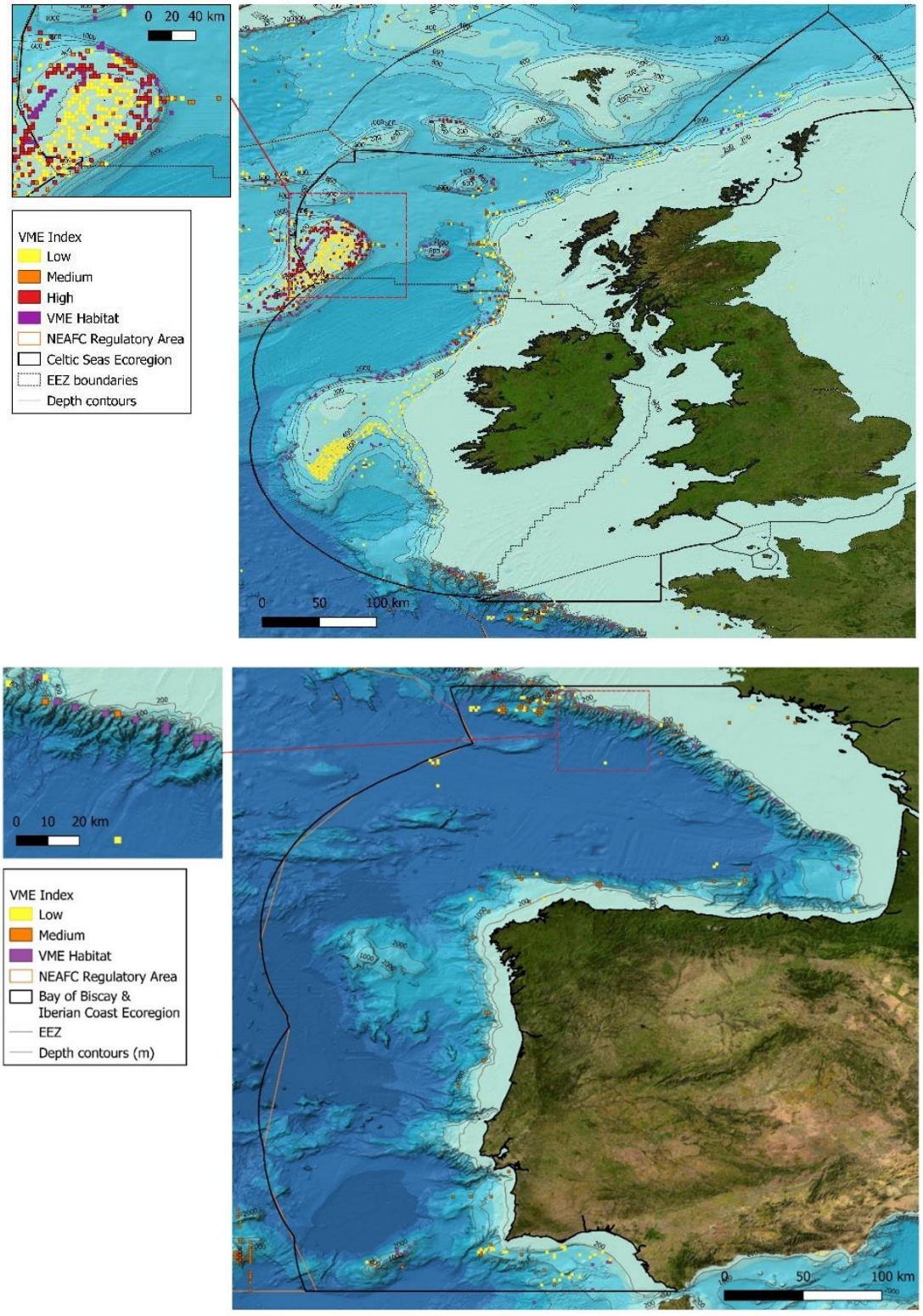
Supplementary Material for:

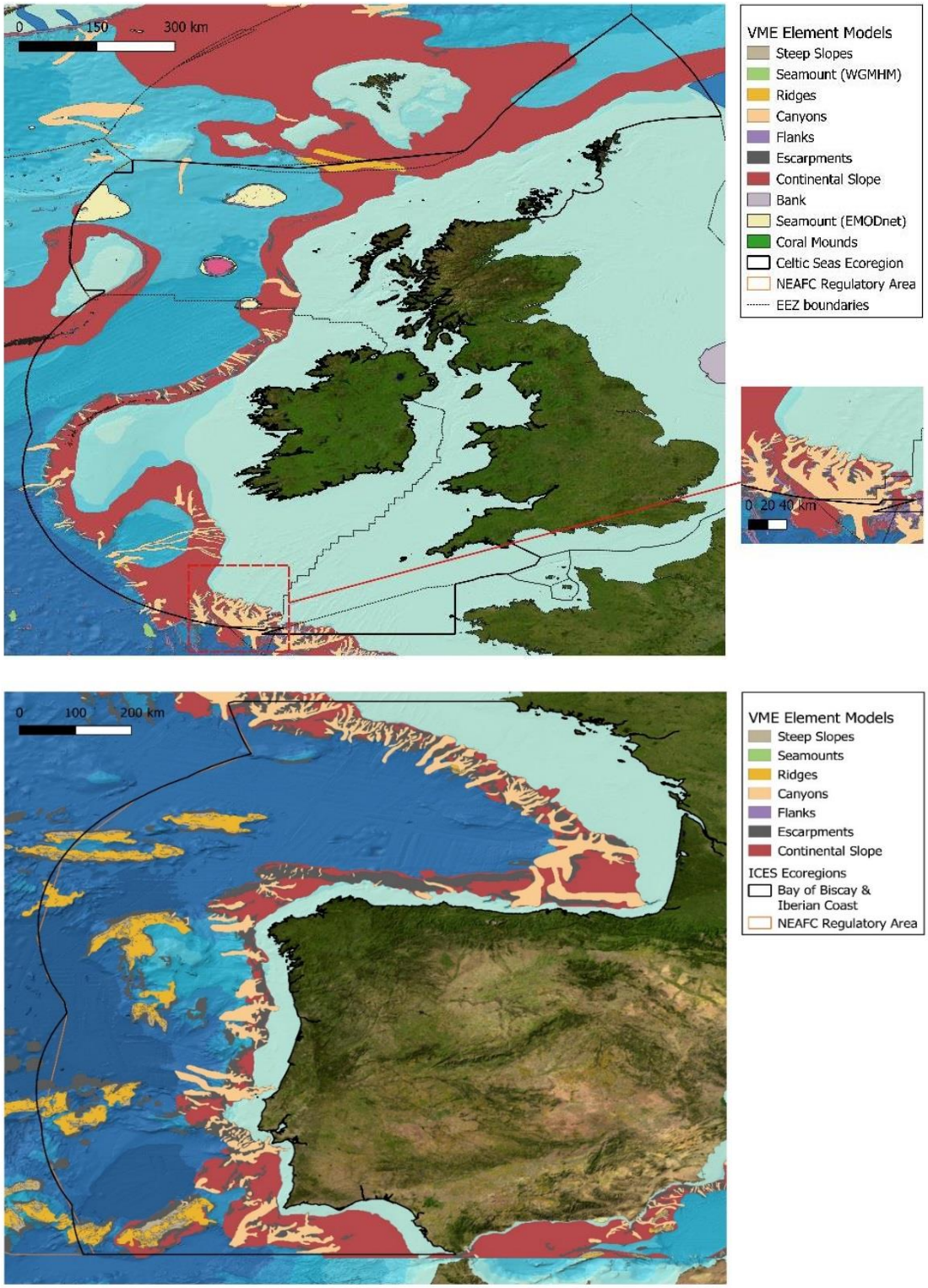
"A Policy-Based Framework for the Determination of Management Options to Protect Vulnerable Marine Ecosystems under the EU Deep-sea Fisheries Regulations"

This file includes:

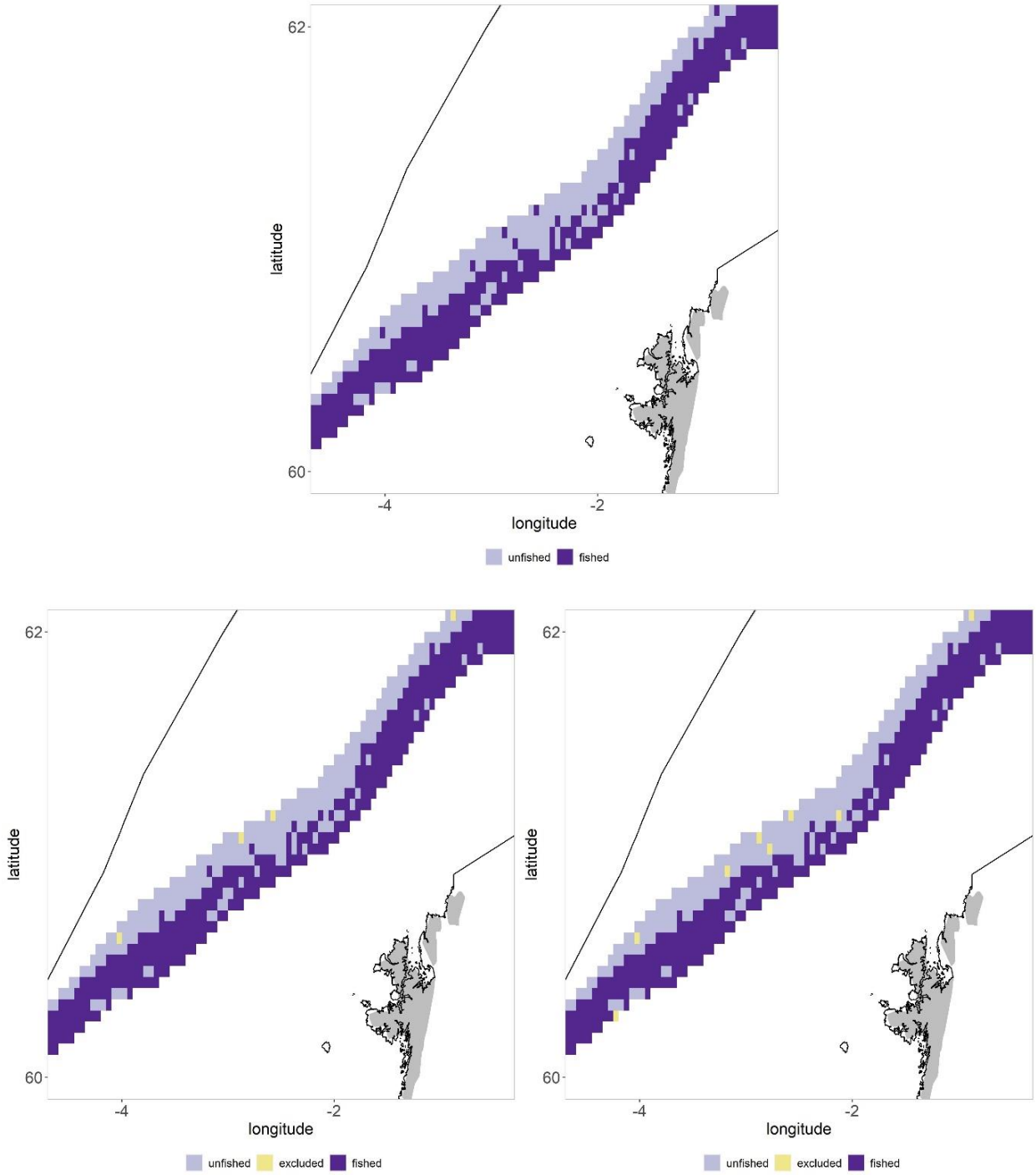
Supplementary Figures and Tables



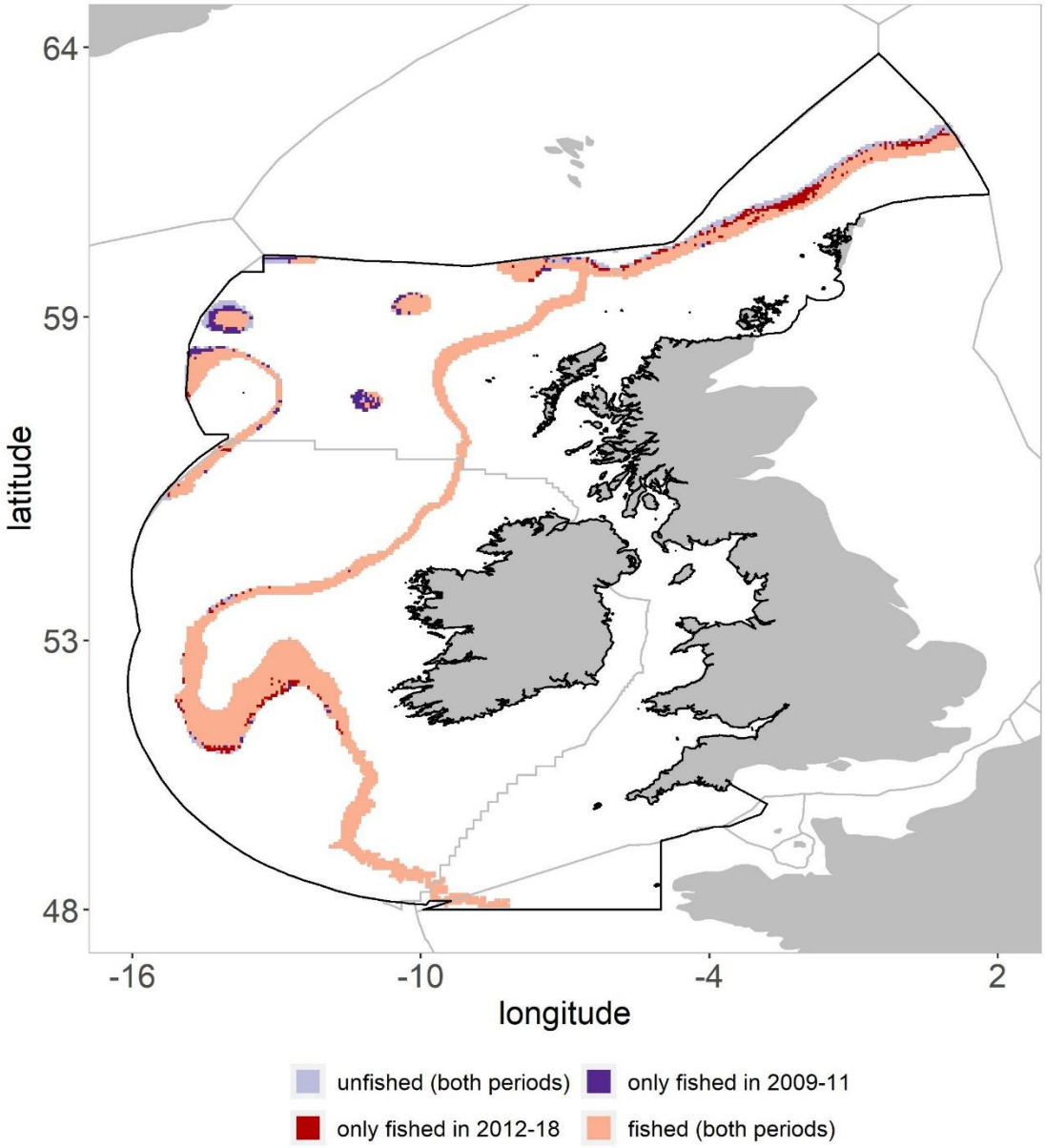
Supplementary Figure S1. Celtic Seas ecoregion (upper) and Bay of Biscay and the Iberian Coast ecoregion (lower), showing areas of known VME (VME Habitat) and High, Medium and Low VME Index, mapped at the scale of C-square grids. Insets show the North West Rockall Bank and the Northern Bay of Biscay respectively.



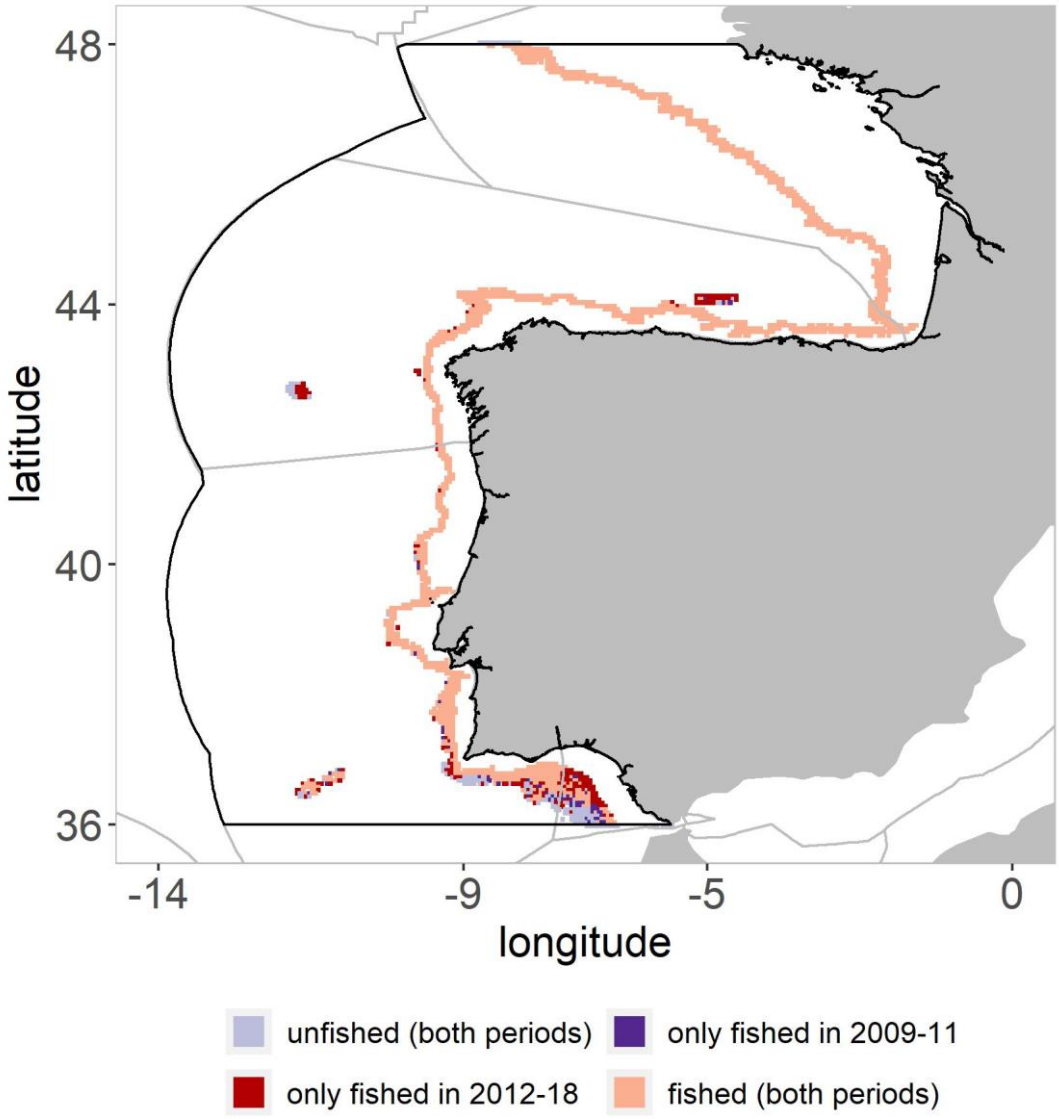
Supplementary Figure S2. Celtic Seas ecoregion (upper) and Bay of Biscay and the Iberian Coast ecoregion (lower), showing locations of VME elements based on models from Seafloor Geomorphic Features Map (see reference in main text) and EMODnet Geology. Note the coarse resolution of the canyon systems. The seafloor geology *(version of April 2019)* used in this map was made available by the EMODnet Geology project, http://www.emodnet-geology.eu funded by the European Commission Directorate General for Maritime Affairs and Fisheries.



Supplementary Figure S3. Illustration of differences between three scenarios as outlined in Supplementary Table 1. Top: Scenario 0 = Fishing footprint (mobile + static) between 400 m and 800 m depth in 2009-2011. Bottom Left: Scenario 2 = Fishing footprint (mobile + static) between 400 m and 800 m depth in 2009-2011 excluding C-squares with no shared vertices. Bottom Right: Scenario 3 = Fishing footprint (mobile + static) between 400 m and 800 m depth in 2009-2011 excluding C-squares that share vertices with less than two other C-squares.



Supplementary Figure S4. Difference in fishing occurrences in C-squares between the reference period (2009-2011) and the period 2012-2018 for the Celtic Seas ecoregion. Most C-squares are either fished or unfished in both of the two periods.



Supplementary Figure S5. Difference in fishing occurrences in C-squares in the Bay of Biscay and the Iberian Coast ecoregion between the fishing footprint of the reference period (2009-2011) and the period 2012-2018. Most C-squares are either unfished or fished in the two periods.

Supplementary Table S1. Proposed scenarios for defining the fishing footprint (presence/absence of mobile bottom contact gear and static gears) using the fishing activity data. Scenario 2 was used to assess fishing overlap with VMEs. See Supplementary Figure S3 for an illustration of these scenarios.

Scenario	Description	Rationale
Scenario 0	C-squares where there is fishing activity recorded during 2009-2011 in waters of European Union member states between 400-800m depth.	The "base case" scenario against which other options can be explored.
Scenario 1	All C-squares in waters of EU member states, bounded by the 400m and 800m isobaths, regardless of fishing activity in the 2009-11 period.	A simple bathymetric rule for establishing the footprint in management measures.
Scenario 2	C-squares as defined in Scenario 0, with a stipulation that to be included in the footprint, a cell must touch one other cell on an edge or vertex.	As for the base case, however "orphaned" C-squares which fall outside of contiguous areas are culled from the footprint.
Scenario 3	C-squares as defined in Scenario 0, with a stipulation that to be included in the footprint, a cell must touch two other cells on an edge or vertex.	As for Scenario 2, but creates smoother edges on the contiguous polygons.

Supplementary Text 1: Closure Scenarios and Options

Steps for Operationalizing Closure Scenarios and Options

Scenario 1: No Consideration of Fishing Pressure

Option 1 - Protection for VME Habitat and Medium and High VME Index C-squares

Step 1. Select all VME Habitat, and High and Medium VME Index C-squares and create a ½ C-square buffer around them (Figure S1). *These cells are known or likely to contain VMEs and the buffer zones account for the offset between vessel positions and the position of their gear, which can be substantial in deep water, and the effects of sediment resuspension, which can have detrimental effects on VMEs.*

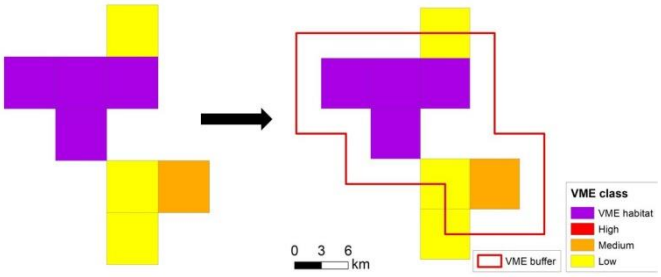


Figure S1. Scenario 1 Option 1, Step 1 illustrating the selection of C-squares and creation of buffer.

Step 2. Where Low VME Index C-squares are adjacent and joining any C-squares in Step 1, these should be selected and a ½ C-square buffer placed around the C-square (Figure S2). *These cells are considered more likely to contain VMEs than other low index cells by their proximity to higher index cells.*

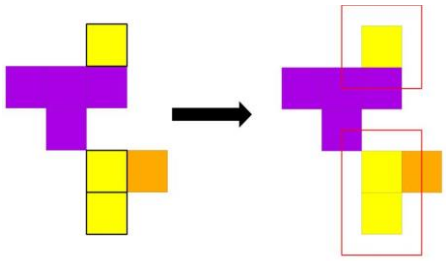


Figure S2. Scenario 1 Option 1, Step 2 illustrating inclusion of adjacent VME Index Low C-squares and associated buffers.

Step 3. Where two or more C-squares from Steps 1 and 2 are joined by their buffers or directly joined (in any way) they will be combined into one VME closure polygon (Figure S3). *This reduces the number of polygons in a data-layer but does not change the protected area.*

Figure S3. Scenario 1 Option 1, Step 3 illustrating the final VME closure polygon with buffers (red line).

Step 4. All satellite VME C-squares in Step 1 above should be defined as individual VME closures with associated ½ C-square buffer (Figure S4). *Many VMEs types can naturally consist of small patches of about one C-square in size or smaller.*

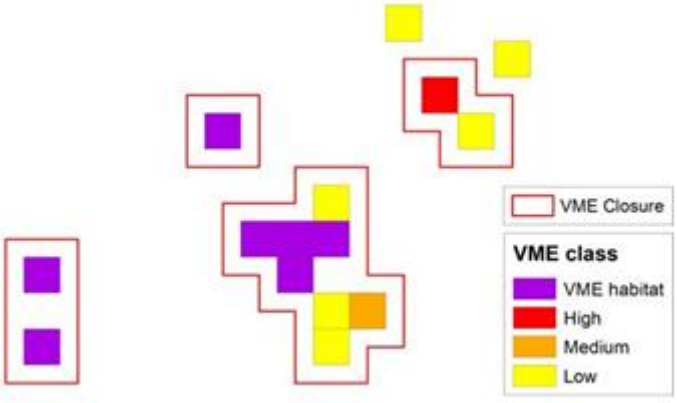


Figure S4. Scenario 1 Option 1, Step 4 illustrating the inclusion of isolated C-squares with buffers.

Step 5. Fill all holes with 1 or 2 C-squares inside VME closures (Figure S5). *Fishing vessels are unlikely to be able to fish effectively in very small areas without risking straying into closed areas. A trawler that fishes at 3.5 knots will cover 7nm in a typical 2h haul, which is equivalent to about between 2 and 3 C-squares. Open holes of less than 3 C-squares are therefore not considered practical.*

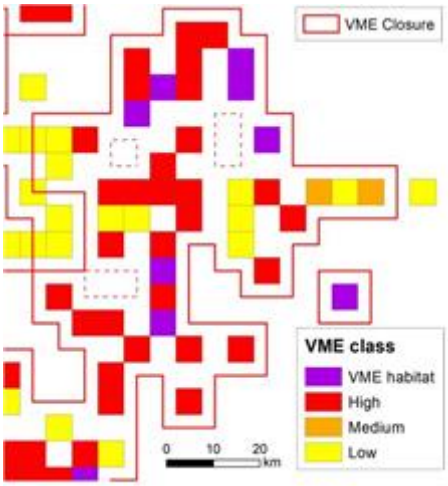


Figure S5. Scenario 1 Option 1, Step 5 illustrating the filling of holes (dashed lines) within the VME polygons

(dark red lines) produced from Steps 1-4.

Option 2 - Protection for VME Habitat, VME Index C-squares and VME Elements

Step 1. Select the VME elements (bank, coral mound, mud volcano, seamount) with an occurrence of a VME Habitat or VME Indicator (High, Medium and Low). VME elements are selected with the VME points (using middle point position) rather than the C-squares to avoid selecting elements that intersect with the buffer of a C-square but not with a VME record per se (Figure S6). *These four VME elements are known to be important drivers of VME presence, and when this is confirmed by the presence of VME indicators, it is likely that the whole element contains VMEs. The VME elements used for Scenario 1 option 2 were limited to topographic highs (seamounts, banks) as well as small elements spatially well constrained (coral mounds, mud volcanoes) in EMODnet. Other VME elements that were large and spatially not well constrained, such as steep slopes or canyon systems, were excluded because their spatial footprint was considered too large relative to the evidence of VME occurrences. Using the point data for the VMEs ensures that the VME element is associated with the VME record.*

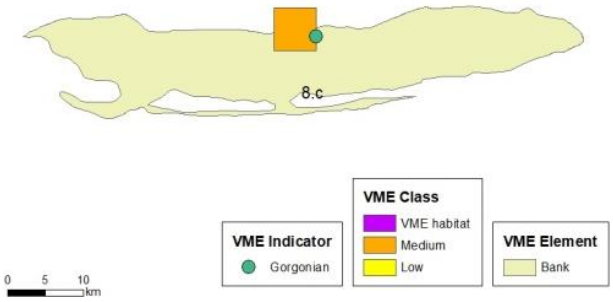


Figure S6. Scenario 1 Option 2, Step 1 illustrating the selection of VME elements (bank) with an occurrence of a VME Indicator (Medium).

Step 2. Clip the VME selected in Step 1 to the 400-800 m depth band.

Step 3. Select the C-squares overlapping with the VME elements selected in step 2 (Figure S7).

These three technical steps bring the VME elements which are most likely to contain VMEs into the closures. At the same time, VME elements for which there are no supporting evidence of VMEs are not included.

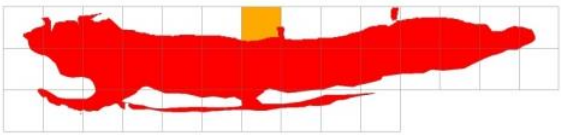


Figure S7. Scenario 1 Option 2, Step 3 illustrating the selection of the C-squares overlapping with the VME elements selected in step 2.

Step 4. Remove the C-square buffer from Scenario 1 Option 1 that intersects with VME elements but does not overlap with the C-squares selected in Step 3 above, and include all C-squares that overlap with the VME element (Figure S8). *The VME elements were not buffered. This is because the areas with VME elements are generally large and only C-squares along the periphery of the VME elements would potentially be subject to direct or indirect effects of bottom contact fishing. Retaining a buffer such as the hatched area in Figure S13 would create buffers only where the VME data happen to overlap with the VME element.*

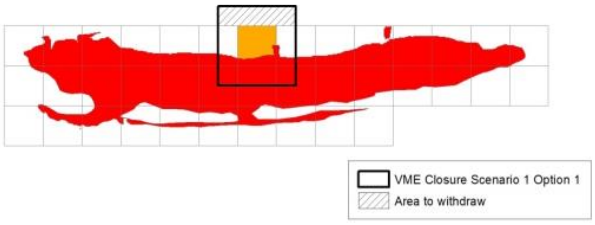


Figure S8. Scenario 1 Option 2, Step 4 illustrating the C-squares and its buffer from Scenario 1 Option 1 that intersect with the VME element (orange C-square with black surrounding buffer). In Step 4 the buffer (hatched area above the C-square) is removed.

Step 5. Merge Step 4 above with Scenario 1 Option 1. *This captures areas where VMEs are known or likely to occur (Figure S9). There may still be an under-representation of sea pen VMEs in this option.*

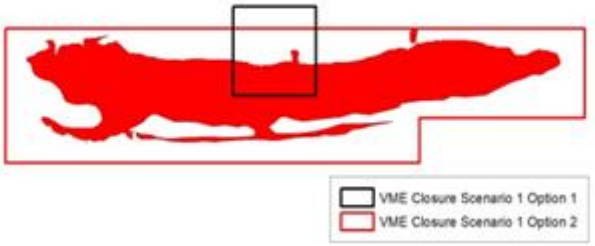


Figure S9. Scenario 1 Option 2, illustrating the difference between Scenario 1 Option 1 that does not include the VME element (black line) and Scenario 1 Option 2 that includes the VME element (red line).

Scenario 2: Consideration of Fishing Pressure

Option 1 - Protection for VME Habitat, Medium and High VME Index C-squares (irrespective of fishing effort) and only Low VME Index C-squares which coincide with Low Fishing Effort

Step 1. Select all VME Habitat, High and Medium VME Index C-squares and create a ½ C-square buffer around them (Figure S1). *These cells are known or likely to contain VMEs and the buffer zones account for the offset between vessel positions and the position of their gear, which can be substantial in deep water, and the effects of sediment resuspension, which can have detrimental effects on VMEs. This selection is the same as in Scenario 1 option 1 Step 1.*

Step 2. Select all Low VME Index C-squares which have a SAR < 0.43 and add a ½ C-square buffer to them (Figure S10). *Because they are fished at intensities that allow persistence of VME types, and because they are less important for fishing, it can be worthwhile closing these C-squares even if the presence of VMEs is uncertain. Due to the bias in the VME Index against sea pens in particular this will ensure that more sea pen habitat is protected.*

Step 3. Where Low VME Index C-squares are adjacent and joining any C-squares in Steps 1 and 2, these should be selected and a ½ C-square buffer placed around the C-square (Figure S10). *These cells are considered more likely to contain VMEs than other Low VME Index cells by their proximity to higher VME Index cells.*

Step 4. Where two or more C-squares from Steps 1, 2 and 3 are joined by their buffers or directly joined (in any way) they will be combined into one VME closure polygon (Figure S10). *This reduces the number of polygons in a data-layer but does not change the number of C-squares in the protected area.*

Step 5. All satellite VME C-squares in Steps 1 and 2 above should be defined as individual VME closures with associated ½ C-square buffer. *Many VME habitats naturally occur at the size of a C-square or smaller. These single C-squares can still offer meaningful protection.*

Step 6. Fill all holes with 1 or 2 C-squares inside VME closures. *Fishing vessels are unlikely to be able to fish effectively in very small areas without risking straying into closed areas. A trawler that fishes at 3.5 knots will cover 7nm in a typical 2h haul, which is equivalent to about between 2 and 3 C-squares. Open holes of less than 3 C-squares are therefore not considered practical.*

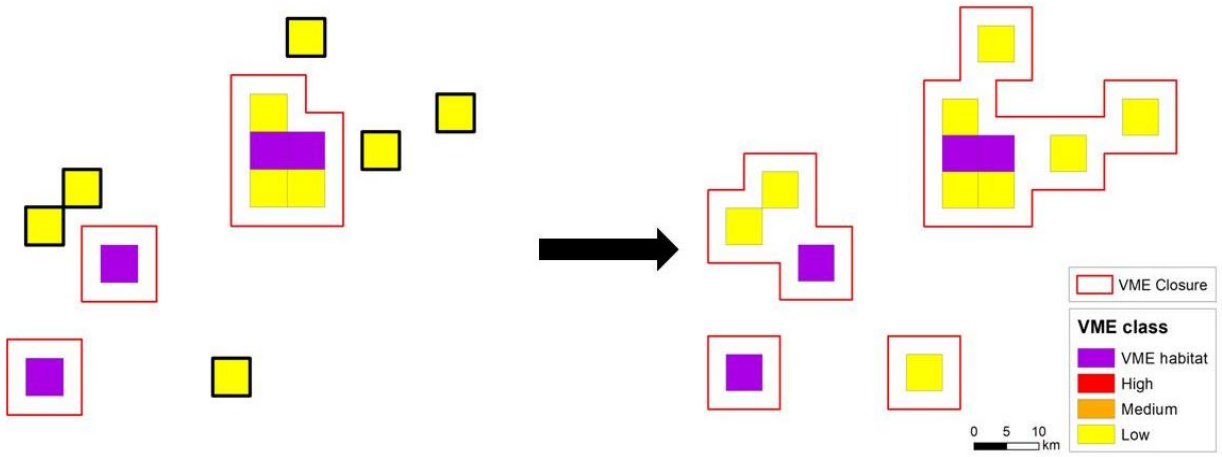


Figure S10. Scenario 2 Option 1, Steps 2 to 4 illustrating the inclusion of Low VME Index C-squares with fishing effort less than 0.43 SAR (yellow outlined in black on left panel).

Option 2 - Protection for all VME Habitat, and Low, Medium and High VME Index C-squares but only in Areas of Low Fishing Effort.

Step 1. Determine the 'core' area of fishing activity which is at or above the SAR VME impact threshold (> 0.43 SAR) as determined for the least sensitive VME indicators species (sea pens) following NAFO methodology (NAFO, 2016). *This area corresponds to a sufficiently high level of fishing activity where effectively the risk of future or new VME impact is low because persistence of VMEs is unlikely due to their vulnerability. The defined area essentially represents an area of 'low risk of further VME fishing impact'.*

Step 2. Select all VME C-squares (Habitat, and High, Medium and Low VME Index) which do not overlap with the 'low risk of further VME fishing impact' or 'core' fishing area as defined in Step 1 above, and create a ½ C-square buffer around them (Figure S11). *These are the VME C-squares which are more likely to have VME present on account of being subject to only low or no fishing pressure.*

Step 3. Where two or more C-squares from Step 2 above are joined by their buffers or directly joined (in any way) they will be combined into one VME closure polygon. *This is because they are likely to form the same VME type.*

Step 4. All satellite VME C-squares in Step 2 above should be defined as individual VME closures with associated ½ C-square buffer. *Many VME habitats naturally occur at the size of a C-square or smaller. These single C-squares can still offer meaningful protection.*

Step 5. Fill all holes with 1 or 2 C-squares inside VME closures. *Fishing vessels are unlikely to be able to fish effectively in very small areas without risking straying into closed areas. A trawler that fishes at 3.5 knots will cover 7nm in a typical 2h haul, which is equivalent to about between 2 and 3 C-squares. Open holes of less than 3 C-squares are therefore not considered practical.*

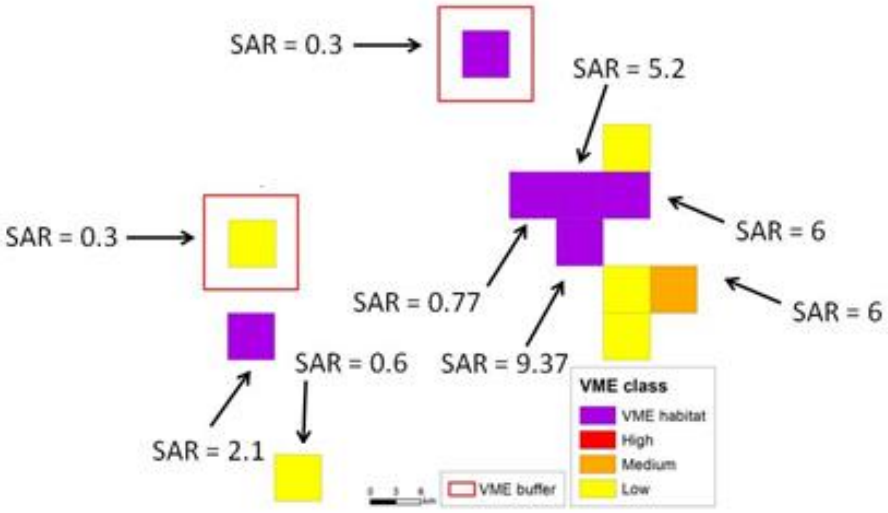


Figure S11. Scenario 2 Option 2, Step 2 illustrating the exclusion of C-squares with VME Habitats and VME Index (Low, Medium or High) when fishing effort is > 0.43 SAR, and the application of the buffer (red lines). In this example only two C-squares have fishing effort < 0.43 SAR, one with VME habitat and one with a Low VME Index.