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The ocean carbon sink enhances countries' inclusive wealth and reduces the cost of national climate policies

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Improving our understanding of future ocean carbon uptake requires a nuanced understanding of the value of the annual ocean sink. Here, we combine an abatement cost-based approach and a climate damage-based approach to assess the value of the annual ocean sink. The former shows that the aggregate cost of national climate policies could increase by up to USD 80 billion if the ocean carbon sink weakens by 10 percent. As a complementary perspective, the damage-based approach shows that the annual ocean carbon sink contributes between USD 300 billion and USD 2,332 billion to countries' inclusive wealth. Despite the conceptual appeal of the damage-based approach for its potential insights into regional wealth redistribution, uncertainties in national social cost of carbon estimates make it less reliable than the abatement cost-based approach, which in turn provides more reliable estimates for a fiscal cost assessment of improved monitoring services of the ocean carbon sink.

Since the pre-industrial era, the ocean has absorbed ~26% of anthropogenic CO₂ emissions¹, reducing climate-change impacts and providing, in addition to many other services, a considerable societal value as a carbon sink. What exactly the societal value of this natural ocean sink is and how it is distributed across different regions needs to be quantified, though. This information is relevant (i) for inclusive wealth accounting and sustainable development assessments, (ii) for justifying improving the accuracy of ocean carbon sink estimates and thus forecasting potential weakening of the ocean carbon sink, and (iii) for assessing deliberate efforts to increase the ocean sink through marine carbon dioxide removal (CDR) technologies.

Various studies investigate the annual, cumulative, or future amount of anthropogenic CO₂ taken up by the ocean. We instead focus on estimating the value of the annual ocean carbon sink based on different CO₂ price estimates and using two different valuation approaches. On the one hand, we consider a cost-benefit approach, taking the perspective that the ocean carbon sink reduces climate damage. On the other hand, we use a cost-effectiveness approach, taking the perspective that the ocean sink influences the remaining anthropogenic CO₂ emissions budget, and, in turn, the CO₂ abatement cost. Accordingly, we combine a climate-change-damage-based approach with an abatement cost-based approach to valuing the ocean carbon sink. The former utilizes information on the social cost of carbon

(SCC), i.e., the marginal damage of an additional ton of CO₂ being released into the atmosphere, and in turn, the marginal avoided damage of an additional ton of CO₂ being absorbed by a carbon sink. The latter utilizes information on marginal abatement costs. In a stylized and optimized global climate policy, the two approaches would coincide, since the marginal abatement cost would be equated across countries (either via a global carbon tax or international emissions trading) at the level of the SCC, i.e., the sum of SCCs for all countries. In reality (and in applied work), the two approaches do not align, since the remaining carbon budget is not derived from a global cost-benefit analysis but rather determined as part of national priorities and a political bargaining process, with different countries using different instruments to reduce their CO₂ and other greenhouse gas emissions. Hence, applying the two approaches to valuing the ocean sink sheds light on conflicting outcomes depending on the stringency of the overall climate policy ambition.

Applying the climate-damage-based approach places the valuation of the annual ocean carbon sink in the natural capital and inclusive wealth (IW) framework^{2–5}. A value estimate derived as the present value of the entire future path of the ocean carbon sink provides an estimate of the total value of the ocean carbon sink while a value estimate in a given year provides an estimate of the ocean carbon sink contribution to comprehensive

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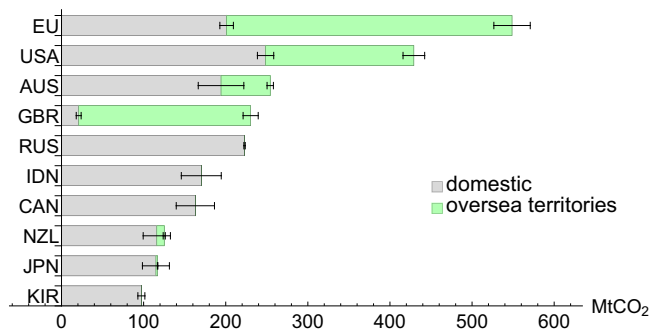


Fig. 1 | The 10 states (or confederation of states) with the largest attribution of the annual ocean sink. We distinguish between domestic attribution and attribution resulting from overseas territories. Error bars represent ± 1 SD of domestic and overseas territories attributed ocean sink. EU29 European Union 27 plus Norway and Iceland, USA United States, AUS Australia, GBR Great Britain, RUS Russia, IDN Indonesia, CAN Canada, NZL New Zealand, JPN Japan, KIR Kiribati.

investment². Comprehensive investment measures the change in IW. Non-negative comprehensive investment, i.e., the aggregate value of investments and disinvestments in all natural and human-made capital stocks, is required to achieve (weak) sustainable development⁶. IW assessments (used to measure sustainable development, i.e., the change in comprehensive investment) are applied in the United Nations (UN) Inclusive Wealth Reports^{7–9}, but do not yet include the wealth contribution of the ocean carbon sink. The United States have recently launched a draft National Strategy to improve its statistical description of economic activity and development by accounting for the wealth contributions of water, air, and other natural assets following the IW approach, but not yet the value of the ocean carbon sink¹⁰.

In terms of valuing the ocean carbon sink, applying the SCC allows us to measure the damage avoided in a given year, i.e., the mitigated reduction in comprehensive investment resulting from CO₂ emissions. Canu et al.¹¹ apply this approach to value the carbon sink in the Mediterranean Sea, estimating an annual value between 127 and 1,722 M EUR (2011). However, different countries are affected differently by climate change and hence it is assumed that climate change will result in wealth redistribution¹². Bertram et al.¹³ account for this aspect by applying the country social cost of carbon (CSCC) in their assessment of coastal blue carbon ecosystem sequestration. They show, for example, that annual carbon sequestration in Australia's coastal ecosystems has a global value of about USD 25 billion per year, of which almost USD 23 billion are received abroad. However, the global annual amount of carbon sequestration attributable to coastal ecosystems with about 81 MtC is rather small¹³.

The uncertainty about climate-change impacts on ecosystems, human health, and economies was the main reason for defining temperature ceilings as part of the Paris Agreement (keeping the global temperature increase well below 2°C above pre-industrial levels and ideally limiting it to 1.5°C). This approach translates into the objective to cost-efficiently achieve compliance with the temperature ceiling, determining the marginal abatement cost, i.e., the CO₂ price that would achieve compliance with the temperature ceiling (i.e., the willingness to pay for compliance with such a temperature ceiling, see Cross-Chapter Box 5 in ref. 14). Accordingly, implemented CO₂ tax levels or observed CO₂ prices on emissions trading markets can be used as information for valuation purposes, again allowing to derive information on comprehensive investment, though with price information implicitly including information on the willingness to pay to achieve emissions reductions targets.

However, CO₂ pricing instruments are not everywhere in place, and in many cases, for example, in the European Union (EU), CO₂ pricing instruments cover only a fraction of the emissions in the region. Hence, economic models have to be used to estimate regional CO₂ prices consistent with the region's emissions-reduction goals. Rehndanz et al.¹⁵ assess the integration of the ocean anthropogenic carbon sink into a hypothetical

carbon market, using model-based estimates for the anthropogenic part of the regional ocean sink¹⁶.

With regard to the integration of (attributed) carbon sinks into climate policy and emissions trading, it should be noted that only those land-based carbon sinks that are managed and, therefore, considered additional are included in climate policy. And even for these, there remain several issues regarding the appropriate accounting in the greenhouse gas (GHG) inventories of countries¹⁷. However, also natural, non-additional, services are of value. Accordingly, it is uncontested that the wealth contribution achieved via carbon sequestration from large forest areas of a specific landlocked country should be considered in IW and sustainable development assessments. In a similar fashion, the fractional ocean carbon sink of a coastal country should be considered as well. Furthermore, any attribution of the ocean carbon sink as part of international climate policy frameworks does not necessarily imply a potential buy-out from ambitious emissions reductions, as the implications for emissions-reduction commitments depend on the particular baseline considered for the ocean carbon sink. In turn, the attribution of a fraction of the ocean sink to a particular country could result in additional responsibility or even liability, i.e., the requirement to increase emission reduction efforts in that country if the ocean sink were to weaken in the future.

Our article aims to shed light on the two approaches, the climate-damage-based approach and the abatement cost-based approach, and how they can be combined to achieve a more nuanced understanding of the contribution of annual ocean carbon sink to wealth and climate policy.

Results

Regional attribution of the ocean sink

Which components of the ocean carbon sink should be included in such a valuation and how these should be attributed to countries is a study object on its own. We use for our valuation the model-based derived global ocean CO₂ sink of 2.8 (SD ± 0.4) GtC (in the year 2022) from the global carbon budget¹ and assign it proportional to the EEZ area of countries. With this area-based approach, ~59% of the ocean carbon sink is attributed to the high seas (see methods). For the ocean carbon sink attributed to countries, Fig. 1 shows the 10 states (or confederation of states) with the largest attributed ocean sink. Note that we included in the EU also Norway and Iceland (EU29) due to the joint climate policy of these states with the EU. The figure shows the large gains from overseas territories of the EU29, the United States, Australia, and Great Britain. Within the EU29, the largest attribution resulting from overseas territories is achieved by France and Denmark (both achieving ~96% of their attributed ocean sink via overseas territories). Furthermore, note that this approach favors small islands states like, for example, Kiribati (KIR), an island nation in the tropical Pacific Ocean, with ~726 km² land area and a 3,550,000-km² EEZ located in the Pacific upwelling area, putting it on the tenth place in Fig. 1 (and attributing a much larger share of the ocean carbon sink compared to a carbon-flux based approach, see methods).

2.2 CO₂ price estimates

Figure 2 shows the various CO₂ price estimates at the global and at the national level, the latter displayed for ten major industrialized and developing regions in international climate policy¹⁸ (Supplementary Fig. SMF1 shows the corresponding information for the countries and regions with the highest CO₂ emissions in the fossil and industrial sector).

There are substantial differences between the two climate-change damage estimates: 227.28 USD/tCO₂ (SD 14.95) based on Dell et al.¹⁹, abbreviated DJO, and 29.17 USD/tCO₂ (SD 3.69) based on Tol²⁰, abbreviated Tol (Fig. 2).

However, even for the rather large DJO-CSCC estimates, in 6 out of the 10 countries shown in Fig. 2, the marginal abatement cost exceeds the country-specific marginal damage for both NDC ambitions, indicating higher-than-optimal abatement efforts for the country from a national, non-cooperative perspective. For these countries, the NDCs apparently include some concern for climate damage that occurs outside their borders.

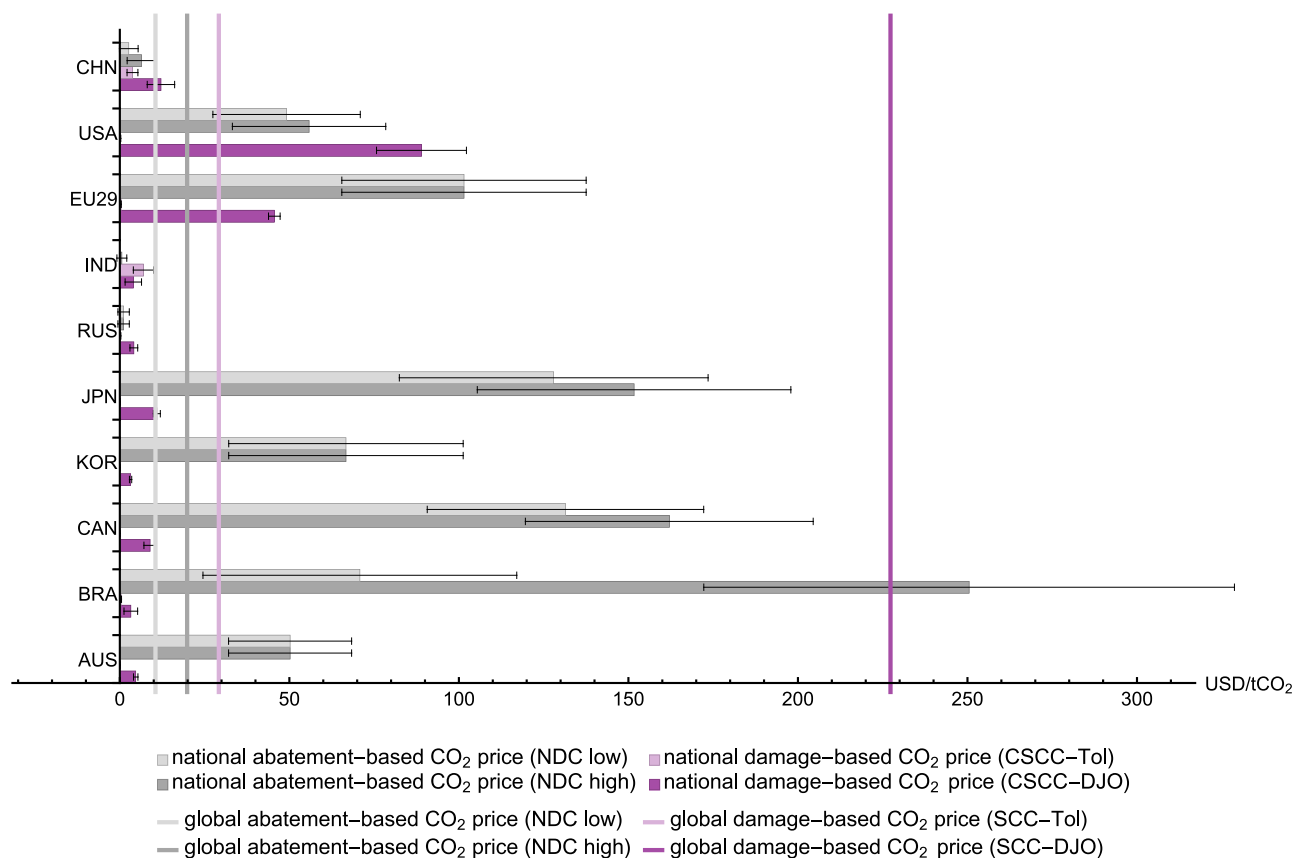


Fig. 2 | National and global CO₂ prices. The bars show the national abatement-based CO₂ prices estimates (i.e., without international emissions trading) for NDCs with low and high ambition levels, respectively, and national damage-based CO₂ prices estimates, (i.e., country social cost of carbon (CSCC)), obtained from Dell et al.¹⁸ in Ricke et al.^{22,23}, abbreviated as DJO, and obtained from Tol¹⁹, abbreviated Tol, respectively. The vertical lines show the global abatement-based CO₂ price estimates (i.e., with international emissions trading), for NDCs with low and high ambition

levels, respectively, and the global damage-based CO₂ estimates (i.e., social cost of carbon SCC), for the DJO and Tol estimate, respectively. Error bars represent ±1 SD for the national CO₂ prices. The figure includes the ten major industrialized and developing regions in international climate policy. Countries are indicated by their ISO3 code: CHN China, USA United States, EU29 European Union 27 with Norway and Iceland, IND India, RUS Russia, JPN Japan, KOR South Korea, CAN Canada, BRA Brazilian, AUS Australia.

Unfortunately, this does not hold true for China, the United States, India, or Russia, where country-specific marginal abatement costs are below their DJO-CSCC estimates. These countries contribute ~59% of the projected CO₂ emissions in 2030 in our study.

Overall, in 106 countries (of the 146 used in the abatement-based approach), the national CO₂ prices—marginal abatement costs for the given NDCs under high ambition—exceed the DJO-CSCC estimate. For the Tol-CSCC estimates, in 107 countries, the national CO₂ prices exceed the CSCC estimate. In turn, that means that even for the comparatively low Tol-CSCC estimates, not every country's marginal abatement cost exceeds its country-specific marginal damage. This especially applies to India (for both NDC ambition levels) and to China (for the low NDC ambition level). Overall, the national carbon price (=marginal abatement cost) falls short of the CSCC in 69 and 65 countries under low NDC ambition levels, and in 40 and 39 countries under high NDC ambition levels, for the DJO and Tol-CSCC estimates, respectively. These countries would experience an economic gain by increasing their emissions reduction ambitions and thus should spend more on abatement efforts for purely selfish reasons.

With full emissions trading, the average (emissions-weighted) CO₂ price falls from 26.46 (SD 18.00) USD/tCO₂ to a market price of 9.64 (SD 5.11) USD/tCO₂ and from 42.08 (SD 20.76) USD/tCO₂ to 19.04 (SD 7.00) USD/tCO₂ for low and high ambition levels in the NDCs, respectively. So, even under high ambition levels in the abatement levels, the market price falls short of the comparatively low Tol-SCC estimate of 29.17 USD/tCO₂ (SD 9.70), indicating that under full emissions trading, the emissions-reduction levels should be increased under cost-benefit consideration.

If there was a global emissions trading scheme, for example, the United States and China would become buyer and seller of international emissions reductions, respectively. Supplementary Fig. SMF1 shows the gains from emissions trading by equalizing marginal abatement costs for the United States and China. Supplementary Fig. SMF2 shows the ten countries/regions with the largest CO₂ emissions in the energy and industrial sector and the costs of emissions reductions for high ambition levels in the NDCs as percentage of their GDP. The full list of CO₂ price data and the costs of achieving the NDCs as percentage of GDP (a negative entry indicates a gain) can be found in the Supplementary Tables ST1 and ST2.

Wealth contribution of the ocean carbon sink

The wealth contribution of the annual global ocean carbon sink of 2.8 GtC, determined as its annual contribution to comprehensive investment, ranges between USD 299.22 (SD 56.95) billion and USD 2,331.70 (SD 178.30) billion under the climate-change-damage-based approach, using the Tol-CSCC estimates and the DJO-CSCC estimates, respectively. Doing the same calculation, but using instead abatement-based CO₂ prices, a global price is only obtained under the market solution (i.e., full trading), and the annual value of the global ocean sink ranges between USD 99.00 (SD 52.55) billion and USD 195.39 (SD 72.14) billion, for NDCs with low and high ambition, respectively. In alternative scenarios, we use national abatement-based CO₂ prices (i.e., there is no international emissions reduction trading) to value the regional ocean carbon uptake. For example, using the model-based CO₂ price in the EU, 101.51 (SD 36.03) USD/tCO₂, implies a value of USD 55.70 (SD 19.92) billion of the ocean carbon sink attributed to the EU29. The

aggregated value obtained when adding the national valuations is USD 189.74 (SD 26.49) billion and USD 304.47 (SD 28.10) billion, for NDCs with low and high ambition, respectively. While these estimates are higher than those obtained under a global CO₂ price, they assign no value to regions without a CO₂ price. Most notably, the value of the carbon sink in the high seas is not taken into account in this approach.

Balance of transboundary wealth contributions of the ocean carbon sink

The climate-change-damage-based approach allows quantification of the balance of transboundary wealth contributions. While applying the (global) SCC yields insights into the global wealth contribution of the ocean carbon sink in each nation's exclusive economic zone (a quantity OCS_i of carbon absorbed per year by the water in the EEZ of country i), only a fraction of this contribution accrues domestically. This fraction is calculated by valuing the domestic ocean carbon sink at the domestic CSCC¹³. In addition, the domestic carbon sink generates wealth abroad, which is calculated by applying the global SCC minus the domestic CSCC. However, at the same time, the ocean sink in the waters of other countries and in the high seas also contribute to reducing climate change impacts domestically. This is calculated by applying the domestic CSCC to the carbon sink in the ocean everywhere except in domestic waters, $OCS - OCS_i$. Netting the outward wealth contribution of the domestic ocean carbon sink with the inward wealth contribution of the non-domestic ocean carbon sink determines the balance of transboundary wealth contribution. A positive (negative) balance indicates that the ocean carbon sink attributed to the country contributes more (less) to foreign wealth than the country receives from abroad. A positive balance in a given year, requires that

$$\frac{OCS_i}{OCS} > \frac{CSCC_i}{SCC}, \quad (1)$$

which means that the fraction of the annual ocean sink attributed to a given country relative to the global ocean carbon sink (OCS_i/OCS) is greater than the fraction of the country's CSCC_{*i*} relative to the global SCC.

Since almost 60% of the annual carbon sink is attributed to the high seas, the individual shares of countries, OCS_i/OCS , are rather small (the largest share is obtained by the EU29 with 5.35%, only 1.96% without their overseas territories). Considering the total annual ocean carbon sink, only 49 and 56 countries have a positive balance, using the Tol-CSCC estimates and the DJO-CSCC estimates, respectively (the figures increase to 56 and 74 if countries are included with an attributed ocean sink but with missing CSCC estimates, i.e., having a CSCC of zero). The largest wealth contribution originates from the carbon sink attributed to the high sea, ranging between USD 175.53 (SD 33.41) billion and USD 1,367.85 (SD 220.96) billion, for the Tol and DJO estimates, respectively.

Accordingly, we focus on the transboundary wealth contribution between countries, in dependence on their share in the attributed ocean carbon sink without the carbon sink in the high seas (i.e., OCS_i/OCS_{woHS}) and their shares of the global SCC (i.e., $CSCC_i/SCC$) in Fig. 3. The figure shows the implications of the different CSCC estimates, as the position on the x axes, i.e., the share in the attributed annual ocean carbon sink does not change between the upper and lower panel. Accordingly, the color code indicates a positive (blue) and negative (orange) balance of transboundary wealth contribution only for those countries with a clear assessment from both CSCC estimates, while countries where the assessment is not robust to the different CSCC estimates, i.e., with a positive balance in the one study and negative balance in the other and vice versa, are indicated by a gray color code. The visual difference between the two estimates is mainly explained by the estimates for the United States and the EU29. According to the DJO-CSCC estimate, the combined share of United States and EU29 at the global SCC is about 60% (with a share of 40 and 20% for the United States and the EU29, respectively), while according to the Tol-CSCC estimate, the combined share is only ~2%. In turn, with the DJO-CSCC estimates, these two regions are the main recipients of the ocean carbon wealth contribution, i.e.,

having a negative balance, while both have a positive balance under the Tol-CSCC estimates.

However, apart from these two extremely different assessments for the United States and the EU29, a total of 87 out of 123 countries with an attributed ocean carbon sink have a clear assessment of the balance of transboundary wealth contribution. If landlocked countries without an attributed ocean sink are included, the number of countries with a clear assessment increases to 123. Under both estimates, China has the largest negative balance, USD −43.04 (SD 22.29) billion and −14.74 (SD 8.05) billion, decreasing to USD −116.00 (44.97) billion and USD −37.19 (SD 17.22) billion under the inclusion of the contribution of the high seas, according to the DJO and Tol estimates, respectively. Also, under both CSCC estimates, Australia has the largest positive balance, USD 37.87 (SD 9.73) billion and USD 7.35 (SD 1.24) billion, decreasing to USD 9.63 (SD 12.09) billion and USD 7.26 (SD 1.24) billion under the inclusion of the contribution of the high seas, according to the DJO and Tol estimates, respectively. The full list with the balance of transboundary wealth contribution for all countries, with and without consideration of the carbon sink attributed to the high sea, can be found in Supplementary Results ST3. The gains in domestic wealth contribution from the ocean carbon sink in overseas territories are discussed in Supplementary Notes 1.

Abatement cost implications from attributing ocean carbon sink

We consider a scenario in which NDCs are increased in proportion to the attributed ocean carbon sink to compensate for the weakening of the global ocean carbon sink. Accordingly, if the global ocean carbon sink decreases by 5% (10%), countries' emission reduction targets are increased by 13.5% (27%) of their attributed ocean carbon sink. The relative increase in the NDC reduction targets needs to be higher than the decrease in the global ocean carbon sink to compensate also for the reduction in the ocean carbon sink of the high seas. For example, a 5% (10%) reduction in the global carbon sink implies that the EU29 would need to reduce its emissions by an additional amount of ~74 (148) Mt CO₂.

Figure 4 shows the change in costs for a weakening of the global ocean carbon sink of 10% for NDCs with high ambition levels under the assumption of no and full emissions reductions trading (Panel a and b, respectively), displaying the ten major industrialized and developing regions in international climate policy (Supplementary Fig. SMF4 shows the corresponding information for the countries and regions with the highest CO₂ emissions in the fossil and industrial sector).

Without emissions reductions trading, for countries and regions with an attributed ocean carbon sink, the abatement cost increase when the ocean carbon sink weakens (since they have to move up on the marginal abatement cost curve, see Fig. SMF2). For example, the cost of the EU29 will increase from 0.23 (0.13) to 0.27 (SD 0.15) and 0.32 (SD 0.16) % of its GDP in 2030, for a weakening of the global ocean carbon sink of 5% and 10%, respectively. Now, the ocean carbon sink in overseas territories becomes an additional burden because, without its overseas carbon sink attribution, the EU29 would only need to increase its NDC by about 27 MtCO₂ and 54 MtCO₂ for a weakening of the global ocean carbon sink of 5% and 10%, respectively. In turn, the cost of the EU29 would “only” increase from 0.23 (0.13) to 0.24 (SD 0.14) and 0.26 (SD 0.14) % of its GDP in 2030, for a weakening of the global ocean carbon sink of 5% and 10%, respectively.

For small island states with a relatively low GDP, but a relatively large EEZ and thus a large ocean carbon sink, such a burden allocation in the event of a weakening of the ocean carbon sink would impose a particular challenge. For example, for the Marshall Islands, the Maldives, and Nauru, the cost increased to 5.65 (SD 0.78), 5.14 (SD 0.44), and 4.72 (SD 0.65) % of their GDP for a weakening of the global ocean sink by 10%.

Figure 4 shows that with emissions reductions trading (Panel b), some of the countries selling emissions reductions would even gain from a weakening of the ocean carbon sink, as this would increase demand for emission permits. This happens for countries with a rather flat marginal abatement cost curve like China and/or with a relatively low ambition level in their NDCs like India. This is because these countries can further decrease

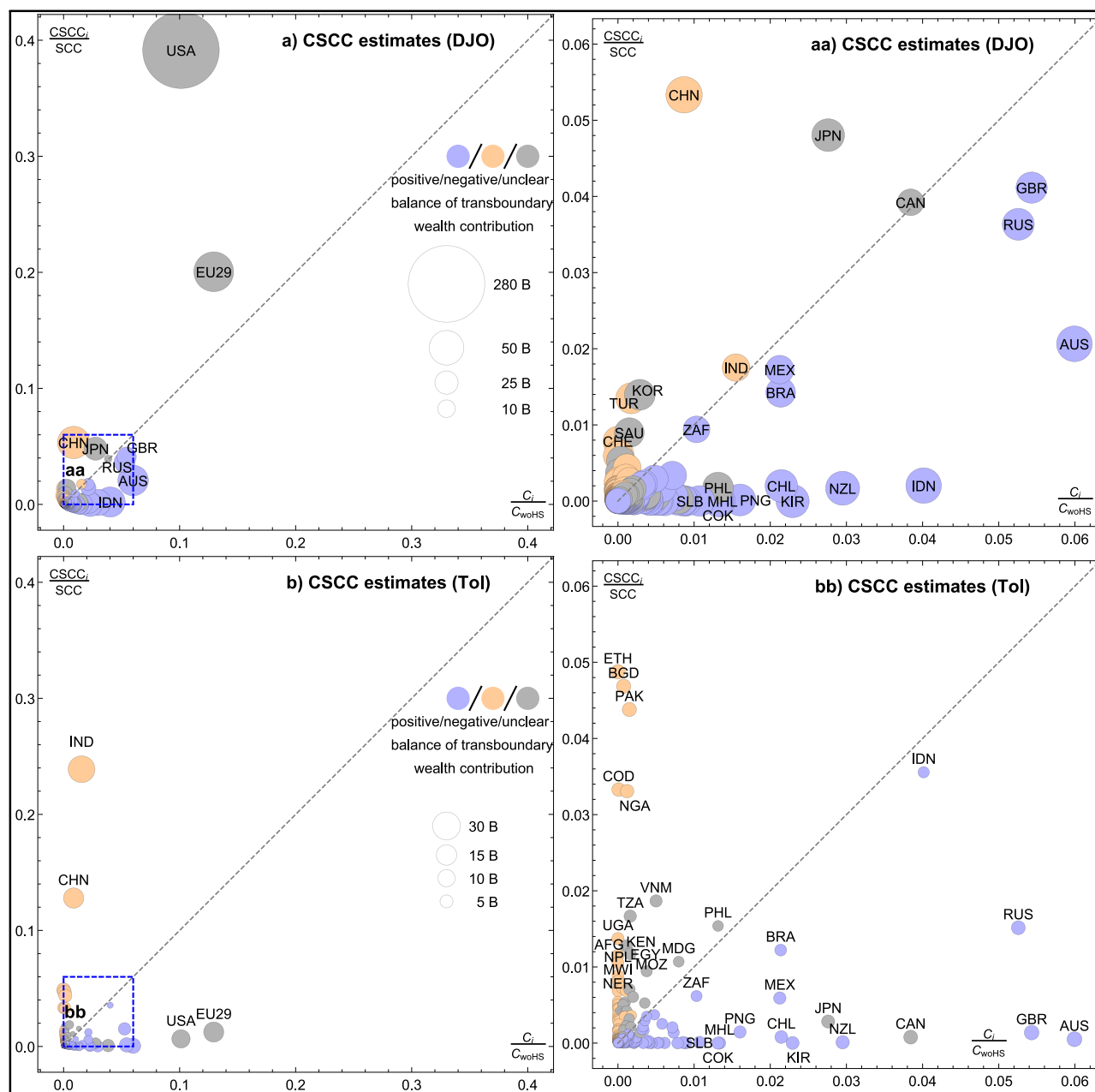


Fig. 3 | Balance of transboundary wealth contribution of countries. Panels **a** and **aa** show the wealth contribution based on the CSCC estimates obtained from Dell et al.¹⁸ in Ricke et al.^{22,23}, abbreviated as DJO, whereby **a** shows all countries and **aa** shows an enlargement of the countries near the origin, which are located in the dashed box in (a). Panels **b** and **bb** show the wealth contribution based on the CSCC estimates obtained from Tol¹⁹, abbreviated Tol, whereby **b** shows all countries and **bb** shows an enlargement of the countries near the origin, which are located in the dashed box in (b). The x-axes show the share of country in the total annual carbon, excluding the ocean carbon sink attributed to the high seas (C_i / C_{woHS}), the y axes show the share of CSCC of country i in the social cost of carbon ($CSCC_i / SCC$). The color code indicates a positive (blue) and negative (orange) balance for countries with a clear assessment

from both CSCC estimates, whereas countries where the assessment is not robust to the different CSCC estimates, are indicated by a gray color code. Countries are indicated by their ISO3 code: AFG Afghanistan, AUS Australia, BGD Bangladesh, BRA Brazil, CAN Canada, CHE Switzerland, CHL Chile, CHN China, COD Congo, COK Cook Islands, EGY Egypt, ETH Ethiopia, EU29 European Union 27 plus Iceland and Norway, GBR United Kingdom, IDN Indonesia, IND India, JPN Japan, KEN Kenya, KIR Kiribati, KOR South Korea, MDG Madagascar, MEX Mexico, MHL Marshall Islands, MOZ Mozambique, MWI Malawi, NER Niger, NGA Nigeria, NPL Nepal, NZL New Zealand, PAK Pakistan, PHL Philippines, PNG Papua New Guinea, RUS Russia, SAU Saudi Arabia, SLB Solomon Islands, TUR Turkey, TZA Tanzania, UGA Uganda, USA United States, VNM Viet Nam, ZAF South Africa.

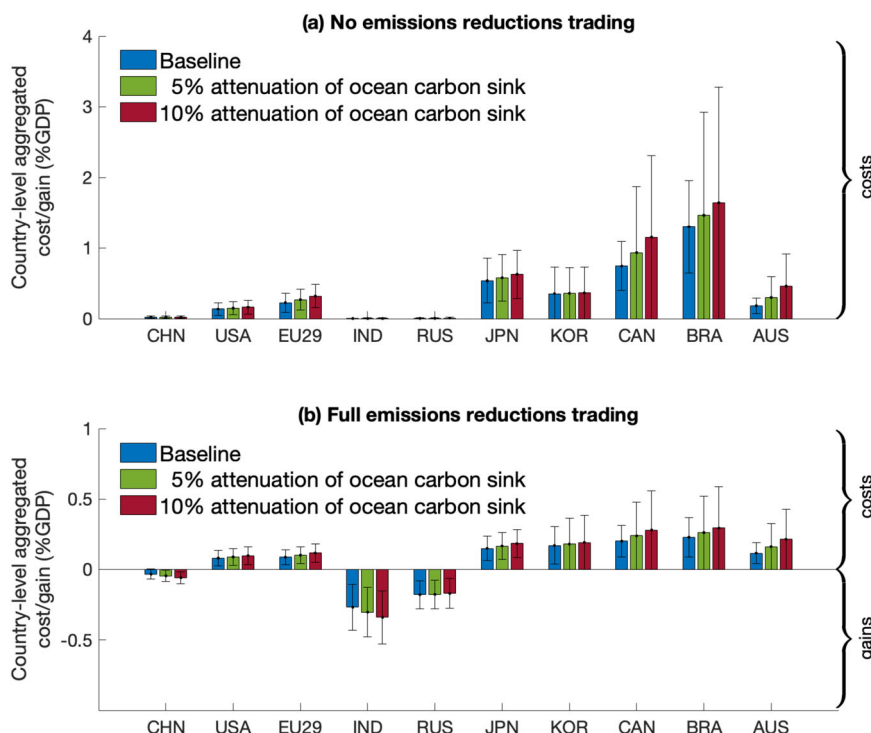
their emissions at a low cost. If the international price of CO₂ rises, these countries would increase their mitigation efforts and, in turn, their profits from selling emission reductions, which may outweigh the additional costs of the NDC increase resulting from the allocation of the burden of the weakening of the ocean carbon sink. Both, China and India have a relatively small attributed ocean carbon sink, which means that they have to increase their emissions reductions by only about 10 and 18 Mt CO₂, respectively, for a weakening of the global ocean carbon sink of 10%. In turn, without

emissions-reduction trading, they have only a very small increase in abatement cost even under high-ambition NDCs (USD 0.06 and USD 0.01 billion, respectively).

However, with emissions-reduction trading, both China and India, which are the two largest emissions-reduction sellers, extend their sales volume from 1,647.52 (SD 449.00) and 936.65 (225.83) MtCO₂ to 1983.42 (SD 439.46) and 1012.63 (SD 223.57) MtCO₂, respectively, for a weakening of the global ocean carbon sink of 10% and NDCs with high ambition. In this

Fig. 4 | Cost implications of the weakening of the ocean carbon sink for national climate policies.

The figure shows the change in costs (or gains in case of a negative cost) from a weakening of the global ocean carbon sink by 5 and 10% for a scenario without emissions reductions trading (a) and for a scenario with full emissions reductions trading (b). The figure includes the ten major industrialized and developing regions in international climate policy. Error bars represent ± 1 SD for the national CO₂ abatement cost/gain (in percent). Countries are indicated by their ISO3 code: CHN China, USA United States EU29 European Union 27 with Norway and Iceland, IND India, RUS Russia, JPN Japan, KOR South Korea, CAN Canada, BRA Brazilian, AUS Australia.



scenario, their net gains from climate policy with emissions trading increase from 0.03 (SD 0.04) and 0.27 (SD 0.16)% to 0.06 (SD 0.04) and 0.34 (SD 0.19) % of their GDP, respectively.

Supplementary Fig. SMF5 shows how aggregated abatement costs and global CO₂ prices increase under the assumption of high-ambition NDCs for scenarios without and with international emissions trading, for a gradual weakening of the global carbon sink by up to 10%. Without international emissions reduction trading, the global CO₂ price is the emissions-weighted average of the national CO₂ prices. Without emissions reductions trading, the global aggregated costs increase by 30%, from USD 262.34 (SD 42.99) to USD 341.83 (SD 49.43) billion, with emissions-reduction trading, the global aggregated costs increase by 28%, from USD 57.12 (SD 23.21) billion to USD 72.91 (SD 27.00), in both scenarios under the assumption of NDCs with high ambition.

The CO₂ price and its response due to the allocation of additional reduction requirements provide information on the incentives to include (marine) CDR. Assuming a weakening of the ocean carbon sink and the suggested allocation of additional emissions reductions, the national CO₂ prices in three potential large CDR markets, the United States, EU29, and Japan, increase from USD/tCO₂ 55.81 (SD 22.61), 101.51 (SD 36.03), and 151.67 (SD 46.24) to USD/tCO₂ 63.25 (SD 23.43), 129.95 (SD 37.80), and 169.48 (SD 46.41), respectively. Accordingly, the economic prospects of marine CDR methods like marine biomass farming and harvesting or ocean alkalinity enhancement would increase under such an allocation of the liability for the ocean carbon sink. However, our calculations show that such prices would only be realized on national markets and that the efficient approach to increase the reduction levels in the NDCs for example, to compensate for the weakening of the ocean carbon sink would be to extend the scope of international emissions reductions trading. The full country list for CO₂ prices and the costs of achieving the NDCs as percentage of GDP under attenuated ocean carbon sink of 5 and 10% can be found in the Supplementary Results ST1 and ST2, respectively.

Discussion and conclusions

The United Nations Decade of Ocean Science for Sustainable Development, coordinated by Intergovernmental Oceanographic Commission (IOC), aims at a “predicted ocean where society understands and can respond to

changing ocean conditions”²¹, p.8]. One key ocean service is removing anthropogenic CO₂ from the atmosphere. In turn, changing net ocean uptake, for example, as a consequence of a decrease in the physical carbon pump²², would be a changing ocean condition relevant for society. Accordingly, calls to expand the global (carbon) ocean observing system would be better able to substantiate their claim with information on the value of the ocean sink.

We combine a climate-change-damage-based approach and an abatement cost-based approach to assess the value of the annual ocean sink. For the former, we include in our assessment the estimates of Ricke et al.^{23,24}, while restricting it to the climate-change impact function provided by Dell et al.¹⁹ due to conceptual problems with the other impact function in that study^{20,25,26}, obtaining an average SCC of USD/tCO₂ 227.28 (SD 14.95). We compare these estimates with Tol et al.²⁰; his estimates add up to USD/tCO₂ 29.17 (SD 3.67). We do not aggregate the two SCC estimates, because they rely on very different assumptions, but instead provide the estimates separately, highlighting the unresolved uncertainties in terms of quantifying the impacts of climate change. The CSCC estimates can be compared at the SCC level (i.e., the sum of the CSCCs) to recent estimates for the SCC in the literature. Kalkuhl and Wenz²⁷ find an empirically derived estimated range for the SCC (in the year 2030) from USD/tCO₂ 92 to 181, the former obtained under a cross-section estimate, the latter under a population-based panel estimate. Similarly, Rennert et al.²⁸ derive a model-based estimate for the SCC of USD/tCO₂ 185 (44–413, 5%–95% range). In turn, the higher SCC estimate, obtained based on Dell et al.¹⁹ appears to be better supported by the literature, yet, the estimates of Tol²⁰ are not disproved. In our assessment of transboundary wealth transfers, we showed that a large part of the difference between the two assessments is based on differences in the estimation for the United States and the EU29. Apart from these two extremely different assessments, 87 out of 123 countries with an attributed ocean carbon sink have a clear assessment of the balance of transboundary wealth contribution. Under both estimates, China has the largest negative balance, and Australia has the largest positive balance.

With respect to the abatement cost-based approach, we calibrated a global CO₂ market model with defined emissions-reduction targets. A previous meta-study provided by Böhringer et al.¹⁸ finds a range for the emissions-weighted global average CO₂ price from USD/tCO₂ 12.66 to

42.86 for implementing the NDCs in 2030. The emissions-weighted global average CO₂ prices in our study are USD/tCO₂ 26.46 (SD 18.00) and 42.08 (SD 20.79) for low and high emissions-reduction ambition levels as defined in the NDCs. Despite the relatively good fit with other studies, it should be acknowledged that such computable general equilibrium models aggregate several countries to regions and consider only some (economically) large countries like China, the United States, Germany, and India separately, while many countries (in particular developing countries in Africa, Asia, and Latin America) are aggregated. The Dynamic Applied Regional Trade (DART) model underlying our estimate provides results for 21 regions, which we break down to the country level, assuming that within a given region, a country with low emissions efficiency (i.e., a high emissions-to-GDP ratio) has lower abatement costs than countries which already have a higher emissions efficiency. However, for large DART regions like Africa, this seems to be a strong assumption, and hence, our results for economically small countries, many of which have comparatively large, attributed ocean carbon sinks, should be considered with caution. On the other hand, the model underlying our calibration implicitly assumes emissions trading across all sectors within the (aggregated) regions, i.e., ignoring the fragmentation and various frictions of national climate policies. Accordingly, the estimated abatement cost-based CO₂ prices are lower than observed, actual and in particular implicit CO₂ prices, resulting from regulations and provisions in national climate policies^{29,30}.

Generally speaking, the climate-change-damage-based assessment approach allows us to value the ocean sink from an IW perspective. Agreeing on an attribution of the ocean carbon sink to countries or regions allows then to obtain further insights into the balance of transboundary wealth contributions. This requires a discussion of which fraction of the biological, chemical, and physical mechanism underlying the global ocean carbon sink (e.g.,³¹) should be considered in the attribution to countries. Abatement cost-based approaches, despite the uncertainty about innovations in emission abatement technologies, appear to yield a narrower range if applied to the valuation of the ocean carbon sink. Accordingly, we suggest that for questions related to, for example, spending to improve the monitoring of the ocean carbon sink, the abatement cost-based approach provides more reliable estimates for a fiscal cost assessment. Furthermore, the abatement cost-based approach provides a framework to assess the implications of a (partly) integration of the ocean carbon sink into climate policy. Any attribution of the ocean carbon sink does not necessarily imply a potential buy-out from ambitious emissions reductions, as the implications for emissions-reduction commitments depend on the particular baseline level considered for the ocean carbon sink. One could argue that the current NDCs are derived in dependence on the current and future carbon sinks, i.e., they are net of the natural CO₂ uptake by the terrestrial biosphere and the ocean. Accordingly, any weakening of the natural sinks would need to be compensated by increasing the ambition level in the NDCs. Such considerations could guide the question of which aspects and which fraction of the ocean carbon sink in general and which fraction of the overseas territories should be attributed to countries, in order to link attribution and thus potential wealth contributions also with potential emission reductions and possible CDR liabilities.

Methods

The attribution of the sink

While the ocean carbon sink is a global common, the ocean-atmosphere CO₂ fluxes differ considerably across the globe. Using regional CO₂-flux data, for example, would result in assigning some countries a carbon sink and others a carbon source, i.e., not an ecosystem service but an ecosystem burden. For example, the highest carbon source (outgassing) would be attributed to KIR, an island nation in the tropical Pacific Ocean, with ~726 km² land area and a 3,550,000-km² EEZ located in the Pacific upwelling area. Almost all of Kiribati's waters are considered to be carbon sources (based on the surface pCO₂ field estimate used here) and would contribute a negative value, i.e., a global cost if the country were held

responsible for its ocean carbon fluxes. However, such an approach would mix the natural with the anthropogenic carbon fluxes. The latter is the consequence of increasing atmospheric CO₂ concentration and in turn all ocean regions are taking up anthropogenic carbon by being at the regional level a lower carbon source than they were under pre-industrial levels, by turning from a carbon source to a carbon sink, or increasing the carbon sink compared to pre-industrial levels. Since a pre-industrial benchmark for these flux data is missing, we use the model-based derived global ocean CO₂ sink of 2.8 (SD ± 0.4) GtC (in the year 2022) from the global carbon budget¹ and assign it proportional to the EEZ area of countries³². We abstract from issues related to temporary carbon storage since we consider the accounting of the carbon sink at the country and not the company level, implying that a strong liability framework is in place and that, in turn, the net method can be applied to carbon sink in a given year³³. The attributed ocean carbon sink is detailed in Supplementary Data M1.

Estimating the wealth contribution of the annual ocean carbon sink

We applied the IW approach and calculated the annual global wealth contribution of the ocean carbon sink in the EEZ of each country *i* in given year, i.e., the annual contribution to global comprehensive investment as

$$W_{i,global} = OCS_i * SCC \text{ with } SCC = \sum_i CSCC_i \quad (2)$$

where *OCS_i* indicates the ocean carbon sink in the EEZ (measured in tCO₂/year), and *SCC* is the (global) social cost of carbon, which is the sum of *CSCC_i*, i.e., the country social cost of carbon (measured in USD/tCO₂)^{11,13}.

Using *CSCC* estimates allowed us to distinguish between domestic, outbound, and inbound wealth contributions of the ocean carbon sink¹³. The domestic ocean carbon wealth contribution is:

$$W_{i,domestic} = OCS_i * CSCC_i \quad (3)$$

the outbound ocean carbon wealth contribution is:

$$W_{i,out} = OCS_i * \left(\sum_{j \neq i} CSCC_j \right) \quad (4)$$

and the inbound ocean carbon wealth contribution for country *i* is:

$$W_{i,in} = \left(\sum_{j \neq i} OCS_j \right) * CSCC_i \quad (5)$$

The balance of transboundary wealth contributions of the ocean carbon sink (in a given year) is the difference between outbound and inbound ocean carbon wealth contributions¹³:

$$BTWC_i = OCS_i * \left(\sum_{j \neq i} CSCC_j \right) - \left(\sum_{j \neq i} OCS_j \right) * CSCC_i \quad (6)$$

which can be simplified to

$$BTWC_i = OCS_i * SCC - OCS_i * CSCC_i \quad (7)$$

Accordingly, a positive balance of transboundary wealth contributions by the ocean sink in a given year requires that $\frac{OCS_i}{OCS} > \frac{CSCC_i}{SCC}$, (see Eq. 1 in the main text), which means that the fraction of the annual ocean sink attributed to a given country relative to the global ocean carbon sink is greater than the fraction of the country's *CSCC* relative to the global *SCC*.

Deriving climate-change-damage-based prices

We obtained estimates from the literature for the *CSCC* from Ricke et al.^{23,24} and Tol²⁰ whereby the former has two different climate-damage function groups, one provided by Burke et al.³⁴ and one provided by Dell et al.¹⁹; we

used only those CCCC estimates based on the damage impact function put forward by Dell et al.¹⁹, which yields (i) a smaller (negative) impact for rich countries, (ii) has a linear specification for the change in temperature, (iii) does not have a U-shaped impact projection towards 2100 for global impacts and is, therefore, more in line with macroeconomic impact estimates of climate change²⁶. Furthermore, the specification of Burke et al.³⁴ implies due to the persistent impacts of climate change on growth, the cumulative gains of the countries with accelerated growth (climate-change winners) start to outweigh the cumulative losses of countries who lose from climate change towards the end of the century.

The estimation strategy put forward by Ricke et al.^{23,24} includes all SSPs and considers three RCPs: RCP45, RCP60, and RCP85. From these scenarios, we used the scenarios obtained for RCP60, as here the emissions were comparable to the baseline emissions in Tol²⁰ and considered the scenarios with a pure rate of time preference of 1% and a marginal elasticity of utility of 1.5 (of the different SSPs). The estimates in Ricke et al.^{23,24} are presented in USD PPP (2005); hence we converted these two market exchange values and used the GDP deflator (both obtained from the World Bank) to obtain estimates in 2020 USD. Based on this approach, we obtained an average SCC (across the different SSPs) of USD/tCO₂ 227.28 (SD 14.95).

Tol²⁰ provides estimates for the impact of climate change on the level of economic activity for different impact functions. We used the estimates obtained from the Tol impact function for the different SSPs and a pure rate of time preference of 1% and income elasticity of impacts of -1.68 . The estimates are provided by ref. 19 in 2010 USD at market exchange rates. We used the USD GDP deflator to convert the estimates into 2020 USD and obtained an average SCC (across the five SSPs) of USD/tCO₂ 29.17 (SD 3.67). The obtained estimates for the CCCC and the corresponding wealth analysis are detailed in Supplementary Data M2.

Deriving abatement cost-based prices

We used the DART model to estimate marginal abatement cost curves, providing information on the abatement cost-based CO₂ price for a given emissions-reduction level. DART is a global and recursive dynamic computable general equilibrium (CGE) model^{35,36}. The advantage of using a global CGE model lies in its ability to capture not just the direct domestic multiplier effects of a carbon price but also indirect implications via changes in international energy prices and trade flows³⁵. Given that economic structures vary across regions, marginal abatement costs differ widely across regions and, therefore, need to be calculated individually.

We calibrated the DART model to the GTAP10 database³⁷ with 2014 as the base year and the baseline dynamics calibrated to the GDP data from IEA³⁸ and updated to include renewable energy data from the IEA³⁹. With this updated model, marginal abatement cost curves (MACC) for the year 2030 were generated separately for each model region by varying the emissions-reduction target of the said region between 0% reduction theoretically up to 100% (relative to 2014 levels) in increments of 5% while assuming that the rest of the regions fulfilled their national determined contribution (NDC) targets¹⁸.

Based on this approach, for each region i , we created cubic abatement cost curves, $AC_i(E_i)$, which imply quadratic marginal abatement cost curves, and $MAC_i(E_i)$ to the modeled values where E_i represents the actual 2030 emissions in the reduction scenario. Let $E_{i,BAU}$ denote the 2030 emissions in the business-as-usual (BAU) scenario without climate policy and $Y_{i,BAU}$ GDP in 2030, then

$$AC_i(E_i) = \alpha_i * \left(1 - \frac{E_i}{E_{i,BAU}}\right)^3 Y_{i,BAU} E_{i,BAU} \quad (8)$$

$$MAC_i(E_i) = \frac{dAC_i(E_i)}{dE_i} = \alpha_i * 3 * \left(1 - \frac{E_i}{E_{i,BAU}}\right)^2 Y_{i,BAU} \quad (9)$$

Note that the marginal abatement costs (MAC) are defined by the derivate with respect to minus E_i since they measure how the abatement cost increases if abatement is increased, i.e., emissions are reduced.

The abatement cost parameters were determined by solving the following minimization problem

$$\min_{\alpha_i} \sum \left(P_{CO_2^{DART}} - (3\alpha_i R_i^2 Y_{i,BAU}) \right)^2 \quad (10)$$

Thus, the cost parameters α_i were calibrated by minimizing the sum of the difference between the CO₂ price $P_{CO_2^{DART}}$ and the CO₂ price following the condition (9). To obtain country-specific abatement cost functions for the DART regions with more than one country, we used the approach proposed by Tol⁴⁰ and assumed a 10-percent spread in relative costs between the country with the highest carbon intensity (CO₂/GDP) and the country with the lowest carbon intensity for a 10-percent reduction. The calibration details can be found in Supplementary Data M3.

To quantify abatement costs, we drew on the latest information on the NDCs from Climate Resource, who provide an NDC database covering each country's initial NDC and the development of its climate policy over time⁴¹. The dataset includes all NDC updates submitted up to November 2nd, 2022. The NDCs vary in their commitment levels depending on the emissions reductions of other countries. We extracted the updated covered GHG data for low and high-ambition targets, respectively. Hot air was included; emissions from the LULUCF sector were not. For both high and low ambitions, the target emissions from 2030 and 2020 were set in ratio. With respect to the BAU emissions in 2030, the low emissions-reduction ambitions imply a reduction of 16.22 (SD 4.28)%, while the high emissions-reduction ambitions imply a reduction of 23.16 (SD 4.16)%.

Furthermore, information on business-as-usual GDP, $Y_{i,BAU}$ and 2030 business-as-usual CO₂ emissions, $E_{i,BAU}$ was obtained from the DART model, and we considered the projections for all SSPs in the baseline (marker) specification⁴² together with the OECD GDP growth projections⁴³. Hence, we considered a total of six scenarios for future GDP and emissions. We transformed this data into values relative to the base year in the specific scenario and used data on GDP from the World Bank⁴⁴ and CO₂ emissions from the Global Carbon Project¹ in 2020 as the common base year values. For each scenario, we calculated the marginal abatement cost for the low and high emissions-reduction targets.

The MACCs also allowed us to derive a market solution, i.e., countries trade emissions reductions. Accordingly, we used the MACCs in the following model framework. The countries, i , face an exogenously set emissions cap A_i (provided by the NDCs). Without emissions reductions, business-as-usual emissions are realized, $E_{i,BAU}$. The total amount of emissions by each country, E_i , is non-negative, and no country can abate more than it emits,

$$0 \leq E_i \leq E_{i,BAU} \quad (11)$$

We allowed for a market on tradable emissions-reduction permits, where the permit price is represented by π and the number of permits each country purchases or sells by T_i . In order to fulfill the emissions target, every country can reduce its baseline emissions and trade permits on the market. Thus, the difference between emissions and the number of permits must not exceed the emissions cap,

$$E_i - T_i \leq A_i. \quad (12)$$

The total cost of achieving a given target A_i is determined by the sum of abatement and permit trading costs (or trading benefits if a country is a net seller of permits, $T_i < 0$). Therefore, each country solves the following optimization problem,

$$\min_{R_i, T_i} C_i = AC_i(R_i) + \pi T_i, \quad (13)$$

subject to Eq. (12). Solving the static optimization problem, assuming an interior solution, yields the well-known efficiency rule that for all countries, the marginal cost of abatement equals the permit price,

$$AC'(E_i^*) = \pi. \quad (14)$$

The market allocates the permits efficiently. Condition (14) shows that the optimal rate of emissions reduction can be expressed as a function of the carbon credit price, $E_i^*(\pi)$. The optimal permit price can be determined using the overall compliance condition,

$$\sum_i^n E_i^*(\pi^*) = \sum_i^n A_i, \quad (15)$$

which states that the sum of all countries' net emissions equals the sum of all countries' emissions caps. With the functional form defined in (8), the solution for the permit price is

$$\pi = \left(\frac{\sum_{i=1}^n E_{i,BAU} - \sum_{i=1}^n A_i}{\sum_{i=1}^n E_{i,BAU} \sqrt{(3\alpha_i Y_i)^{-1}}} \right)^2 \quad (16)$$

which then determines via (14) and (12) the country-specific emissions levels and trading positions. The inclusion of the ocean sink (i.e., compensation for a weakening ocean sink) is achieved by reducing each country's A_i accordingly. In both solutions, the market solution (full CO₂ trade) in comparison to the no-trade solution, the CO₂ price shows the maximum cost at which a specific (marine) CDR method would need to be realized to be cost-competitive⁴⁵. The two solutions are detailed in Supplementary Data M4.

Reporting summary

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

Data availability

The authors declare that the data on the sink attribution, the derivation of the CO₂ prices, the IW contribution and redistribution, the calibration of the CO₂ abatement cost model, and the country-specific abatement costs are included in the GitHub repository <https://github.com/wilmwilmsen/OceanValue>.

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Author contributions

W.R., F.M., M.Q.: conception and design of the work, analysis, and interpretation of data, writing original draft and review and editing; J.K.: analysis, acquisition, collection, and interpretation of data, writing original draft; S.P., S.R., S.T., C.P., C.W., A.V., and P.G.: analysis, acquisition, collection, and interpretation of data. All authors read and approved the final manuscript.

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The authors declare no competing interests.

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