm{SCC}_{2020}^{\mathrm{Ocean}} = \sum_{t=2020}^{2300} \mathrm{DF}_t \times \left(\sum_c \frac{\Delta \mathrm{Utility}_{c,t}}{\frac{\partial \mathrm{Utility}_{c,t}}{\partial c_{c,t}}} \times \mathrm{pop}_{c,t} \right) \quad (9)$$

We report SCC values for our central runs as well as the Monte Carlo simulations exploring uncertainties related to the new set of parameters introduced into the model. As an additional test, we also ran a grid of carbon prices verifying that the welfare levels are maximized at the level of the SCC obtained. In the Supplementary Information, we also explore additional socioeconomic scenarios, as well as running a Monte Carlo analysis computing the blue SCC in 10,000 simulations (Supplementary Information).

Reporting Summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this Article.

Data availability

The underlying analysis can be found at http://github.com/berbastien/blue-scc (https://doi.org/10.5281/zenodo.17649110). Source data are provided with this paper.

Code availability

Code for the blue SCC replication is provided at http://github.com/witch-team/RICE50xmodel/releases/tag/v2.6.0 (https://doi.org/10.5281/zenodo.17649366).

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Author contributions

Except for the first and last authors, all other authors are listed in alphabetical order. B.A.B.-O. provided conceptualization, investigation, methodology, visualization and formal analysis, and contributed to writing the original draft. F.G. and J.E. contributed to methodology, visualization, formal analysis and software. M.T. contributed to methodology, supervision and resources. K.R. contributed to methodology and supervision, writing of the original draft, resources and funding acquisition. All authors contributed equally to data curation, validation, and review and editing.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-025-02533-5.

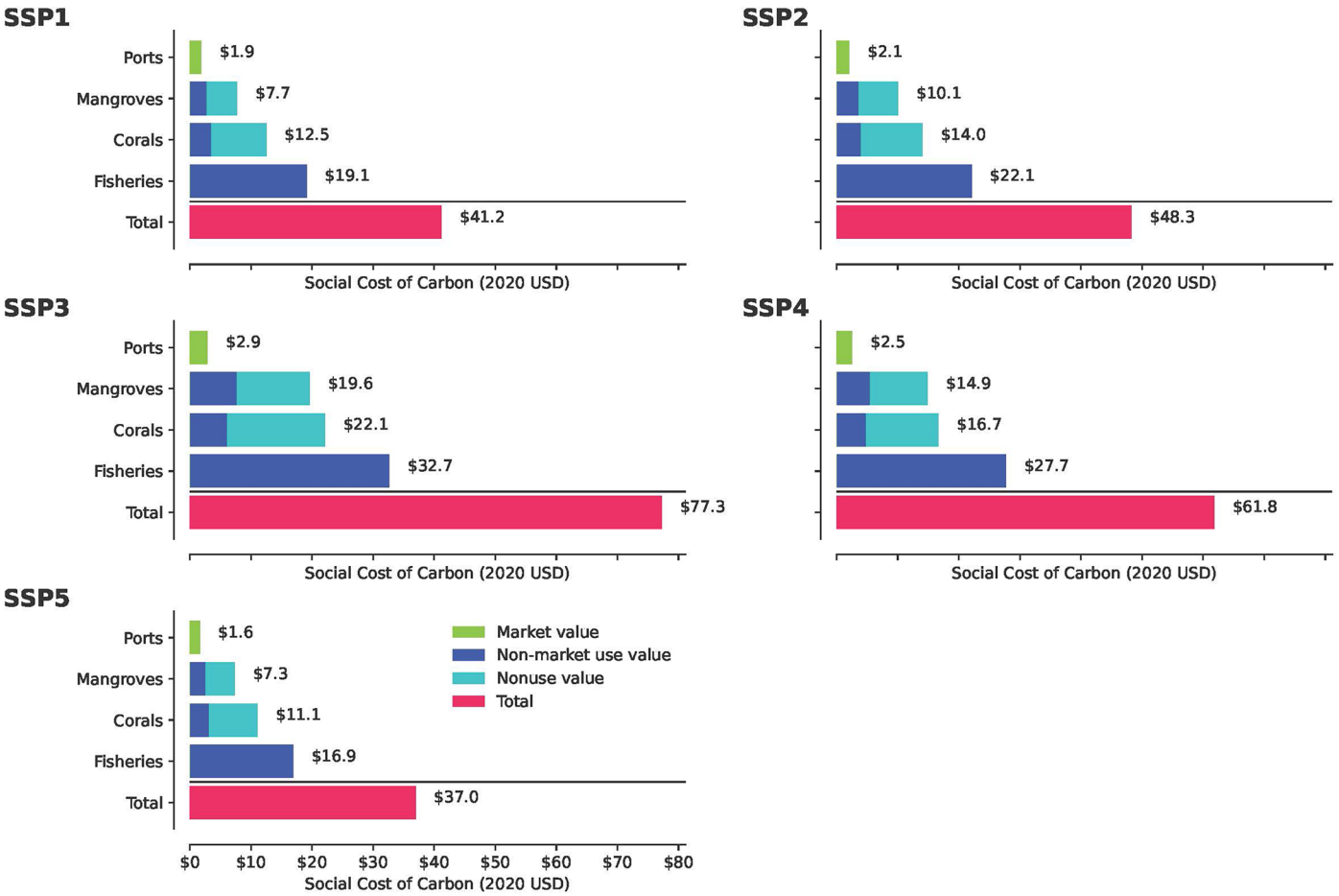
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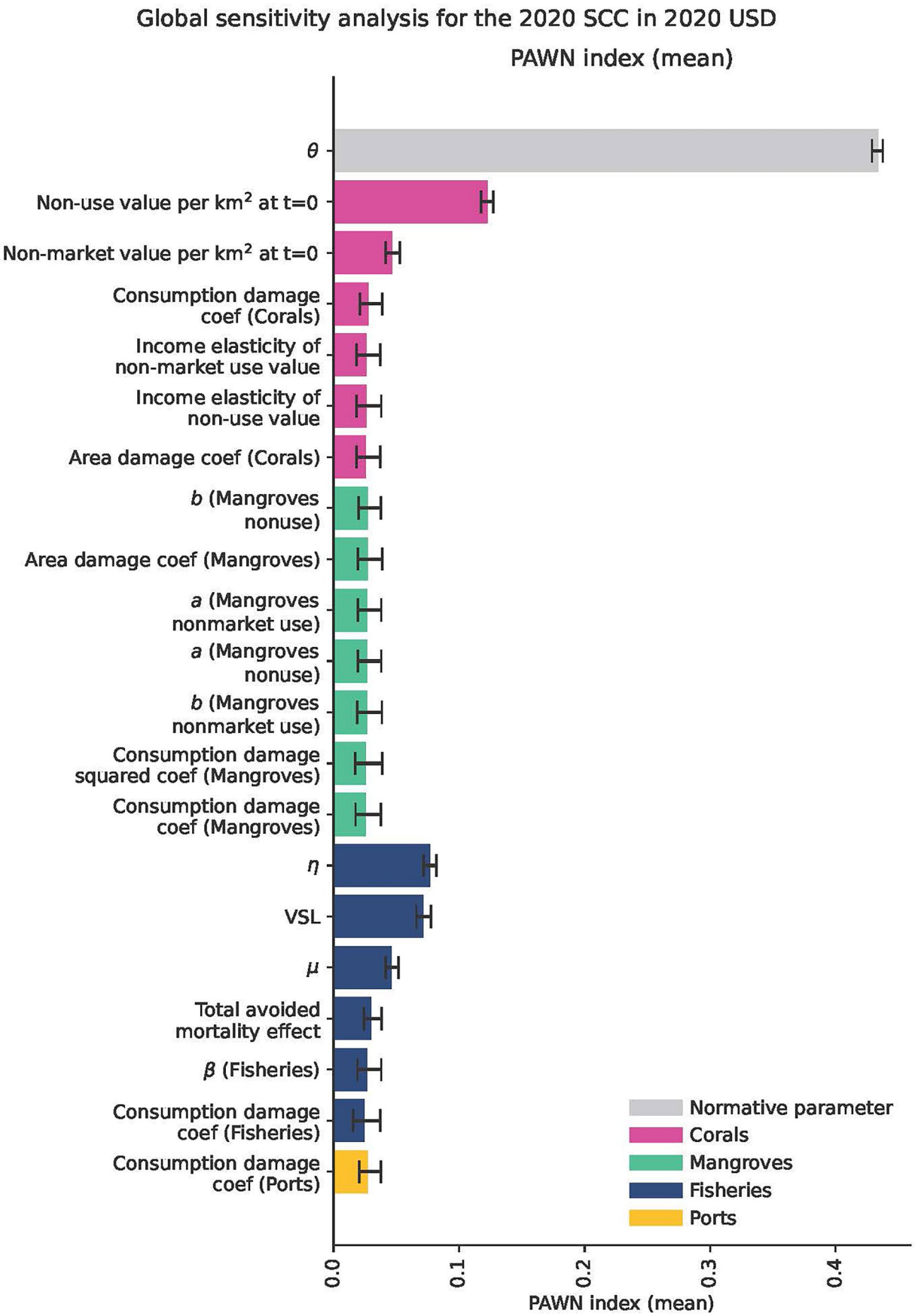
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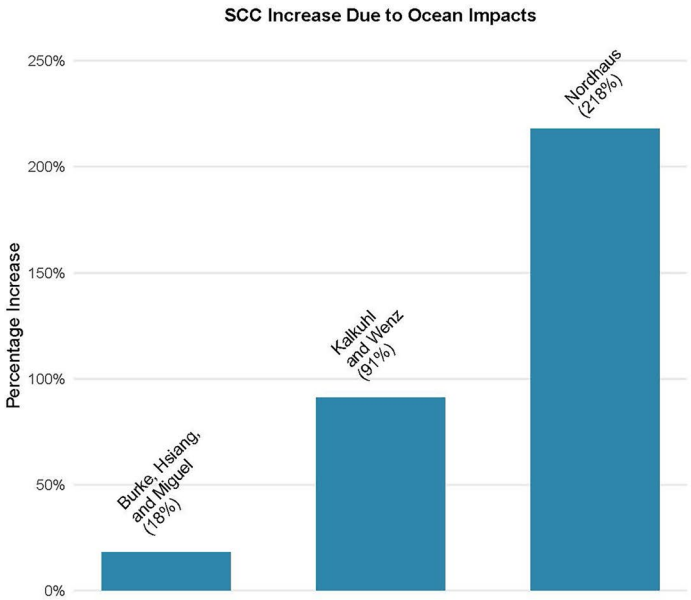
Extended Data Fig. 1 | Blue Social Cost of Carbon under alternative Shared Socioeconomic Pathways. Estimated Blue SCC across five SSPs, reflecting different trajectories of socioeconomic development and associated emissions. Each SSP results in a different increase in global mean temperature by 2100 relative to pre-industrial levels. End-of-century global mean surface temperature increases are as follows: SSP1: 2.60 °C, SSP2: 3.58 °C, SSP3: 4.18 °C, SSP4: 3.82 °C, SSP5: 3.95 °C.

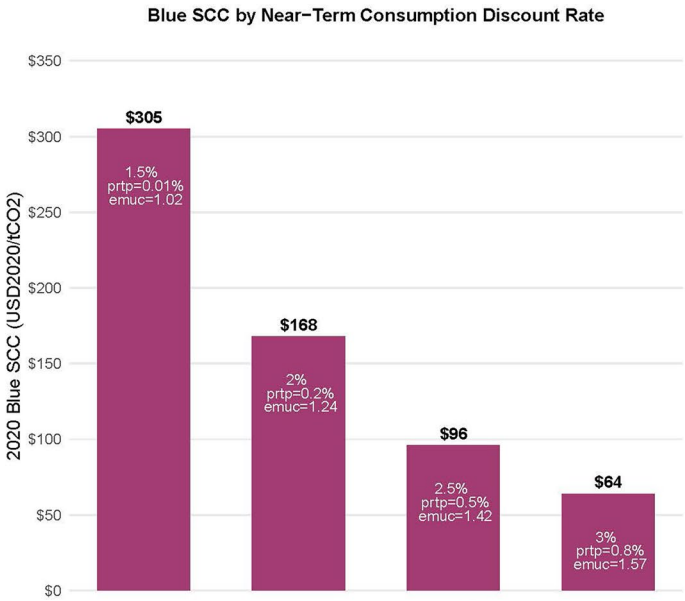
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Extended Data Fig. 2 | Sensitivity of the Blue Social Cost of Carbon to key input parameters (PAWN index). Mean PAWN index values and 95% confidence intervals showing the influence of each input parameter on the blue SCC, based on global sensitivity analysis with bootstrapping. The elasticity of substitution between blue capital components (θ) is the most influential parameter. Other important drivers include the non-use value of corals, the fraction of non-substitutable nutrients from fisheries, and the Value of a Statistical Life (VSL).

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Extended Data Fig. 3 | Blue SCC compared to standard SCC and its sensitivity to discount rate. Left: Percentage increase in the SCC when adding ocean-based damages to three alternative baseline damage functions in RICE50 + . Right: Blue SCC estimates using alternative pure rate of time preference (prtp) and elasticity of marginal utility of consumption (emuc) pairs calibrated to near-term discount rates of 1.5–3%.

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☐	☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒ For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐ Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data was collected from previously published articles. All data sources is documented in the supplementary materials.
Data analysis	All data analysis was done using R and Python

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data availability
The underlying analysis can be found at: github.com/berbastien/blue-scc. DOI: https://doi.org/10.5281/zenodo.17649110

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	NA
Reporting on race, ethnicity, or other socially relevant groupings	NA
Population characteristics	NA
Recruitment	NA
Ethics oversight	NA

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We collected quantitative data on climate impacts on ecosystems, and economic valuation studies of the benefits of those ecosystems to people
Research sample	Data was collected from 6 peer reviewed studies
Sampling strategy	We collected the results from all global studies of climate change impacts on ocean-based welfare that reported results disaggregated at the country level
Data collection	Data was collected from the public repositories of such studies and we contacted the corresponding author when not readily available
Timing	from 2022 to 2024
Data exclusions	To the best of our knowledge no data was excluded
Non-participation	No declined participation
Randomization	*If participants were not allocated into experimental groups, state so OR describe how participants were allocated to groups, and if allocation was not random, describe how covariates were controlled.*

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA