APPLIED ECOLOGY

Tracking bottom-fishing activities in protected vulnerable marine ecosystem areas and below 800-m depth in European Union waters

Lissette Victorero[1]*, Russell Moffitt[2], Natasha Mallet[3], Frédéric Le Manach[3]

Numerous studies have highlighted bottom-contact fishing gears as the primary threat to vulnerable marine ecosystems (VMEs). In November 2022, the European Commission closed 87 VME protection polygons to bottom fishing in European waters. Using public automatic identification system (AIS) data, we found an 81% decrease in bottom-contact fishing effort within these areas in the year following the closures. However, approximately 3500 hours of bottom-contact fishing persisted within the closures. We also quantified up to 17,600 hours of bottom-contact fishing in unprotected areas where VMEs are known or likely to occur. Last, our analysis revealed ongoing bottom trawling below 800 meters in European waters totaling 19,200 hours over 2 years. These findings underscore the urgent need for states to enhance surveillance and monitoring of their fleets to ensure effective fisheries management.

INTRODUCTION

"Vulnerable marine ecosystems" (VMEs) is a term developed and promoted by the United Nations General Assembly and the Food and Agriculture Organization of the United Nations to describe deep-sea ecosystems that are particularly sensitive to human activities and environmental changes (*1*). In the deep ocean, these ecosystems denote areas on the ocean floor characterized by habitat-forming organisms, including deep-sea sponge clusters, cold-water corals, sea pens, crinoid fields, and prominent features such as seamounts and hydrothermal vents (*1*). The species are typically fragile, slow-growing, and highly susceptible to harm from activities such as deep-sea fishing, mining, or other disturbances, and slow to recover (*2*–*4*). VMEs exhibit high biodiversity due to the variety of habitats they offer, resulting in increased faunal richness, diversity, abundance, and biomass (*5*–*7*). Commercial fish populations and other taxa use VME habitats to aggregate, spawn, forage, and for shelter (*8*, *9*).

The widespread occurrence of VMEs suggests that the ecosystem services that they provide contribute substantially to the overall health of the ocean. VMEs offer regulating services through ecosystem processes (e.g., climate regulation and carbon sequestration), supporting services (e.g., nutrient cycling and primary production); provisioning services derived from their habitats (e.g., seafood, minerals, and pharmaceuticals) and cultural services (e.g., indigenous/customary rights and interests, scientific research, education, and aesthetic enjoyment) (*10*–*13*). The economic value of protecting VMEs could exceed the economic value of fisheries. In Ireland, the public expressed a willingness to contribute financially €1 to 10 annually to protect areas with deep-sea corals and ban trawling (*14*). When extrapolated to the 3.2 million adults, this protection is valued at €3.2 to 32 million annually (*14*). The fish targeted by the fishing industry also contribute to carbon sequestration. Along the UK and Irish continental slope, which is already heavily overexploited, deep-sea fish were estimated to provide a carbon storage pathway of more than 1 million tons of carbon dioxide (CO_2) every year (*15*). This ecosystem service of carbon sequestration is valued at EUR 8 to 14 million per year, representing 10 to 50% of the estimated market value of the fish landed from the area (*15*).

A substantial body of scientific literature documents the physical destruction of VMEs caused by deep-sea trawling, which in turn affects deep-sea biodiversity, disrupts ecological functioning, and diminishes vital ecosystem services [(*3*) and references within]. Commonly reported impacts encompass physical disturbances to the seafloor, routine removal of a substantial portion of benthic fauna, including meiofauna, and declines in faunal biodiversity, cover, and abundance (*3*, *16*–*18*). Other notable effects include biogeochemical alterations (*19*), resuspension of sediments that smother seafloor organisms (*20*), the disposal of bycatch and processing waste (*3*), and direct pollution from discarded or lost fishing gear (*21*). The impacts of static gears, such as set longlines and gillnets, are less pronounced than that of trawling, although there are fewer studies on the subject (*22*). Instances of longline fisheries impacting sponges and corals have been documented in several studies (*22*–*26*). In southern Portugal, 85% of deployed gillnets had coral bycatch entangled in the nets (*27*). In addition, research conducted on the Hatton Bank shows that discards from longlines consist primarily of the adult fraction of vulnerable deep-water sharks (*26*).

To manage the impacts of deep-sea fisheries, the General Assembly of the United Nations (UNGA) has adopted a series of resolutions, obliging states to prevent significant adverse impacts (SAIs) to VMEs (UNGA resolutions 61/105 in 2006 and 64/72 in 2009 and subsequent resolution). SAIs are characterized as impacts that compromise ecosystem integrity by altering ecosystem structure or function in a permanent or long-lasting manner across six factors (*1*). Impacts are evaluated for their intensity, spatial and temporal scales, and the ecosystem's vulnerability, recovery potential, and alteration of ecosystem functions. Research specifically identifying seabed damage as SAIs remains limited. However, a study on the Emperor Seamount Chain, North-western Hawaiian Ridge, identified SAIs on all surveyed seamounts (*28*). Mapping by autonomous underwater vehicles revealed vast barren areas, scars on the seabed, and coral

[1]Deep Sea Conservation Coalition, Amsterdam, Netherlands. [2]Marine Conservation Institute, Glen Ellen, CA, USA. [3]Bloom Association, Paris, France.
*Corresponding author. Email: lissette.victorero@gmail.com

stumps, with very few observations of the coralliid octocorals that formerly supported the world's largest precious coral fishery (*28*).

Fisheries management strategies to conserve marine resources include gear restrictions, quotas, and temporal management, but permanent spatial closures are deemed the most effective for protecting VMEs due to their fragility and slow recovery (*29*). Research has shown that adequately designed closures can increase the protection of VMEs while simultaneously minimizing economic losses to the fishing industry, retaining at least 75% of the total historical catch (*30*).

In 2016, to fulfill their international obligations to protect VMEs from SAIs caused by bottom-contact fishing gears, the European Union (EU) introduced the Deep-sea Access Regulation (EU) 2016/2336 (*31*), prohibiting bottom trawling in EU waters below 800 m.

To further advance the protection of VMEs, the European Commission tasked the International Council for the Exploration of the Sea (ICES) with overseeing an advisory process to identify areas in the EU waters in the North-East Atlantic where VMEs are known or likely to occur between depths of 400 to 800 m (*32*). ICES was requested to provide an annual assessment leading to recurring advice, predicated on the best scientific and technical information available. On the basis of this advisory process, the Commission was expected to implement fisheries closures by January 2018, but the process encountered notable delays (*32*). The initial set of closures was implemented in November 2022, establishing 87 VME protection polygons closed to bottom fishing across the Celtic Seas and the Bay of Biscay and Iberian Coast ecoregions (Fig. 1) (*33*). These closures prohibit bottom trawling, bottom-set gillnets, bottom-set longlines, and the use of pots and traps within VME protection polygons at depths of 400 to 800 m. The total area of the closures is stated to be 16,419 km^2 (*33*).

In 2023, ICES released five updated spatial management scenarios, labeled A to E, modifying the VME protection polygons from the advice provided in 2021 (*34*). The scenarios vary in the criteria for delineating VME protection polygons and their management implications. However, the implementation of the newly proposed closures has been delayed due to political considerations. The fishing industry's lack of support for the current closures, coupled with these delays, raises concerns about compliance. The Irish industry believes there are mistakes in the delineations of several polygons (*35*). The government of Spain has lodged an appeal to the EU Court of Justice against the closures (*36*), claiming that the closures are disproportionate, fail to use the best scientific and technical information, and violate the principles of the Common Fisheries Policy.

In this study, we present the first attempt to monitor bottom-fishing activities within VME protection polygons in the deep sea. We assess the effects of the 2022 closures by analyzing apparent fishing effort based on automatic identification system (AIS) data within the 400- to 800-m depth range of the VME protection polygons, both before and after the closures. Our analysis focuses on determining the degree of compliance by EU member states, any changes in fleet behavior, and pinpointing the states involved in bottom-fishing activities within the VME protection polygons. Furthermore, we aim to identify the current and newly proposed VME protection polygons most susceptible to SAIs and provide insights into trawling activity occurring below 800 m.

RESULTS

Our calculations show that there are 56,300 km^2 of seabed area between 400- and 800-m depth in the EU waters of the North Atlantic. The VME protection polygons at the 400- to 800-m depth range cover an area of 5553 km^2. This contrasts with the full closure polygon area of 16,419 km^2 claimed by the European Commission. The implementation of the closures reduced bottom-fishing efforts within the 400- to 800-m depth range of VME protection polygons by 81%. In the year preceding the closures, there was ca. 19,000 hours of fishing effort by 392 vessels, reduced to ca. 3500 hours in the year following the implementation of closures (Fig. 2). Since the implementation of closures in November 2022, there has been 664 fishing events conducted by 312 vessels across 63 VME protection polygons, continuing until the end of our study period October 2023 (data S1). Our findings suggest that ca. 1600 fishing effort hours occurred fully within the high-confidence zones, where Global Fishing Watch (GFW) grid cells were fully contained within the 400- to 800-m depth range of a VME protection polygon (Fig. 3).

Spain exhibited the highest fishing effort within the VME protection polygons, with 1769 hours across 428 incursions by 183 vessels (Fig. 3). The French fleet, comprising 68 vessels, accounted for 620 hours of fishing effort across 145 incursions (data S1). Notably, the highest fishing efforts by individual vessels from these countries were 62 hours by a Spanish vessel and 43 hours by a French vessel (data S1), accomplished through frequent and brief incursions. Our observations suggest that there was a consistent trend of recurrent, short fishing incursions within many polygons, especially along their inner boundaries, by both fleets (Fig. 3).

We observed that up to 20 VME protection polygons continued to encounter between 50 and 680 hours of fishing effort in a 1-year period (data S1). The fishing effort decreased after the implementation of closures, reducing from 10,634 hours to 2872 hours in the Bay of Biscay and Iberian Coast ecoregion and from 8374 hours to 660 hours in the Celtic Seas ecoregion (Fig. 4). Within the high-confidence zones of the VME protection polygons, our results show that, particularly, VME polygon 13 on the West Iberian Shelf encountered over 500 hours of fishing effort despite the closures (Fig. 4A). This polygon is fished mainly by the Portuguese fleet, where three vessels were responsible for the majority of the fishing. Two of these vessels were equipped with drifting longlines as their secondary gear based on the EU registry, but the GFW algorithm suggests that the vessels were trawling (figs. S1 and S2) based on a slow steady speed and the duration of the fishing operations (*37*). Overall, these three vessels are potentially the most severe transgressors throughout the closures. We also note that there was still a degree of fishing activity across several polygons in this ecoregion and that fishing effort increased in VME polygon 42 in the Bay of Biscay by ca. 100 hours inside the high-confidence zone (Fig. 4A).

In the Celtic Seas ecoregion, fishing effort reduced overall, with little fishing effort seen in the high-confidence zones (Fig. 4B). In the VME polygon 57 in the Porcupine Bank, the fishing effort reduced by more than 97% (Fig. 4B). However, there were still 15 vessels from France, the United Kingdom, and Ireland showing fishing effort within the high-confidence zone (Fig. 5A and data S1). In the Rockall Trough VME polygon 85, a British vessel had 117 hours of fishing activity (data S1). This vessel according to the EU registry operated with unspecific gillnets and longlines. The predominant main gears used by vessels fishing within the VME polygons are bottom trawls followed closely by set gillnets (Fig. 5B), notably preferred in Spain (data S1). Collectively, these two fishing methods represented 2900 hours of fishing effort.

Our analysis also suggests that the newly proposed VME protection polygons under ICES spatial management scenarios labeled C

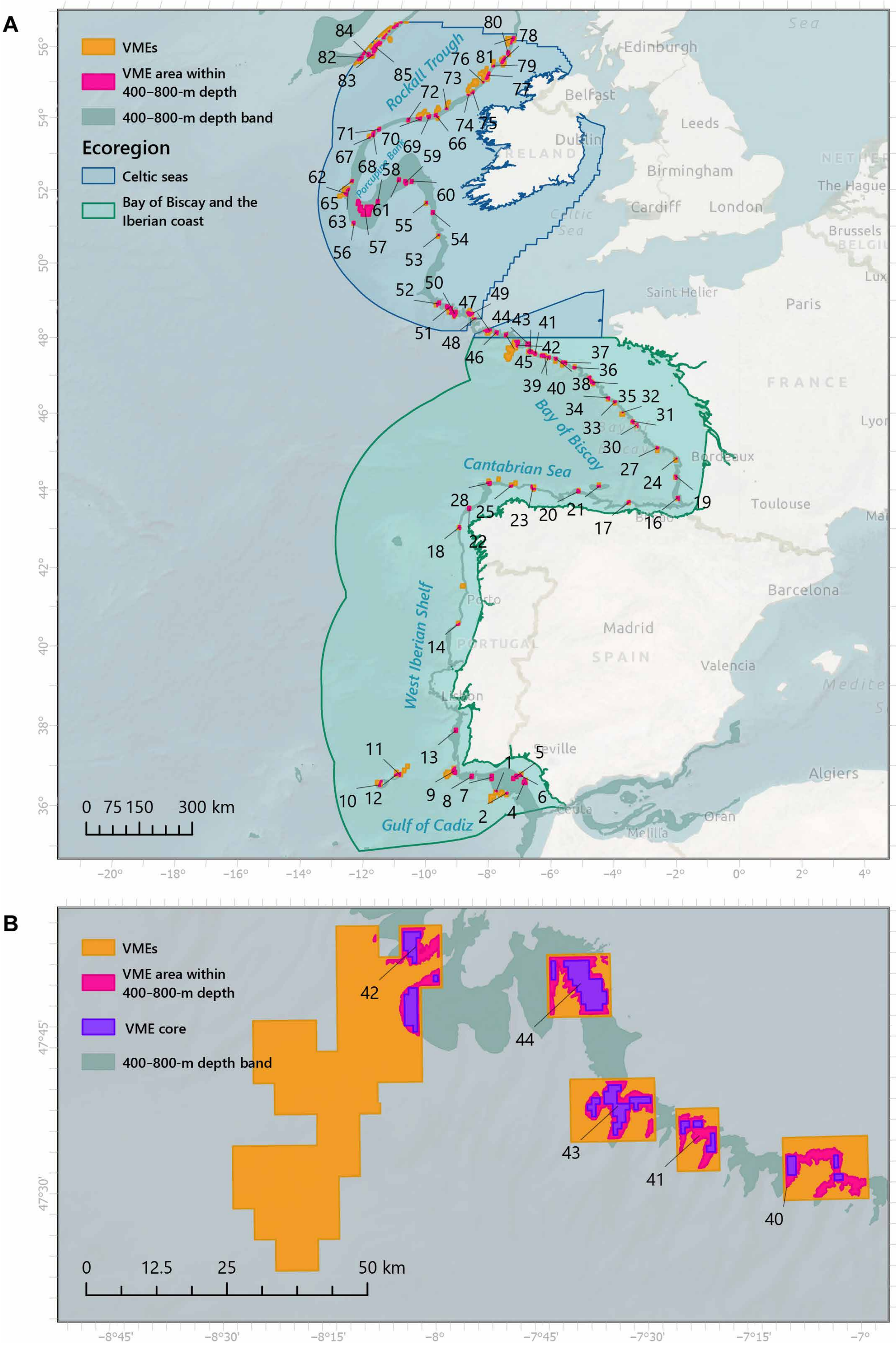

Fig. 1. The vulnerable marine ecosystem protection polygons in European waters. (**A**) Vulnerable marine ecosystem protection polygons in European waters across ecoregions. (**B**) Polygon boundaries illustrate the full polygons numbered 40 to 42, the 400- to 800-m depth band and the VME core, which represents the high-confidence zones within the polygons.

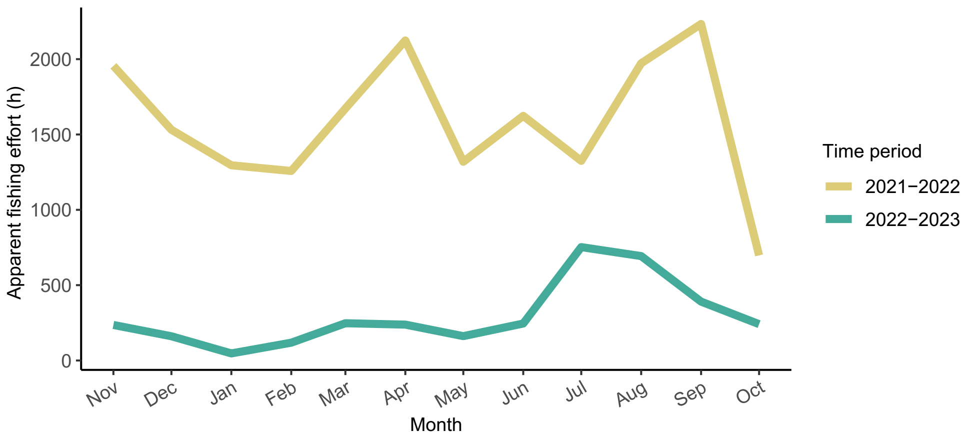

Fig. 2. Monthly fishing effort the year before and after the implementation of the vulnerable marine ecosystem protection polygons.

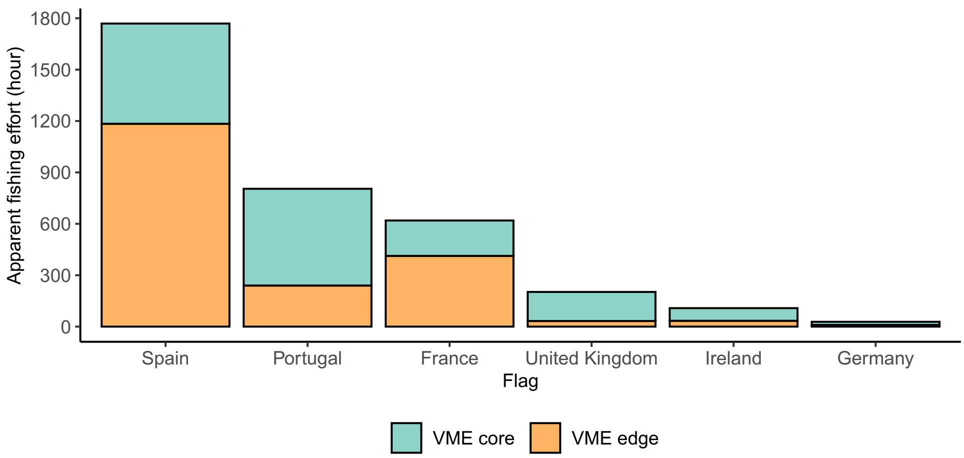

Fig. 3. Fishing effort per state across all vulnerable marine ecosystem protection polygons, segmented into high-confidence and edge areas. The VME core represents the high-confidence zone, while the edge denotes the area outside this zone but within the VME protection polygon. Number of vessels per state: Spain = 183, Portugal = 34, France = 68, United Kingdom = 7, Ireland = 17, and Germany = 3.

and D experienced substantial fishing activity primarily conducted by the Spanish fleet (Fig. 6). Under scenario C, the proposed VME protection polygons experienced ca. 17,600 hours of fishing effort, while under scenario D, this effort reduced to ca. 6200 hours (data S2). Under scenario C, in the Cantabrian Sea, the areal expansions of VME polygon 20 and the newly proposed VME polygon 43 encountered more than 2700 hours of fishing effort (Fig. 6A). In the Celtic Seas, the new VME polygon 83 also encountered more than 2500 hours of fishing effort (Fig. 6B). In scenario D, the areal expansions in the Bay of Biscay of VME polygon 34 experienced more than 600 hours of fishing effort, while the areal expansion of VME polygon 30 showed more than 700 hours (Fig. 6B). In addition, a new polygon (d.51) exhibited more than 800 hours of fishing effort (Fig. 6B). Over the 2-year period covered by this study, ca. 19,200 hours of trawling activity were recorded at depths below 800 m in EU waters (data S1), with most of this effort attributed to the Portuguese fleet.

DISCUSSION

Our study monitored the response of the industrial bottom fishing fleet to the VME protection polygons established by the European Commission. We show that closures in EU waters have proven partially effective, reducing fishing activity in areas where VMEs are known or are likely to occur as identified by the ICES advice (Fig. 2). The implementation of closures was generally respected until the main fishing season of summer 2023, when compliance decreased (Fig. 2). Despite most vessels cooperating with the closures, 19% of estimated bottom contact fishing activities persisted within the VME protection polygons, posing a risk of SAIs to VMEs in EU waters (Fig. 2). We observed a higher amount of fishing activity at the edges of the 400- to 800-m depth band than in the high-confidence zones (Fig. 3). Together, with the fishing patterns observed by the GFW algorithm of repeated incursions into the edge of the polygons, these results indicate that the industry is cognisant of the spatial boundaries set by regulation (EU) 2016/2336 for VME polygons. These patterns are particularly evident in the Spanish fleet, which demonstrates high fishing efforts through frequent but brief fishing activities within and along these boundaries (Fig. 3). Short fishing incursion into small VME polygons could go unnoticed by vessel monitoring system (VMS) data, as legally the EU requests vessels to provide a VMS data point only every 2 hours. Therefore, for effective monitoring, the Deep-sea Access Regulation

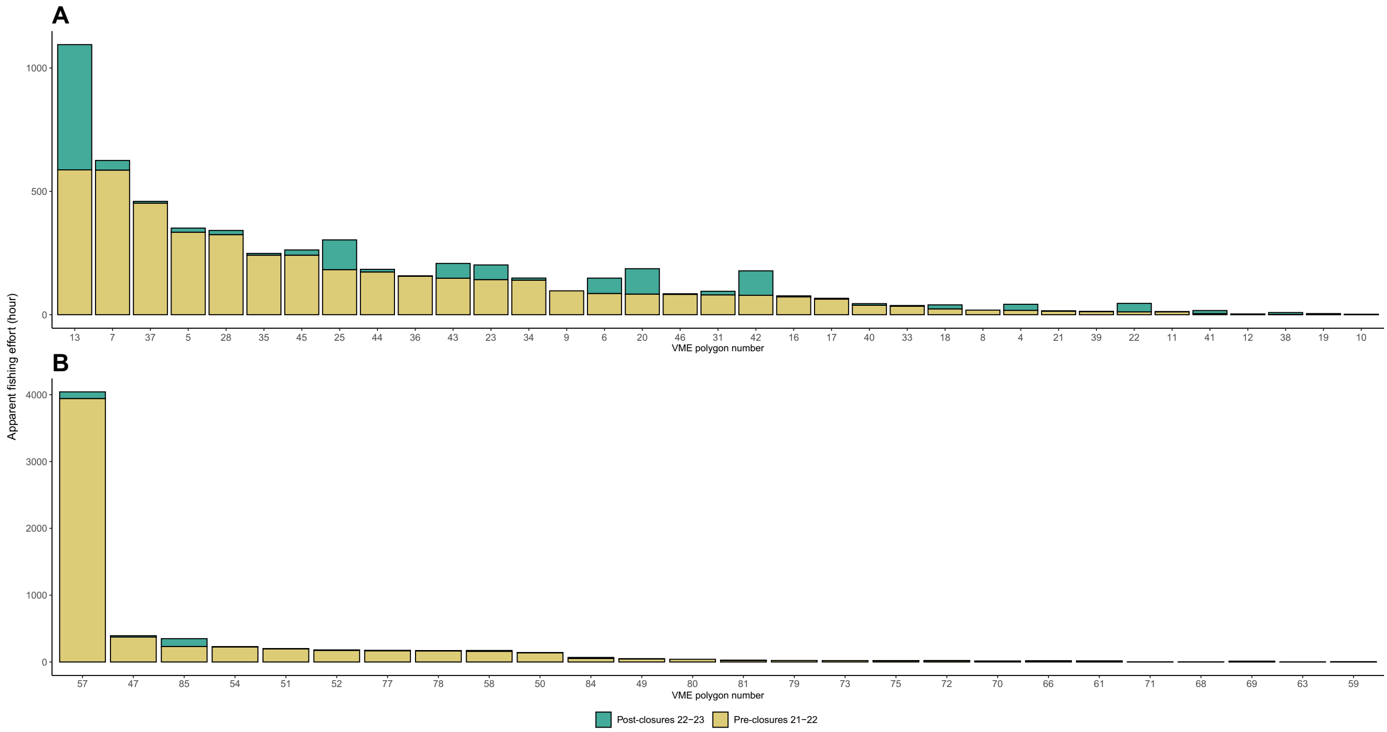

Fig. 4. Fishing effort per vulnerable marine ecosystem protection polygon from 2021 to 2023 within the high-confidence zone of the polygons. (**A**) Bay of Biscay and Iberian Coast and (**B**) Celtic Seas ecoregions.

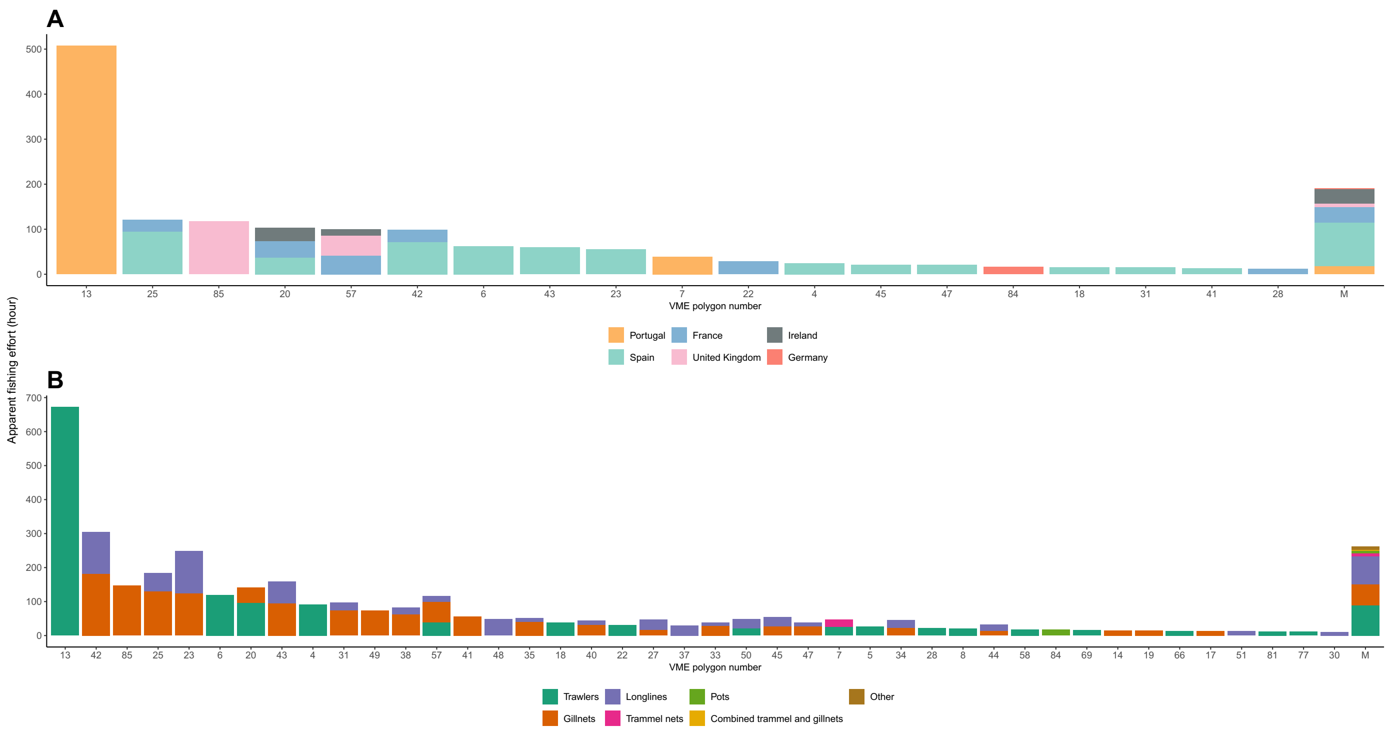

Fig. 5. Fishing effort within the vulnerable marine ecosystem protection polygons during closures in 2022–2023. Fishing effort within the vulnerable marine ecosystem protection polygons (**A**) per state within the high-confidence zone of the polygons, and (**B**) per main fishing gear within the total polygon area. Minor polygons (M) represent polygons that have less than 10 hours of fishing effort. The high-confidence zone refers to the 0.01° grid cells completely contained between 400- and 800-m isobaths. Polygons numbered below 47 are within the Bay of Biscay and Iberian Coast ecoregion, and those numbered above are in the Celtic Seas ecoregion.

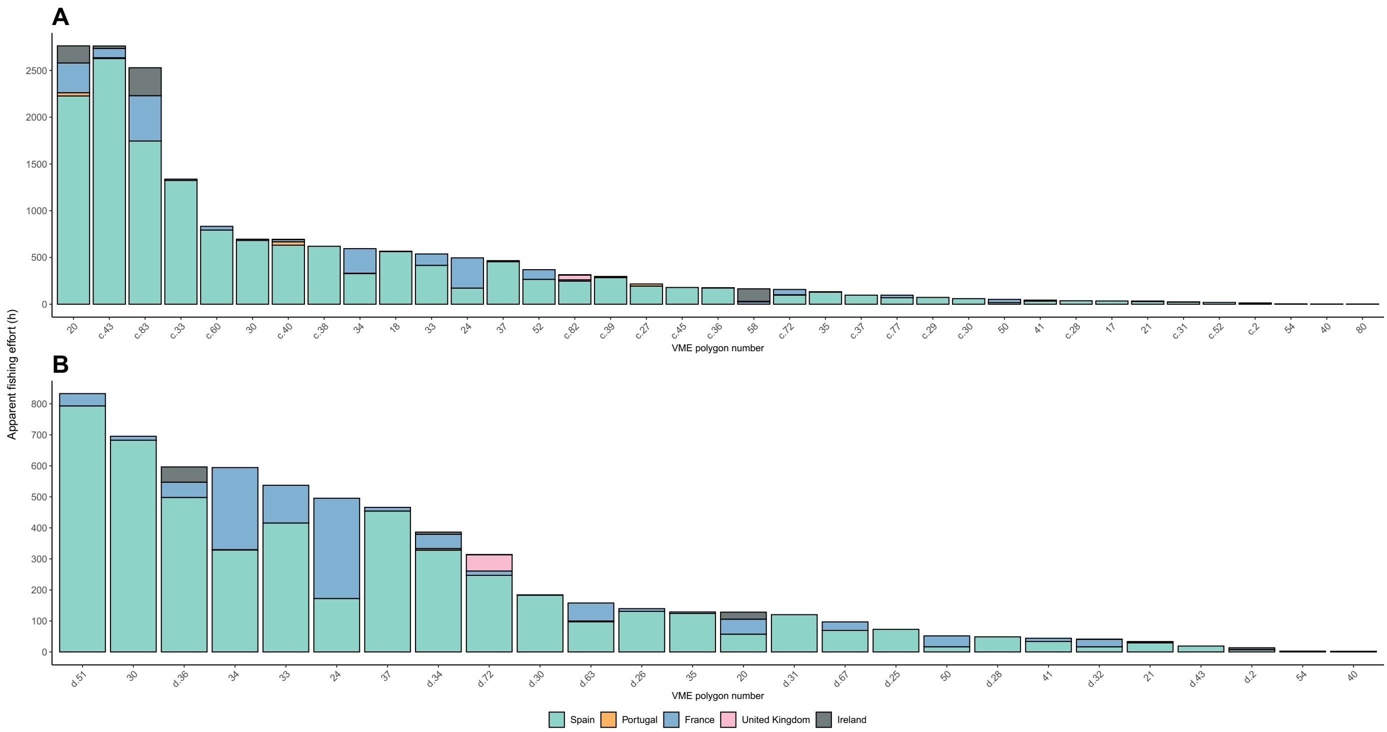

Fig. 6. Fishing effort within newly proposed vulnerable marine ecosystem protection polygons according to the ICES 2023 advice for spatial management scenarios during 2022–2023. (**A**) Scenario C and (**B**) scenario D. Polygon numbers labeled with letters indicate newly identified delineations, while unlabeled polygons represent spatial extensions of existing 2022 VME protection polygons. For their locations, see figs. S3 and S4.

encourages using AIS data for states to monitor their fleets because AIS provides position data at 6- to 12-s intervals, surpassing VMS data in capturing a vessel's course in real time (*32*).

In the Celtic Seas, we observe higher levels of compliance compared to the Bay of Biscay and Iberian Coast ecoregion (Fig. 4). Previous research established the Iberian Portuguese region as one of the most heavily trawled deep-sea areas within EU waters (*38*). Studies in this region have revealed the detrimental impact of bottom trawling fisheries on the physical integrity of the seafloor, leading to a reduction in biodiversity and the absence of mega-epibenthic assemblages (*39*). We identified three Portuguese vessels that consistently fished within the high confidence zones of VMEs, demonstrating a fishing behavior similar to that observed before the closures were implemented. The main VME protection polygon affected was no. 13 on the West Iberian Shelf (Fig. 5A and fig. S1). One vessel even appeared to have increased its fishing effort in this polygon in the year following the closures. This VME protection polygon has encountered 1400 hours of bottom fishing effort in the 2-year period of our study, and the ongoing fishing activity indicates the fishery is not being managed to prevent SAIs as required by UNGA resolution 61/105. This pattern suggests potential challenges in the implementation of closures and monitoring of the fleet in Portugal. Other polygons in the Cantabrian Sea and Bay of Biscay overall experience low fishing effort by multiple vessels, mainly from Spain and France (Fig. 5A).

As part of the 2023 ICES advice data submission process, member states provided both new and updated VME records and VMS data (*34*). In response, ICES released five updated spatial management scenarios, which modified the VME protection polygons from the advice provided in 2021. These modifications encompass additions, expansions, and reductions in both the number and size of VME polygons. Our findings indicate that these additions and spatial extensions are subject to 6200 (scenario D) to 17,600 hours (scenario C) of fishing activity per year depending on the management scenario (Fig. 6). This fishing effort suggests that SAIs are occurring in the Cantabrian Sea in VME polygon 20 and its extended areas, in a new polygon in the Porcupine Bank, and in several new polygons in the Bay of Biscay. Further delays of closures in these areas, where VMEs are known or are likely to occur, imply that these fisheries are not being managed to prevent SAIs.

In the updated spatial management scenarios, several VME protection polygons could be reopened based on VMS data resubmitted by member states despite ICES's scientific recommendation to maintain closures until evidence confirms the absence of VMEs (*34*). The updated VMS data result in increased fishing intensity in certain areas above a threshold (swept area ratio > 0.43) that presumes that the fishing effort is evenly distributed and that the area is critically degraded, so future trawling will not induce further SAIs (*40*). However, areas with a high probability of VMEs, as identified by the VME index applied by ICES, can still contain intact VME patches even when fishing intensity exceeds the threshold, as documented by several studies in heavily fished regions (*41*–*43*). One of the areas that could be reopened is VME polygon 57 on the Porcupine Seabight, a nephrops fishing ground that experienced the highest fishing pressure of any VME protection polygon before closures and still experienced ca. 100 hours of fishing effort in the year following the closures (Fig. 4B). Within this area, fisheries surveys have recorded trawl marks in 38% of the surveyed stations in addition to four species of sea pens, a VME indicator taxa (*44*). In the same region, temporal studies provided evidence that bottom trawling reduced deep-sea sponge aggregations by an order of magnitude compared to the population in 1983–1984 (*45*). However, even in their degraded state, the sponge aggregations continued to have a positive impact on the diversity of the megafaunal assemblage (*45*). Furthermore, habitat patches that withstand bottom fishing play a crucial role in preserving local sources of recruits for repopulating affected areas; large species recover faster when conspecifics are abundant within a 6-km radius (*46*). Thus, any assumed absences of VMEs based on fishing intensity thresholds should be verified by visual surveys or high-resolution mapping to avoid compromising existing VMEs or their recovery potential.

Our calculations show that the closures are much smaller than publicly presented. We quantify that the actual area protected, where fisheries are being managed to prevent SAIs in EU waters, is 5553 km^2. This represents ca. 10% of EU waters within the 400- to 800-m depth range and ca. 1% of waters above 800 m. The current VME polygons are generally small and fragmented, with a few exceptions. This is because the closures are based predominantly on VME indicator taxa data collected during fisheries surveys and commercial fishing operations (*47*) as opposed to high-resolution mapping, habitat suitability, or species distribution modeling. It is well established that taxa collected by fishing gear do not accurately represent the community present and impacted on the seafloor, and thus, no true absence data can be obtained using bycatch data (*4*, *48*–*50*). Consequently, the distribution of VMEs in EU waters is likely underestimated (*51*).

This underestimation is further compounded by the fact that VME geophysical elements in EU waters, which are areas where VMEs are likely to occur, are only protected when states submit VME indicator records. Geophysical elements include seamounts, banks, coral mounds, mud volcanoes, and canyons. The exclusion of canyon complexes, particularly, which are abundant in both ecoregions, substantially reduces the area of the closures (*40*). While features such as seamounts are recognized as VMEs under UNGA resolutions (*4*, *52*), they are absent from the Deep-sea Access Regulation Annex III VME indicator species list. This list is limited to cold-water coral reefs and gardens, sponge aggregations, sea pen fields, tube-dwelling anemone patches, mud- and sand-emergent fauna, and bryozoan patches. If seamounts were included in the VME Indicator species list, then supplementing the ICES VME physical elements data layer with peer-reviewed seamount datasets (*53*–*55*) shows that up to 545 km^2 of seamount area within the 400- to 800-m depth range could be integrated into ICES spatial management scenario E, which incorporates VME geophysical elements into the closures. This would result in more comprehensive protection of VMEs in EU waters, ensuring closer alignment with the objectives and language of the UNGA resolutions.

Our data indicate that over a 2-year period, ca. 19,200 hours of fishing effort, occurred below 800 m. The 150 vessels in our dataset that fished below 800 m are exclusively equipped with bottom-trawling gear, according to the EU Fleet Register. Since 2017, the Deep-sea Access Regulation has prohibited bottom trawling below 800 m, stating that "no fishing authorisations shall be issued for the purpose of fishing with bottom trawls below 800 m depth" (*56*). This regulation intends to offer comprehensive protection to VMEs below 800 m against adverse impacts caused by bottom trawls, regardless of the status of these ecosystem in relation to VME criteria (*31*, *32*). However, the regulation includes a lesser-known caveat: If a vessel is not targeting any of the 46 deep-sea species listed in Annex I, then it is legal to bottom trawl below 800 m. A vessel is considered to be targeting deep-sea species if its catch reports for a given calendar year include "at least 8% of deep-sea species in any fishing trip" (*31*). In addition, trawling below 800 m is allowed for vessels whose overall catch of deep-sea species totals less than 10 metric tons in the calendar year concerned (*31*). Given that the primary trawling fleets involved are from Portugal, it is likely that these vessels are targeting crustaceans below 800 m (*55*). These fleets discard up to 70% of the total catch weight, with more than 140 different species recorded as bycatch (*57*). Overall, there is limited understanding of the impact these activities have on VMEs off Portugal at these depths raising concerns about SAIs on VMEs (*58*).

According to member states, no infringements have been detected regarding the 800-m bottom trawling ban, suggesting a high level of compliance with the regulation (*32*). However, a review of the regulation noted that vessels can operate up to three nautical miles at depths below 800 m and then move out again without detection (*32*). Moreover, the edges of the 800-m contour can be crossed without triggering detection by the fisheries monitoring centers of member states using VMS (*32*). To confirm whether our estimated trawling activity is authorized, we would need to cross-check the list of EU vessels with fishing authorization below 800 m in EU waters. Now, this can only be provided by each relevant member state (personal communication Directorate-General for Maritime Affairs and Fisheries). In contrast, there is a publicly available database of fishing authorizations issued to EU vessels fishing outside EU waters and for non-EU vessels fishing in EU waters. The lack of publicly available information on EU vessel authorizations constrains the monitoring of EU vessels' fishing activities within EU waters in relation to existing legislation and contributes to a discrepancy in the scrutiny of EU vessels compared to foreign vessels. Future work is required to identify the extent of potential infringements by bottom trawlers operating below 800 m across EU waters.

There are several limitations and caveats in our study. Our results provide conservative estimates for the apparent fishing effort given that a substantial portion of global industrial fishing activity, including operations within EU waters, remains absent from public monitoring systems (*59*). We excluded foreign vessels from our analysis because these vessels are not mandated to provide the same ancillary data on their gear as the EU fleet. We also applied a 500-m buffer to the VME polygons to avoid false positives using the GFW data. In our study, all vessels were assumed to exert equal fishing effort measured in hours. However, in practice, variations in vessel length and gear types result in notable differences in their impact on VMEs. The application of AIS to understand fishing effort implies that our analysis may underrepresent the fishing effort of small vessels because the EU does not require vessels under 15 m long to broadcast AIS. There are 48,609 vessels under 15 m in length with bottom contact gear in the EU fleet register from the member states discussed in this study. In the GFW database, vessels under 12 m represent less than 1% of the global fleet. The broadcast of AIS is variable, not every message is detected or recorded. In addition, areas with high vessel density can interfere with AIS broadcasts, and vessels can turn off their AIS system when engaging in illegal fishing. A small minority of vessels using prohibited bottom contact gear also had nonbottom gear on board and could potentially have been fishing with permitted gear within the VME polygons despite the GFW algorithm assignation of prohibited gear type. With these caveats in mind, our results provide an estimate of fishing effort. For a more detailed analysis of effort, member states can use VMS data with short time intervals alongside AIS data and logbooks to cross-check and monitor vessels and enforce the VME protection polygons.

In conclusion, our study shows a notable reduction in bottom-contact fishing within the 87 VME protection polygons. However, the continued presence of approximately 3500 hours of bottom fishing within VME protection polygons, alongside 17,600 hours of bottom-contact fishing in unprotected areas where VMEs are known or likely to occur and 19,200 hours of bottom trawling below 800 m in European waters, poses a serious risk of SAIs on VMEs. These findings highlight the urgent need for states to enhance surveillance and monitoring and for the European Commission to implement additional closures. These measures are essential for ensuring effective and comprehensive fisheries management that prevents SAIs on VMEs, halts and reverses biodiversity loss, and protects deep-sea ecosystems in EU waters, in accordance with UNGA resolutions.

MATERIALS AND METHODS

We utilized publicly available data from the GFW application programming interface (API v3) (*60*) to derive the "apparent fishing effort," hereafter simplified to "fishing effort," within the VME protection polygons located in the Celtic Seas, and the Bay of Biscay and Iberian Coast ecoregions at depths between 400 and 800 m and below 800 m (Fig. 1). Data were obtained and analyzed for the comparative period before the implementation of the closures from November 2021 to October 2022 and from November 2022 to October 2023 to understand the effect of the closures (data S1). We also obtained data for the newly proposed VME protection polygons based on the ICES advice in 2023 to identify potential areas where SAIs might continue to occur if the next round of closures is not implemented. We focused our examination of the ICES 2023 advice on the newly proposed VME protection polygons labeled spatial management scenarios C and D. Both scenarios prioritize protecting areas where VMEs occur or are likely to occur, but scenario C additionally protects areas with low fishing activity, while scenario D excludes intensely fished areas. We only obtained fishing effort data for the areas in each scenario not previously covered by a 2022 VME protection polygon.

GFW uses automatic identification system (AIS) transmissions to provide information on individual vessel behavior and algorithmically determines where along a vessel's track fishing occurs based on speed and changes in trajectory (*61*). We delineated the VME protection polygons from the coordinates specified in the VME implementing regulation Annex II (*33*) and calculated the spatial extent of each polygon occurring within 400- to 800-m depth from the EMODnet Bathymetry Digital Terrain Model 1/16 arc minute raster (https://emodnet.ec.europa.eu/en/bathymetry). To minimize false positives from fishing activity occurring along the boundaries of VME protection polygons, we took a conservative approach by only including fishing effort inset 500 m from the outer boundary of each VME protection polygon (Fig. 1). We also delineated a high-confidence zone within each inset VME protection polygon, where grid cells from GFW outputs were completely contained within the 400- to 800-m zone inside a VME polygon. These zones precisely align with the 0.01° square grid cells used in GFW outputs for its aggregate display of fishing effort. However, a limitation of the high confidence zones is evident in cases where certain VME polygons have a narrow 400- to 800-m depth band. (Fig. 1). Consequently, specific VME polygons may not feature any high-confidence zones, and thus, we obtained both the total fishing effort and the high-confidence fishing effort within the 400- to 800-m band in each VME.

We filtered the vessels equipped with bottom-contact gears for which GFW detected any fishing activity within 400- to 800-m inside VME areas. We acquired information on fishing gears from the EU Fleet Register (*62*) by matching the combination of maritime mobile service identity, International Maritime Organization number, call sign, and vessel name provided by GFW. Because gears assigned to each vessel in the EU Fleet Register can change over the study time period, we assigned bottom-contacting gears to individual daily fishing effort data points from GFW based on date ranges. In the case of the Spanish fleet, some vessels were missing from the EU Fleet Register, so we also accessed the Spanish National Fleet Register (*63*). On the basis of this information, we produced a final list of 467 vessels that had bottom trawls, bottom-set gillnets, bottom-set longlines, or pots and traps as their stated gear and quantified their fishing effort in hours within the VME protection polygons in waters between 400 and 800 m. When we found vessels with nonbottom contact subsidiary gear, such as drifting gillnets (data S1), we accepted the type of fishing activity assigned by GFW and looked at the fishing tracks. GFW does not currently distinguish between the tracks of bottom and mid-water trawlers. We identified 42 vessels utilizing bottom trawls as their primary gear and mid-water trawls as a subsidiary gear. Their combined fishing effort amounted to just 255 hours, which we consider negligible, and therefore, we assumed that these vessels were operating their main gear.

When analyzing fishing activity below 800 m in EU waters, we filtered the vessel list to include only the 150 vessels equipped solely with bottom-trawling gear (data S1), as there is no publicly available authorization list for vessels permitted to fish with bottom trawls below 800 m per Article 8 (*4*) of the Deep-sea Access Regulation (EU) 2016/2336.

To grasp the full extent of the closures, we quantified the total seabed area and the area of the closures within the 400- to 800-m depth band in EU waters.

The analysis was performed in R version 4.3.1 (*64*) using a customized library for accessing the GFW API v3 and the open-source R packages "sf" (*65*, *66*) and "tidyverse" (*67*). The complete code is available in an open-access digital repository (https://doi.org/10.5281/zenodo.13630299), and the data, including gear data, are available in the Supplementary Materials (data S1 and S2).

Supplementary Materials

The PDF file includes:

Figs. S1 to S4

Legends for data S1 and S2

Other Supplementary Material for this manuscript includes the following:

Data S1 and S2

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