Atmospheric carbon emissions from benthic trawling depend on water depth and ocean circulation

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Through its vastness, resilience and biogeochemical complexity, the ocean offers humanity some of the largest potential natural pathways for removing carbon dioxide from the atmosphere while avoiding new sources of anthropogenic emissions. In proposing a network of new marine protected areas in service of global ocean conservation, Sala et al.[1] describe a potentially large climate benefit of such a strategy: a reduction or elimination in carbon emissions that can result from the resuspension and subsequent remineralization of organic matter in ocean sediments following benthic trawling and dredging. Sala et al.[1] estimated that as much as 1.47 Pg CO_2 yr^{-1} — equivalent to 4% of all global CO_2 emissions in 2020[2] — could be produced globally in the first year disturbance associated with benthic trawling, with CO_2 "emissions" from trawling activity declining after roughly a decade to 0.58 Pg CO_2 yr^{-1}.

However, using the published output from a series of experiments in an inverse ocean circulation model[3] to account explicitly for the timescale of atmospheric ventilation, we show that the Sala et al.[1] estimate of global CO_2 efflux in the first year after trawling must be discounted by at least 33%, yielding an adjusted flux of 0.99 Pg CO_2 yr^{-1}, if one aims to ultimately estimate emissions to the atmosphere (Fig. 1; Extended Data Fig. 2; Extended Data Table 1). Similarly, the cumulative CO_2 emissions attributable under the Sala et al.[1] model to a continuous pattern of global benthic trawling activity over a 30-year timescale must be discounted by at least 12% (compare 19.6 and 17.2 Pg CO_2; Fig. 1; Extended Data Table 1).

We do not disagree that benthic trawling represents a severe source of disturbance to many benthic ecosystems[4,5] and that, under certain conditions, some of the organic carbon stored in ocean sediments may be remineralized back into CO_2 when subjected to disturbances such as benthic trawling and deep-sea mining. In addition, much of the world's trawling activity takes place in the relatively shallow waters of continental shelves (Extended Data Fig 1; Extended

Data Table 1), where one might assume the shallow bottom water depth would result in rapid communication of remineralized carbon to the atmosphere. However, current empirical evidence and modeling studies, including our analysis, do not support a universal connection between physical disturbance, remineralization and consequent transmission of any remineralized CO_2 back to the atmosphere.[6] A complete description of our methods and calculations, including a validation of the use of the Siegel et al. inverse ocean circulation model output using an independent dataset of global ocean mixed layer depths[7], is presented in the Supporting Information.

While Sala et al.[1] acknowledged they did not know what fraction of the remineralized CO_2 was likely to reach the atmosphere, their choice of the term "emissions" to describe the transformation and flux and of carbon from sediment to bottom waters, and their presentation of restrictions on bottom trawling as a promising nature-based solution to climate change predicated on avoided atmospheric carbon emissions, continue to support misinterpretation and confusion over their results, making imperative the need for adjusted estimates of the sort we present here. The original, uncorrected estimates of sediment CO_2 efflux contained in Sala et al.[1] have already been advanced as a low-cost-per-ton climate mitigation solution that could be included today in nationally determined contributions (NDCs) under the 2015 Paris Agreement[8], and media have directly compared these uncorrected sediment fluxes with the global atmospheric emissions of the airline industry.[9]

Two overarching patterns can be seen in the results of our accounting for ventilation time. First, globally and for all exclusive economic zones (EEZs) for which we produced adjusted estimates, the relative discount that must be applied to account for ventilation time (measured in terms of percent deviation) becomes smaller as one considers cumulative emissions from continuous trawling activity over longer time horizons (Extended Data Fig. 2; Extended Data Table 1; Supplementary Table 1).

Second, because atmospheric ventilation time is a function of both water depth and ocean circulation patterns[3], the effect of this accounting does not manifest uniformly across different ocean basins and EEZs (Fig. 2). For nations whose EEZs are uniformly shallow, or where the benthic trawling activity is concentrated in waters of relatively shallow bottom depth, this accounting for ventilation time requires a relatively minor adjustment. In contrast, consideration of this fundamental feature of the ocean results in a dramatic adjustment for nations in whose EEZs the benthic trawling activity is concentrated in waters of relatively deep bottom depth. The average bottom depth of the trawled EEZ area, weighted by mass according to the efflux estimated by Sala et al.[1] for each model grid square, explained almost three-quarters of the variation in the percent deviation between our adjusted emissions estimates and the original estimates of CO_2 efflux.

For example, the Sala et al. estimate of CO_2 efflux from sediments in the Chinese EEZ must be discounted by just 3.1% to obtain an estimate of cumulative emissions to the atmosphere over 30 years (Fig. 2; Extended Data Table 1). China is responsible for an average of 4.4 Mt yr^{-1} in landings from benthic trawling[10] — far more than any other country — but the nation's trawling activity is concentrated in waters whose average bottom depth, weighted by mass according to the efflux estimated by Sala et al.[1], is just 25 m (Extended Data Table 1). However, a similar 30-year estimate of cumulative CO_2 efflux from continuous benthic trawling in the EEZ of Morocco — responsible for the fifth-most global landings from benthic trawling, at 1.9 Mt biomass yr^{-1} — must be discounted by more than 45% (Fig. 2; Extended Data Table 1). The mass-weighted average bottom depth of the portion of the Moroccan EEZ that is subjected to benthic trawling is 473 m (Extended Data Table 1).

While we present adjusted estimates of cumulative emissions for continuous trawling over several additional timescales (Extended Data Table 2; Supplementary Table 1), we considered a 30-year timescale most relevant to the time horizon over which the Intergovernmental Panel on Climate Change has concluded we must act to achieve global net zero emissions by mid-century.[2] We believe there are additional grounds on which one might question the estimates presented in Sala et al.[1] — for example, the implicit assumption that much of the sediment organic carbon hypothesized to be remineralized through benthic trawling would not otherwise be remineralized by natural biogeochemical processes, the failure to consider potential feedbacks associated with the release of nutrients, and apparent gaps in the AIS data used to drive much of the spatial analysis. Concerning the latter deficiency, which has been addressed in a previous reply[11], we found there were no efflux data in the Sala et al.[1] dataset for model grid squares in the EEZs of Myanmar, Pakistan, Bangladesh or Guyana, even though these countries are responsible for at least 1.0 Mt yr^{-1} in landings from benthic trawling[10] (Supplementary Table 1). We note also that the Sala et al.[1] analysis did not extend to areas of the emerging Arctic, where sea ice retreat and climate-driven migration of fish stocks could incentivize the trawling of large sections of seabed that have not been previously subjected to anthropogenic disturbance.[12]

Our results — based on an accounting for just one of many potential sources of uncertainty associated with the estimation of carbon emissions from anthropogenic disturbance of ocean sediments — suggest that any natural climate solution based on restricting or limiting the footprint of benthic trawling must be carefully scrutinized for scientific integrity, and that ocean scientists with an understanding of both biogeochemistry and physical oceanography should be involved in the design and implementation of any such schemes. Perhaps most importantly, given the striking geographic heterogeneity we identified in the potential for atmospheric emissions from benthic trawling over timescales relevant for climate mitigation, there are serious implications for equity since not all coastal nations will likely be able to share equally in the benefits that would accrue from these restrictions or limitations.

Data availability

All input datasets used in this analysis are available at https://github.com/jamesrco/global-trawling-CO2 or by direct download from the URLs provided in the text. The results of our analysis — including output data and adjusted emissions estimates by exclusive economic zone — are available at https://github.com/jamesrco/global-trawling-CO2/tree/main/data/global_trawling/derived/output

Code availability

The MATLAB and R code used in this analysis is available at https://github.com/jamesrco/global-trawling-CO2

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Author contributions

All authors contributed to development of the ideas presented in this Comment. J.R.C. performed the analysis, prepared the figures and wrote the first draft of the manuscript. All authors contributed to subsequent drafts of the manuscript and approved the final submitted version.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information is available for this paper.

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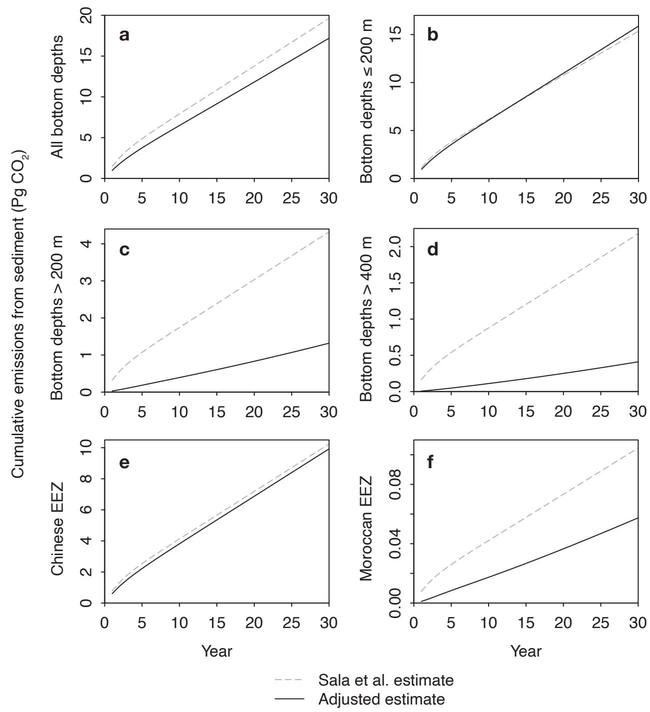


Fig. 1 | Cumulative carbon emissions from benthic trawling according to original model of Sala et al.[1] and an adjusted model (this study) that accounts for timescale of ventilation to the atmosphere. To isolate the role of bottom depth and ocean circulation for purposes of our analysis, we assumed for our adjusted emissions estimates (solid lines) the same underlying model of sediment remineralization upon which Sala et al.[1] based their estimates (dashed lines). **a**, Cumulative carbon emissions from benthic trawling activity for all bottom depths within the Sala et al model domain. **b-d,** Estimates of emissions originating from trawling across three ranges of bottom depth: (**b**) Waters with bottom depths ≤ 200 m, (**c**) waters with bottom depths > 200 m, and (**d**) waters with bottom depths > 400 m. Trawling in waters with bottom depths ≤ 200 m accounted for 78% of the total C remineralization estimated by Sala et al.[1] for the first year of trawling, while trawling in waters with bottom depths > 400 m accounted for 11% of total remineralization; see Extended Data Fig. 1 and Extended Data Table 1. **e-f,** Estimates of emissions originating from benthic trawling in two exclusive economic zones (EEZs) with divergent bottom depth profiles: (**e**) China, where the emissions-weighted mean bottom depth of the area subjected to benthic trawling is just 25 m, and (**f**) Morocco, where the weighted mean bottom depth of the area subjected to benthic trawling is 473 m. The mean bottom depth for each grid square in the Sala et al.[1] sediment CO_2 efflux dataset was retrieved from the database described in ref. [13]. EEZ emissions estimates were calculated by applying the EEZ boundaries described in ref. [14]; a link to the appropriate code is provided in the Code Availability statement. Estimates of cumulative emissions over a 200-year time scale for the same bottom depth ranges and EEZs are presented in Extended Data Fig. 2

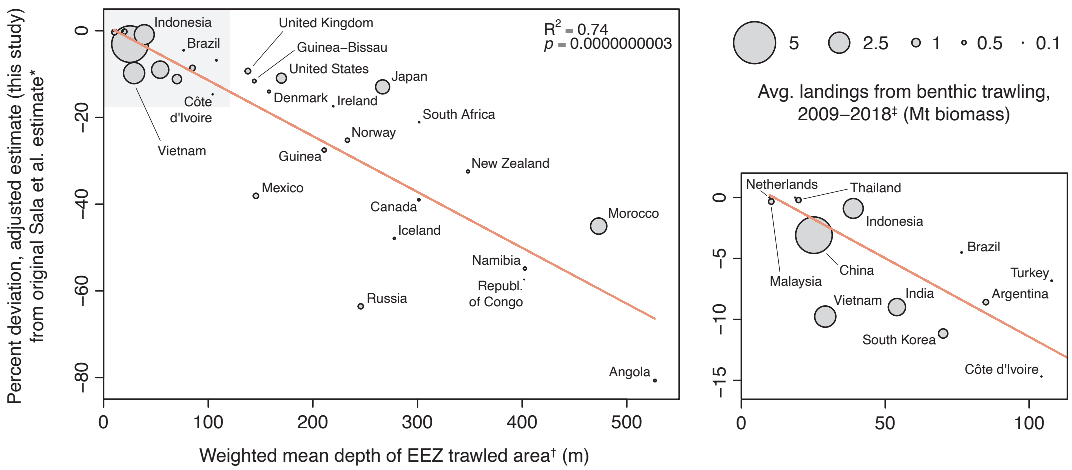
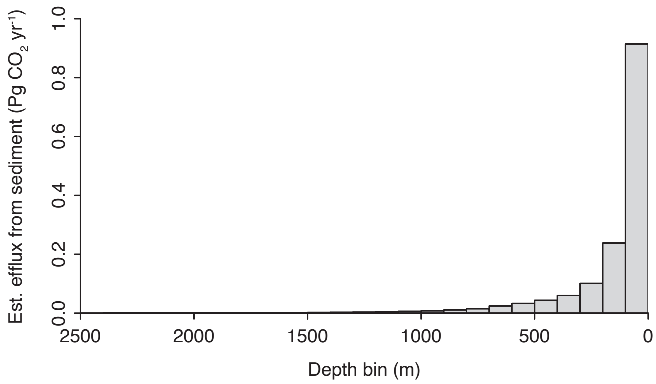


Fig. 2 | Effect of mass-weighted EEZ bottom depth on carbon emissions to the atmosphere from benthic trawling. Values on the *y*-axis represent the percent deviation of our adjusted estimate (accounting for the timescale of atmospheric ventilation) from the original emissions estimate of Sala et al.[1] This percent deviation is plotted against the weighted mean bottom depth of the EEZ area subjected to benthic trawling for the 30 countries with the greatest average landings from benthic trawling from 2009-2018 (according to ref. [10]) and for the top 10 countries ranked by percentage of total EEZ catch from bottom trawling (according to ref. [15]). Each circle represents a different country; symbol size corresponds to the quantity of biomass landed within that country from benthic trawling. The red line shows the result of a Model I linear regression ($R^2 = 0.74$; $p < 0.0001$). The right-hand panel is an expansion of the shaded region shown on the main panel. All supporting data is presented in Supplementary Table 1.

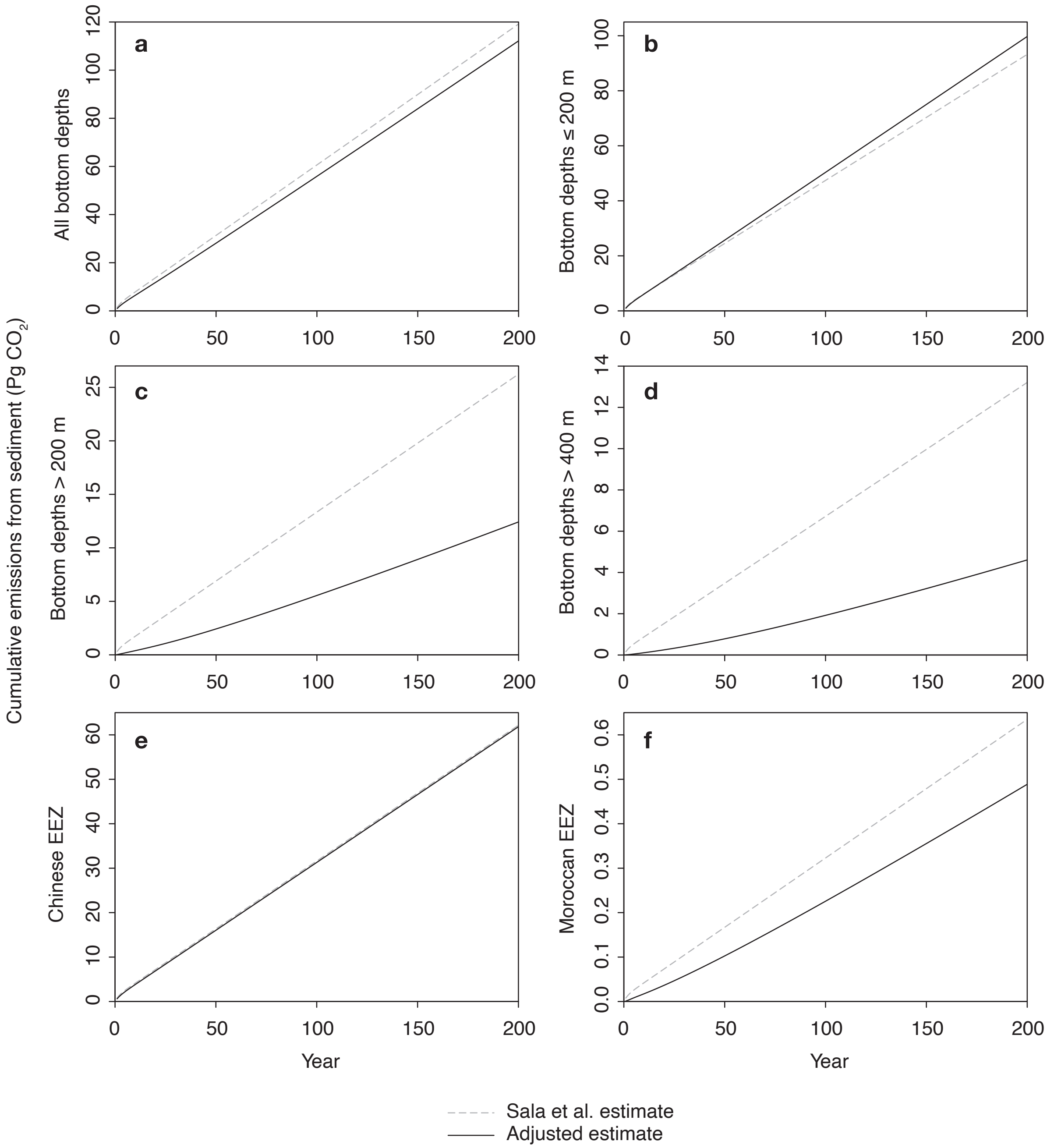
[*]Percent deviation based on comparison of estimates of cumulative emissions after 30 years of benthic trawling; percent deviations between our estimates and those of Sala et al. for other time horizons are presented in Extended Data Table 1 and Supplementary Table 1.

[†]Geographic subsetting was performed using the exclusive economic zone boundaries described in ref. [14]. We weighted the bottom depth of the area within each EEZ that was subjected to benthic trawling according to the rates of remineralization estimated by Sala et al.[1] The mean bottom depth for each grid square in the Sala et al. CO_2 efflux dataset was retrieved the database described in ref. [13]; this depth was then weighted by the mass of CO_2 that Sala et al. estimated was produced in that grid square in the first year of benthic trawling. A link to the appropriate code is provided in the Code Availability statement.

[‡]Catch data were retrieved from the Sea Around Us database[10] using the code to which a link is provided in the Code Availability statement.



Extended Data Fig. 1 | Mass distribution of carbon remineralized as a result of benthic trawling according to bottom depth. The figure was produced by segregating sediment CO_2 efflux estimates reported by Sala et al.[1] into 100 m bins according to bottom depth. The mean bottom depth for each grid square in the Sala et al. CO_2 efflux dataset was retrieved from the database described in ref. [13]. The fraction of the total mass present within selected depth bins is given in Extended Data Table 1; all supporting data are available via the link provided in the Code Availability statement.



Extended Data Fig. 2 | Cumulative carbon emissions from benthic trawling according to original model of Sala et al.[1] and an adjusted model (this study) that accounts for timescale of ventilation to the atmosphere. This figure presents results for the same bottom depth ranges and exclusive economic zones (EEZs) shown in Fig. 1, but over a 200-year time scale. We assumed for our adjusted emissions estimates (solid lines) the same underlying model of sediment remineralization upon which Sala et al.[1] based their estimates (dashed lines). **a,** Cumulative carbon emissions from benthic trawling activity for all bottom depths within the Sala et al model domain. **b-d,** Estimates of emissions originating from trawling across three ranges of bottom depth: (**b**) Waters with bottom depths ≤ 200 m, (**c**) waters with bottom depths > 200 m, and (**d**) waters with bottom depths > 400 m. **e-f,** Estimates of emissions originating from benthic trawling in two exclusive economic zones (EEZs) with divergent bottom depth profiles: (**e**) China, where the emissions-weighted mean bottom depth of the area subjected to benthic trawling is just 25 m, and (**f**) Morocco, where the weighted mean bottom depth of the area subjected to benthic trawling is 473 m.

Bottom depth* range	**Fraction by mass of total est. sediment C remineralization in first year†**
≤ 100 m	0.62
≤ 200 m	0.78
> 200 m	0.22
≤ 400 m	0.89
> 400 m	0.11

Extended Data Table 1 | Fraction by mass of total estimated sediment C remineralization from benthic trawling according to bottom depth. The complete mass distribution, divided into 100 m depth bins, is presented in Extended Data Fig. 1.

*The mean bottom depth for each grid square in the Sala et al.[1] sediment CO_2 efflux dataset was retrieved from the database described in ref. [13].

†For the first year after start of benthic trawling activity, from the model of sediment remineralization posited by Sala et al.[1]

Bottom depth range or exclusive economic zone (EEZ) area	**Avg. landings from benthic trawling, 2009-2018***		**Weighted mean bottom depth of area subjected to benthic trawling[†]**		**Fraction by mass of total est. global sediment C remineralization[‡]**		**Cumulative emissions after years of continuous trawling**						
	Mt biomass	**Rank by EEZ[§]**	**m**	**Rank by EEZ[§]**	**—**	**Rank by EEZ[§]**	**After 1 yr Pg CO_2**	**After 1 yr Rank by EEZ[§]**	**After 5 yr Pg CO_2**	**After 30 yr Pg CO_2**	**After 30 yr Rank by EEZ[§]**	**After 200 yr Pg CO_2**	**After 200 yr Rank by EEZ[§]**
Global trawled ocean area, all bottom depths					1								
Original estimate (Sala et al.)							1.47		4.87	19.6		119	
Adjusted estimate (this analysis)							0.991		3.74	17.2		112	
Percent deviation							–33		–23	–12		–5.9	
Global trawled ocean area, bottom depths[‖] ≤ 200 m					0.78								
Original estimate (Sala et al.)							1.15		3.81	15.4		93.2	
Adjusted estimate (this analysis)							0.962		3.56	15.9		99.7	
Percent deviation							–16		–6.6	3.4		7	
Global trawled ocean area, bottom depths[‖] > 200 m					0.22								
Original estimate (Sala et al.)							0.324		1.07	4.32		26.2	
Adjusted estimate (this analysis)							2.83×10^{-2}		0.185	1.32		12.4	
Percent deviation							–91		–83	–69		–53	
Global trawled ocean area, bottom depths[‖] > 400 m					0.11								
Original estimate (Sala et al.)							0.163		0.54	2.18		13.2	
Adjusted estimate (this analysis)							6.91×10^{-3}		4.81×10^{-2}	0.411		4.61	
Percent deviation							–96		–91	–81		–65	

Bottom depth interval or exclusive economic zone (EEZ) area	Avg. landings from benthic trawling, 2009-2018*		Weighted mean bottom depth of area subjected to benthic trawling†		Fraction by mass of total est. global sediment C remineralization‡		Cumulative emissions after years of continuous trawling						
							After 1 y		After 5 y	After 30 y		After 200 y	
	Mt biomass	Rank by EEZ§	m	Rank by EEZ§	—	Rank by EEZ§	Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Rank by EEZ§	Pg CO_2	Rank by EEZ§
China	4.4	1	25	27	0.52	1							
Original estimate (Sala et al.)							0.769	1	2.54	10.2	1	62.2	1
Adjusted estimate (this analysis)							0.605	1	2.22	9.92	1	61.8	1
Percent deviation							–21	25	–13	–3.1	26	–0.53	26
India	2.1	4	54	24	0.002	24							
Original estimate (Sala et al.)							2.88×10^{-3}	24	9.53×10^{-3}	3.84×10^{-3}	24	0.233	24
Adjusted estimate (this analysis)							2.02×10^{-3}	19	8.06×10^{-3}	0.035	23	0.221	23
Percent deviation							–30	21	–15	–9	22	–5.4	16
Indonesia	2.4	3	39	25	1.2×10^{-8}	31							
Original estimate (Sala et al.)							1.71×10^{-8}	31	5.64×10^{-8}	2.27×10^{-7}	31	1.38×10^{-6}	31
Adjusted estimate (this analysis)							1.56×10^{-8}	31	5.41×10^{-8}	2.25×10^{-7}	31	1.38×10^{-6}	31
Percent deviation							–8.4	27	–4	–0.9	27	–0.15	27
Morocco	1.9	5	473	2	0.0053	20							
Original estimate (Sala et al.)							7.85×10^{-3}	20	2.59×10^{-3}	0.105	20	0.635	20
Adjusted estimate (this analysis)							1.06×10^{-3}	22	8.42×10^{-3}	5.75×10^{-2}	20	0.489	21
Percent deviation							–86	5	–68	–45	6	–23	6
Vietnam	2.5	2	29	26	0.00062	28							
Original estimate (Sala et al.)							9.2×10^{-4}	28	3.04×10^{-3}	1.23×10^{-2}	28	7.44×10^{-2}	28
Adjusted estimate (this analysis)							5.66×10^{-4}	27	2.12×10^{-3}	1.11×10^{-2}	27	7.31×10^{-2}	28
Percent deviation							–38	18	–30	–9.8	20	–1.7	24

Extended Data Table 2 | Fisheries landings and cumulative CO_2 emissions estimates from benthic trawling for selected bottom depth ranges and exclusive economic zones, with rankings where appropriate. Table presents cumulative emissions estimates from both the original Sala et al.[1] model and this study, which applies the methods described in the text to account for ventilation time to the atmosphere. Data and emissions estimates for additional time horizons and EEZs are presented in Supplementary Table 1.

*Catch data were retrieved from the Sea Around Us database[10] using the code to which a link is provided in the Code Availability statement.

†We weighted the bottom depth of the area within each EEZ that was subjected to benthic trawling according to the rates of remineralization estimated by Sala et al.[1] The mean bottom depth for each grid square in the Sala et al.[1] CO_2 efflux dataset was retrieved from the database described in ref. [13]; this depth was then weighted by the mass of CO_2 that Sala et al.[1] estimated was produced in that grid square in the first year of benthic trawling.

‡For the first year after start of benthic trawling activity, from the model of sediment remineralization posited by Sala et al.[1]

§Geographic subsetting was performed using the exclusive economic zone boundaries described in ref. [14]. A link to the appropriate code is provided in the Code Availability statement.

‖The mean bottom depth for each grid square in the Sala et al.[1] sediment CO_2 efflux dataset was retrieved from ref. [13].

Supplementary information

for

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Methods

Objective and assumptions

Sala et al.[1] combined a global dataset of sediment carbon concentrations[2], fishing vessel track densities derived from automatic identification systems (AIS) data, prior findings concerning the sediment penetration depth and track width of various types of benthic trawling gear[3,4], and a simple model of remineralization, to estimate the remineralization rate of sediment organic carbon due to benthic trawling and the consequent flux of CO_2 to overlying bottom waters. We sought to correct these flux estimates for ventilation time — the time it takes for an interior ocean water mass to come into contact with the atmosphere as a function of bottom depth and ocean circulation — to predict the fraction remineralized CO_2 one might expect to reach the atmosphere as a source of emissions. To focus our analysis on the importance of accounting for ventilation time, we used the same model of sediment remineralization upon which Sala et al. based their uncorrected estimates, including the authors' assumptions concerning the (lesser) fraction of carbon remineralized within a given model grid square with each successive year of continuous trawling activity. As we note in the main text, there are several potentially serious deficiencies in this underlying model; we did not formally address these sources of error in our analysis, leaving the development of a more realistic model of remineralization to future study.

Adjustment of Sala et al.[1] efflux estimates for ventilation time

The primary input for our analysis was the Sala et al. data file containing estimates of sediment CO_2 efflux in Mg CO_2 km^{-2} (1 km × 1 km resolution; file "co2_efflux.tif," available at https://doi.org/10.25349/D9N89M). Because these data were very sparse (flux values of zero were assigned to > 99% of grid squares), we performed our analysis on a subset of the data that contained only nonzero values while retaining the coordinates to facilitate spatial subsetting. The R and MATLAB codes we used to perform these and the other calculations described below are available at https://github.com/jamesrco/global-trawling-CO2. Calculations in R[5] were performed using the packages sp[6,7], rgdal[8], sf[9], raster[10], data.table[11], R.matlab[12], and maptools[13].

To correct the Sala et al. flux estimates for ventilation time, we modified the published output from a series of experiments by Siegel et al.[14] in an inverse ocean circulation model. Siegel et al.[14] sought to estimate the fraction of injected CO_2 that would be retained at various locations in the ocean over different timescales; we sought to estimate the complementary quantity (i.e., the fraction of remineralized CO_2 that would be emitted to the atmosphere after a given time t). We therefore used in our analysis the complement (i.e., $1 - f(t)$) of Siegel et al.'s *sequestration fractions*, which we termed *emissions fractions*. The Siegel et al. sequestration fractions (gridded data of 2° × 2° horizontal resolution and vertical resolution of 48 depths, proceeding from resolution of the underlying inverse circulation model) and accompanying MATLAB code were retrieved from https://doi.org/10.6084/m9.figshare.15228690.v2. A file containing the 48 depths in the model is available at https://github.com/jamesrco/global-trawling-CO2/blob/main/data/global_trawling/derived/benthic_seqfractions/OCIM_modelDepths.csv. Assuming that trawling begins in some theoretical year 1, the emissions fraction for a given year n represents the fraction of CO_2 remineralized and discharged into bottom waters at a given location n years ago that will have reached the atmosphere by year $1 + n$.

For each year of interest (1 to 200 yr in one-year increments, and then 300 to 1000 yr in increments of 100 yr) we retrieved from the Siegel et al. model output the values closest in space (based on latitude and longitude) to the coordinates of the centroid of each grid square in the Sala et al. CO_2 efflux dataset. We then selected the depth in the Siegel et al. model output that was closest to the mean bottom depth of the Sala et al. 1 km × 1 km model grid square. We assigned bottom depths to the Sala et al. grid squares from version 8 of the SRTM30 digital elevation model, a 1 km × 1 km resolution global digital elevation model that includes ocean bathymetry.[15] Details concerning this DEM are available at https://eatlas.org.au/data/uuid/80301676-97fb-4bdf-b06c-e961e5c0cb0b.

We then adjusted the Sala et al. flux estimate for each grid square using the best-fit emissions fraction for each ventilation timescale. We calculated cumulative atmospheric emissions estimates for a variety of time horizons (presented in Fig.1, Extended Data Fig. 2, Extended Data Table and Supplementary Table 1) by summing the adjusted flux estimates over the indicated timescale.

First-order validation using mixed layer depth data

Because the inverse ocean circulation model used by Siegel et al. is not optimized for the relatively shallow, near coastal waters where most benthic trawling takes place (Extended Data Fig. 1; Extended Data Table 1), we validated our approach based on emissions fractions using an independent calculation based on the maximum annual mixed layer depth (MLD_{max}). For purposes of this comparison, we assumed conservatively that any remineralized CO_2 discharged from sediments into waters whose bottom depth was $\leq MLD_{max}$ at that location would reach the atmosphere within one year. By comparing an estimate of annual atmospheric emissions based on this criterion to the one we obtained for the first year of trawling using the Siegel et al. emissions fractions, we sought to make a crude, first-order validation of our approach.

From the April 2022 version of a 1° × 1° resolution global database of mixed layer depths[16,17] (available at http://mixedlayer.ucsd.edu) we first extracted the MLD_{max} for the coordinates nearest the centroid of each grid square in the Sala et al.[1] CO_2 efflux dataset. We then subsetted the Sala et al. efflux dataset to include only those grid squares whose bottom depth (assigned from ref. [15], as described above) was $\leq MLD_{max} \pm 10$ m. By summing the flux values within this subset of grid squares, we obtained an estimate of first-year atmospheric emissions of 0.92 Pg CO_2. This estimate fell within 0.07 Pg (approx. 7%) of the atmospheric emissions estimate of 0.99 Pg CO_2 yr^{-1} we produced for the first year using the emissions fractions derived from the Siegel et al.[14] model output (Extended Data Table 1). This favorable comparison suggested that the inverse ocean circulation model used in ref. [14] did not lead to a fatal bias, at least for purposes of our simple analysis. Further, almost one-fourth of the global potential CO_2 efflux (on a mass basis, as estimated by Sala et al.[1]) originates in sediments underlying waters of 200 m or greater bottom depth (Extended Data Table 1), suggesting that the consequences of benthic trawling are not confined only to shallow coastal waters. Substantial off-shelf sediment transport — in which sediment resuspended by benthic trawling was advected by ocean currents into deeper waters — was also documented independently in another recent study[18], validating the use of an approach that attempts to account for the effects of ocean circulation.

Subsetting by exclusive economic zone (EEZ)

We used the EEZ boundary shapefiles described in ref. [19] to subset our adjusted estimates (and those of Sala et al.) to waters of the 30 countries with the greatest average landings from benthic trawling from 2009-2018 (according to ref. [20]) and the top 10 countries ranked by percentage of total EEZ catch from bottom trawling (according to ref. [21]). Results are presented in Extended Data Table 1 and Supplementary Table 1.

Catch data

Catch data for annual landings from benthic trawling (in Mt biomass yr^{-1}) were extracted for these same countries from the Sea Around Us database[20] using the R code to which a link is provided in the Data availability statement. We extracted landings data for 2009-2018 and averaged these to obtain the values we report in Extended Data Table 1 and Supplementary Table 1.

Supplementary Table 1 | Fisheries landings and cumulative CO_2 emissions estimates from benthic trawling for selected bottom depth ranges and EEZs, with rankings where appropriate

Bottom depth range or exclusive economic zone (EEZ) area	**Avg. landings from benthic trawling, 2009-2018***		**Weighted mean bottom depth of area subjected to benthic trawling†**		**Fraction by mass of total est. global sediment C remineral-ization‡**		**Cumulative emissions after years of continuous trawling**											
	Mt biomass	**Rank by EEZ§**	**m**	**Rank by EEZ§**	**—**	**Rank by EEZ§**	**1**		**5**	**10**	**25**	**30**		**50**	**75**	**100**	**200**	
							Pg CO_2	**Rank by EEZ§**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Rank by EEZ§**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Rank by EEZ§**
Global trawled ocean area, all bottom depths					1													
Original estimate (Sala et al.)							1.47		4.87	7.91	16.7	19.6		31.3	46	60.6	119	
Adjusted estimate (this analysis)							0.991		3.74	6.49	14.5	17.2		28.1	42	55.9	112	
Percent deviation							–33		–23	–18	–13	–12		–10	–8.7	–7.8	–5.9	
Global trawled ocean area, bottom depths‖ ≤ 200 m					0.78													
Original estimate (Sala et al.)							1.15		3.81	6.19	13.1	15.4		24.5	36	47.4	93.2	
Adjusted estimate (this analysis)							0.962		3.56	6.1	13.4	15.9		25.7	38	50.3	99.7	
Percent deviation							–16		–6.6	–1.5	2.8	3.4		4.8	5.7	6.2	7	
Global trawled ocean area, bottom depths‖ > 200 m					0.22													
Original estimate (Sala et al.)							0.324		1.07	1.74	3.68	4.32		6.9	10.1	13.3	26.2	
Adjusted estimate (this analysis)							0.0283		0.185	0.392	1.07	1.32		2.42	3.94	5.55	12.4	
Percent deviation							–91		–83	–77	–71	–69		–65	–61	–58	–53	
Global trawled ocean area, bottom depths‖ > 400 m					0.11													
Original estimate (Sala et al.)							0.163		0.54	0.877	1.85	2.18		3.47	5.1	6.72	13.2	
Adjusted estimate (this analysis)							0.0069		0.0481	0.11	0.328	0.411		0.784	1.33	1.92	4.61	
Percent deviation							–96		–91	–87	–82	–81		–77	–74	–71	–65	
Angola	0.29	22	527	1	0.011	8												
Original estimate (Sala et al.)							0.0166	8	0.0549	0.0893	0.188	0.221	8	0.354	0.519	0.684	1.34	8
Adjusted estimate (this analysis)							0.0008	24	0.0058	0.0124	0.0344	0.0428	21	0.0846	0.158	0.252	0.745	14
Percent deviation							–95	2	–89	–86	–82	–81	1	–76	–70	–63	–45	1
Argentina	0.65	11	85	21	0.002	23												
Original estimate (Sala et al.)							0.003	23	0.0098	0.016	0.0338	0.0397	23	0.0633	0.0929	0.122	0.241	23
Adjusted estimate (this analysis)							0.0024	17	0.0084	0.0141	0.0307	0.0363	22	0.0587	0.0871	0.116	0.231	22
Percent deviation							–21	26	–14	–12	–9.1	–8.6	23	–7.3	–6.2	–5.6	–4.1	18

Bottom depth interval or exclusive economic zone (EEZ) area	Avg. landings from benthic trawling, 2009-2018*		Weighted mean bottom depth of area subjected to benthic trawling†		Fraction by mass of total est. global sediment C remineral-ization‡		Cumulative emissions after years of continuous trawling											
	Mt biomass	Rank by EEZ§	m	Rank by EEZ§	—	Rank by EEZ§	1		5	10	25	30		50	75	100	200	
							Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§
Bangladesh¶	0.15	28																
Original estimate (Sala et al.)																		
Adjusted estimate (this analysis)																		
Percent deviation																		
Brazil	0.16	27	77	22	0.0016	25												
Original estimate (Sala et al.)							0.0023	25	0.0076	0.0124	0.0262	0.0308	25	0.0491	0.0721	0.095	0.187	25
Adjusted estimate (this analysis)							0.0017	20	0.0066	0.0114	0.0249	0.0294	24	0.0475	0.0702	0.0929	0.184	25
Percent deviation							–28	22	–13	–8.2	–5	–4.5	25	–3.4	–2.6	–2.2	–1.4	25
Canada	0.28	23	301	7	0.0074	16												
Original estimate (Sala et al.)							0.0108	16	0.0358	0.0582	0.123	0.144	16	0.231	0.338	0.446	0.877	16
Adjusted estimate (this analysis)							0.0023	18	0.0141	0.0286	0.0729	0.0882	15	0.151	0.232	0.314	0.656	17
Percent deviation							–78	8	–61	–51	–41	–39	7	–35	–32	–30	–25	5
China	4.4	1	25	27	0.52	1												
Original estimate (Sala et al.)							0.769	1	2.54	4.13	8.71	10.2	1	16.3	24	31.6	62.2	1
Adjusted estimate (this analysis)							0.605	1	2.22	3.82	8.4	9.92	1	16	23.7	31.3	61.8	1
Percent deviation							–21	25	–13	–7.6	–3.6	–3.1	26	–2	–1.3	–1	–0.53	26
Côte d'Ivoire	0.1	31	104	20	0.0006	29												
Original estimate (Sala et al.)							0.0008	29	0.0028	0.0046	0.0096	0.0113	29	0.018	0.0265	0.0349	0.0686	29
Adjusted estimate (this analysis)							0.0002	28	0.0014	0.0031	0.008	0.0096	29	0.0162	0.0244	0.0327	0.066	29
Percent deviation							–78	9	–49	–31	–17	–15	14	–10	–7.9	–6.4	–3.8	19
Denmark	0.32	21	158	15	0.027	4												
Original estimate (Sala et al.)							0.0396	4	0.131	0.213	0.449	0.528	4	0.843	1.24	1.63	3.21	4
Adjusted estimate (this analysis)							0.0301	3	0.107	0.178	0.385	0.454	3	0.731	1.08	1.43	2.84	4
Percent deviation							–24	23	–18	–16	–14	–14	15	–13	–13	–12	–11	11
Germany	0.088	33	19	29	0.009	11												
Original estimate (Sala et al.)							0.0132	11	0.0436	0.0708	0.15	0.176	11	0.281	0.412	0.543	1.07	11
Adjusted estimate (this analysis)							0.0132	7	0.0436	0.0708	0.15	0.176	8	0.281	0.412	0.543	1.07	9
Percent deviation							–0.055	30	–0.009	–0.005	–0.002	–0.002	30	–0.001	-8×10^{-4}	-6×10^{-4}	-3×10^{-4}	30

Bottom depth interval or exclusive economic zone (EEZ) area	Avg. landings from benthic trawling, 2009-2018*		Weighted mean bottom depth of area subjected to benthic trawling†		Fraction by mass of total est. global sediment C remineral-ization‡		Cumulative emissions after years of continuous trawling											
	Mt biomass	Rank by EEZ§	m	Rank by EEZ§	—	Rank by EEZ§	1		5	10	25	30		50	75	100	200	
							Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§
Guinea	0.49	17	211	13	0.0008	26												
Original estimate (Sala et al.)							0.0011	26	0.0037	0.006	0.0127	0.015	26	0.0239	0.0351	0.0463	0.0909	26
Adjusted estimate (this analysis)							0.0006	26	0.0024	0.004	0.0091	0.0109	28	0.0182	0.028	0.0382	0.0808	27
Percent deviation							–49	15	–37	–33	–29	–28	10	–24	–20	–17	–11	12
Guinea–Bissau	0.42	18	144	17	0.0051	21												
Original estimate (Sala et al.)							0.0075	21	0.0247	0.0401	0.0847	0.0996	21	0.159	0.233	0.307	0.604	21
Adjusted estimate (this analysis)							0.0048	12	0.0199	0.0339	0.0743	0.088	16	0.144	0.215	0.287	0.578	19
Percent deviation							–36	20	–19	–16	–12	–12	17	–9.6	–8	–6.8	–4.3	17
Guyana¶	0.036	35																
Original estimate (Sala et al.)																		
Adjusted estimate (this analysis)																		
Percent deviation																		
Iceland	0.25	24	278	8	0.0085	14												
Original estimate (Sala et al.)							0.0125	14	0.0413	0.067	0.142	0.166	14	0.266	0.39	0.514	1.01	14
Adjusted estimate (this analysis)							0.0042	13	0.0181	0.0316	0.0727	0.0867	17	0.144	0.217	0.291	0.606	18
Percent deviation							–67	11	–56	–53	–49	–48	5	–46	–44	–43	–40	2
India	2.1	4	54	24	0.002	24												
Original estimate (Sala et al.)							0.0029	24	0.0095	0.0155	0.0327	0.0384	24	0.0613	0.09	0.119	0.233	24
Adjusted estimate (this analysis)							0.002	19	0.0081	0.0136	0.0296	0.035	23	0.0565	0.0836	0.111	0.221	23
Percent deviation							–30	21	–15	–12	–9.5	–9	22	–7.8	–7	–6.6	–5.4	16
Indonesia	2.4	3	39	25	1.2×10^{-8}	31												
Original estimate (Sala et al.)							1.71×10^{-8}	31	5.64×10^{-8}	9.16×10^{-8}	1.93×10^{-7}	2.27×10^{-7}	31	3.63×10^{-7}	5.33×10^{-7}	7.02×10^{-7}	1.38×10^{-6}	31
Adjusted estimate (this analysis)							1.56×10^{-8}	31	5.41×10^{-8}	8.96×10^{-8}	1.91×10^{-7}	2.25×10^{-7}	31	3.61×10^{-7}	5.30×10^{-7}	7.00×10^{-7}	1.38×10^{-6}	31
Percent deviation							–8.4	27	–4	–2.2	–1.1	–0.9	27	–0.57	–0.39	–0.3	–0.15	27
Ireland	0.13	30	219	12	0.0095	10												
Original estimate (Sala et al.)							0.0141	10	0.0465	0.0755	0.159	0.187	10	0.299	0.439	0.579	1.14	10
Adjusted estimate (this analysis)							0.008	10	0.0342	0.0595	0.131	0.155	11	0.25	0.37	0.49	0.976	11
Percent deviation							–43	16	–26	–21	–18	–17	13	–16	–16	–15	–14	10
Japan	1.7	6	267	9	0.0098	9												
Original estimate (Sala et al.)							0.0144	9	0.0477	0.0775	0.164	0.192	9	0.307	0.45	0.594	1.17	9
Adjusted estimate (this analysis)							0.0016	21	0.0207	0.0518	0.139	0.167	9	0.282	0.425	0.568	1.14	8
Percent deviation							–89	4	–57	–33	–15	–13	16	–8.2	–5.7	–4.4	–2.3	21

Bottom depth interval or exclusive economic zone (EEZ) area	**Avg. landings from benthic trawling, 2009-2018***		**Weighted mean bottom depth of area subjected to benthic trawling†**		**Fraction by mass of total est. global sediment C remineral-ization‡**		**Cumulative emissions after years of continuous trawling**											
	Mt biomass	**Rank by EEZ§**	**m**	**Rank by EEZ§**	**—**	**Rank by EEZ§**	**1**		**5**	**10**	**25**	**30**		**50**	**75**	**100**	**200**	
							Pg CO_2	**Rank by EEZ§**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Rank by EEZ§**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Pg CO_2**	**Rank by EEZ§**
Malaysia	0.65	10	10	30	0.0062	18												
Original estimate (Sala et al.)							0.0091	18	0.0301	0.0489	0.103	0.121	18	0.194	0.284	0.374	0.736	18
Adjusted estimate (this analysis)							0.0085	9	0.0296	0.0485	0.103	0.121	13	0.193	0.284	0.374	0.736	15
Percent deviation							−6.4	28	−1.6	−0.85	−0.39	−0.33	28	−0.21	−0.14	−0.11	−0.055	28
Mexico	0.64	13	146	16	3.8×10^{-5}	30												
Original estimate (Sala et al.)							5.59×10^{-5}	30	0.0002	0.0003	0.0006	0.0007	30	0.0012	0.0018	0.0023	0.0045	30
Adjusted estimate (this analysis)							2.23×10^{-5}	30	8.67×10^{-5}	0.0002	0.0004	0.0005	30	0.0008	0.0013	0.0019	0.004	30
Percent deviation							−60	13	−53	−49	−41	−38	8	−30	−24	−19	−11	13
Morocco	1.9	5	473	2	0.0053	20												
Original estimate (Sala et al.)							0.0079	20	0.0259	0.0422	0.089	0.105	20	0.167	0.245	0.323	0.635	20
Adjusted estimate (this analysis)							0.0011	22	0.0084	0.0174	0.0468	0.0575	20	0.103	0.163	0.226	0.489	21
Percent deviation							−86	5	−68	−59	−47	−45	6	−39	−34	−30	−23	6
Myanmar¶	0.64	12																
Original estimate (Sala et al.)																		
Adjusted estimate (this analysis)																		
Percent deviation																		
Namibia	0.37	19	403	3	0.0088	12												
Original estimate (Sala et al.)							0.013	12	0.0428	0.0696	0.147	0.173	12	0.276	0.404	0.533	1.05	12
Adjusted estimate (this analysis)							0.0007	25	0.0075	0.0175	0.0606	0.078	18	0.155	0.262	0.374	0.851	13
Percent deviation							−95	3	−83	−75	−59	−55	4	−44	−35	−30	−19	7
Netherlands	0.092	32	10	31	0.02	6												
Original estimate (Sala et al.)							0.0301	6	0.0993	0.161	0.341	0.401	6	0.64	0.938	1.24	2.43	6
Adjusted estimate (this analysis)							0.0301	4	0.0993	0.161	0.341	0.401	5	0.64	0.938	1.24	2.43	5
Percent deviation							−0.017	31	−0.002	−0.001	-6.1×10^{-4}	-5.2×10^{-4}	31	-3.2×10^{-4}	-2.2×10^{-4}	-1.7×10^{-4}	-8.5×10^{-4}	31
New Zealand	0.34	20	348	5	0.0054	19												
Original estimate (Sala et al.)							0.008	19	0.0263	0.0428	0.0903	0.106	19	0.169	0.249	0.328	0.644	19
Adjusted estimate (this analysis)							0.003	15	0.0133	0.0247	0.0596	0.0717	19	0.122	0.187	0.255	0.536	20
Percent deviation							−62	12	−50	−42	−34	−32	9	−28	−25	−22	−17	9

Bottom depth interval or exclusive economic zone (EEZ) area	Avg. landings from benthic trawling, 2009-2018*		Weighted mean bottom depth of area subjected to benthic trawling[†]		Fraction by mass of total est. global sediment C remineral-ization[‡]		Cumulative emissions after years of continuous trawling											
							1		5	10	25	30		50	75	100	200	
	Mt biomass	Rank by EEZ[§]	m	Rank by EEZ[§]	—	Rank by EEZ[§]	Pg CO_2	Rank by EEZ[§]	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ[§]	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ[§]
Norway	0.49	16	233	11	0.018	7												
Original estimate (Sala et al.)							0.0261	7	0.0863	0.14	0.296	0.348	7	0.555	0.815	1.07	2.11	7
Adjusted estimate (this analysis)							0.0105	8	0.0523	0.0956	0.219	0.26	7	0.428	0.643	0.859	1.74	7
Percent deviation							–60	14	–39	–32	–26	–25	11	–23	–21	–20	–18	8
Pakistan[¶]	0.21	25																
Original estimate (Sala et al.)																		
Adjusted estimate (this analysis)																		
Percent deviation																		
Republ. of Congo	0.053	34	402	4	0.0023	22												
Original estimate (Sala et al.)							0.0035	22	0.0114	0.0185	0.0391	0.046	22	0.0734	0.108	0.142	0.279	22
Adjusted estimate (this analysis)							0.0001	29	0.0018	0.0051	0.0159	0.0196	25	0.0354	0.0577	0.0828	0.199	24
Percent deviation							–97	1	–84	–72	–59	–57	3	–52	–46	–42	–29	4
Russia	0.61	15	246	10	0.057	2												
Original estimate (Sala et al.)							0.0847	2	0.28	0.455	0.96	1.13	2	1.8	2.64	3.48	6.85	2
Adjusted estimate (this analysis)							0.0148	6	0.0671	0.125	0.328	0.411	4	0.81	1.39	1.99	4.51	2
Percent deviation							–83	6	–76	–73	–66	–64	2	–55	–48	–43	–34	3
South Africa	0.14	29	302	6	0.0066	17												
Original estimate (Sala et al.)							0.0098	17	0.0322	0.0524	0.111	0.13	17	0.208	0.304	0.401	0.789	17
Adjusted estimate (this analysis)							0.0032	14	0.018	0.0347	0.0851	0.103	14	0.174	0.265	0.358	0.733	16
Percent deviation							–67	10	–44	–34	–23	–21	12	–16	–13	–11	–7.1	15
South Korea	1.1	8	70	23	0.0081	15												
Original estimate (Sala et al.)							0.012	15	0.0395	0.0642	0.136	0.159	15	0.254	0.373	0.492	0.967	15
Adjusted estimate (this analysis)							0.0025	16	0.0203	0.0459	0.118	0.142	12	0.236	0.355	0.474	0.949	12
Percent deviation							–79	7	–49	–29	–13	–11	18	–7	–4.8	–3.7	–1.9	23
Thailand	0.62	14	20	28	0.0007	27												
Original estimate (Sala et al.)							0.001	27	0.0034	0.0055	0.0116	0.0136	27	0.0217	0.0318	0.0419	0.0824	27
Adjusted estimate (this analysis)							0.001	23	0.0033	0.0055	0.0115	0.0135	26	0.0216	0.0318	0.0419	0.0824	26
Percent deviation							–2.6	29	–0.8	–0.47	–0.24	–0.21	29	–0.14	–0.095	–0.073	–0.039	29

Bottom depth interval or exclusive economic zone (EEZ) area	Avg. landings from benthic trawling, 2009-2018*		Weighted mean bottom depth of area subjected to benthic trawling†		Fraction by mass of total est. global sediment C remineral-ization‡		Cumulative emissions after years of continuous trawling											
	Mt	Rank	m	Rank	—	Rank	1		5	10	25	30		50	75	100	200	
	biomass	by EEZ§		by EEZ§		by EEZ§	Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§	Pg CO_2	Pg CO_2	Pg CO_2	Pg CO_2	Rank by EEZ§
Turkey	0.16	26	108	19	0.0085	13												
Original estimate (Sala et al.)							0.0125	13	0.0415	0.0674	0.142	0.167	13	0.267	0.392	0.516	1.01	13
Adjusted estimate (this analysis)							0.0079	11	0.0348	0.0597	0.132	0.156	10	0.253	0.375	0.498	0.993	10
Percent deviation							–37	19	–16	–11	–7.5	–6.8	24	–5.2	–4.1	–3.5	–2.1	22
United Kingdom	0.67	9	138	18	0.032	3												
Original estimate (Sala et al.)							0.0477	3	0.158	0.256	0.541	0.636	3	1.01	1.49	1.96	3.86	3
Adjusted estimate (this analysis)							0.0363	2	0.134	0.226	0.489	0.577	2	0.928	1.37	1.81	3.58	3
Percent deviation							–24	24	–15	–12	–9.6	–9.3	21	–8.6	–8.1	–7.9	–7.2	14
United States	1.2	7	170	14	0.021	5												
Original estimate (Sala et al.)							0.0307	5	0.101	0.165	0.348	0.409	5	0.653	0.959	1.26	2.48	5
Adjusted estimate (this analysis)							0.0182	5	0.0739	0.133	0.306	0.365	6	0.602	0.9	1.2	2.4	6
Percent deviation							–41	17	–27	–20	–12	–11	19	–7.9	–6.1	–5.1	–3.5	20
Vietnam	2.5	2	29	26	0.0006	28												
Original estimate (Sala et al.)							0.0009	28	0.003	0.0049	0.0104	0.0123	28	0.0196	0.0287	0.0378	0.0744	28
Adjusted estimate (this analysis)							0.0006	27	0.0021	0.0039	0.0092	0.0111	27	0.0183	0.0275	0.0366	0.0731	28
Percent deviation							–38	18	–30	–22	–11	–9.8	20	–6.2	–4.3	–3.3	–1.7	24

Supplementary Table 1 presents cumulative emissions estimates from both the original Sala et al.[1] model and this study, which applies the methods described in the text to account for ventilation time to the atmosphere. Data and emissions estimates are presented for the 30 countries with the greatest average landings from benthic trawling from 2009-2018 (according to ref. [20]; see note below) and for the top 10 countries ranked by percentage of total EEZ catch from bottom trawling (according to ref. [21]).

*Catch data were retrieved from the Sea Around Us database[20] using the code to which a link is provided in the Code Availability statement.
†We weighted the bottom depth of the area within each EEZ that was subjected to benthic trawling according to the rates of remineralization estimated by Sala et al.[1] The mean bottom depth for each grid square in the Sala et al. CO_2 efflux dataset was retrieved from the database described in ref. [15]; this depth was then weighted by the mass of CO_2 that Sala et al.[1] estimated was produced in that grid square in the first year of benthic trawling.
‡For the first year after start of benthic trawling activity, from the model of sediment remineralization posited by Sala et al.[1]
§Geographic subsetting was performed using the exclusive economic zone boundaries contained in the database described in ref. [19]. A link to the appropriate code is provided in the Code Availability statement.
‖The mean bottom depth for each grid square in the Sala et al.[1] sediment CO_2 efflux dataset was retrieved from the database described in ref. [15].
¶Sala et al.[1] estimated no sediment CO_2 emissions for grid squares within this EEZ boundary.

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