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Footprint of the patagonian scallop bottom trawl fishery on the argentine shelf between 2012 and 2021

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Informe

FOOTPRINT OF THE PATAGONIAN SCALLOP BOTTOM TRAWL FISHERY ON THE ARGENTINE SHELF BETWEEN 2012 AND 2021

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RESUMEN. Superficie barrida por la pesquería de vieira patagónica entre 2012 y 2021. Los ecosistemas marinos están siendo afectados por las actividades humanas, principalmente a través del cambio climático y la pesca. En este contexto hay un interés creciente por cuantificar y entender los impactos de la pesca sobre estos ecosistemas, particularmente de la pesca de arrastre sobre los hábitats del fondo marino. Para entender los efectos de las pesquerías de arrastre de fondo sobre los ecosistemas marinos es necesario conocer (entre otros factores) la frecuencia y distribución geográfica de los arrastres. La pesquería de la vieira patagónica (*Zygochlamys patagonica*) cuenta con información precisa de posicionamiento de cada uno de sus lances comerciales. En este informe se realiza un análisis exploratorio de la distribución espacial y temporal de los lances de pesca de la última década. Los resultados mostraron que anualmente se barre una proporción ínfima de la plataforma continental argentina e incluso de las unidades de manejo de la pesquería. Si bien no hubo tiempo para cuantificar en detalle las superposiciones de lances, los análisis para la unidad de manejo más barrida, así como resultados previos, sugieren que año a año se van rotando las áreas más barridas, con una proporción de re-visitas a áreas previamente barridas baja. Estos resultados coinciden con estudios globales (basados en información menos precisa) que muestran un uso relativamente bajo del área.

ABSTRACT. Marine ecosystems are being affected by human activities, mainly through climate change and fishing. In this context there is a growing interest in quantifying and understanding the impacts of fishing on these ecosystems, particularly through bottom trawling. To understand the effects of bottom trawl fisheries on marine ecosystems it is necessary to know (among other factors) the frequency and geographic distribution of trawling. The Patagonian scallop (*Zygochlamys patagonica*) fishery has precise positioning information for each of its commercial trawls. In this report, I perform an exploratory analysis of the spatial and temporal distribution of fishing trawls during the last decade. The results showed that a tiny proportion of the Argentine continental shelf and even of the fishery management units are swept annually. Although there was no time to quantify in detail the overlapping sets, the analyses for the most swept management unit, as well as previous results, suggest that the most swept areas are rotated from year to year, with a low proportion of revisits to previously swept areas. These results coincide with global studies (based on less precise information) that show a relatively low use of the area.

Palabras clave: solapamiento de lances, superficie barrida, unidades de manejo, vieira patagónica, *Zygochlamys patagonica*.
Key words: tow overlap, trawled surface, management units, Patagonian scallop, *Zygochlamys patagonica*.

INTRODUCTION

Human footprint on marine ecosystems began centuries ago (Brander et al. 2010) and is still increasing (Halpern et al. 2015) mainly due to climate change and fishing (Halpern et al. 2008, 2015). Particularly the concern regarding potential impacts of fishing began centuries ago and has grown since then (Jennings and Kaiser 1998). One key aspect that has been concentrating attention is the impact on non-target benthic species, and thus, the activities of bottom-trawl fisheries (Kaiser et al. 2002; Thrush and Dayton 2002; Eigaard et al. 2017; Pitcher et al. 2022). In an attempt to address these issues, the US National Research Council (2002) identified three categories of information needed for a complete assessment of the ecosystem effects of trawling, including: (a) effects of specific trawling techniques on different habitats (obtained experimentally), (b) physical and biological characteristics of the seabed in the fishing areas (i.e., seabed mapping), and (c) frequency and geographic distribution of bottom trawling. Regarding this last point, the use of information produced by vessel monitoring systems generated an invaluable and enormous amount of data that allow estimating fishing effort around the Earth (e.g. Global Fishing Watch). However, these data are relatively coarse-grained, while high-precision data remain scarce, and thus the available data suffer from limitations in their spatial resolution (US National Research Council 2002). As the spatial resolution decreases, the area in which the trawls are clustered increases, which generally leads to overestimates of the swept area. For example, depending on the clustering grain used, estimates of the area trawled by five bottom fisheries in the Argentine Sea range from 14.2 to 45.3 $\geq$ 50% (Amoroso et al. 2018).

Considering the above scenario along with the need for high precision fishing information, the Patagonian scallop's fishery can provide unique data to analyze the spatial distribution of fishing effort as well as return intervals. This fishery has accurate information for each fishing trawl from each vessel, including (but not limited to) initial position, final position, date, time, duration of trawl and nets used. Therefore, below I analyze the spatial distribution of *Zygochlamys patagonica* fishing hauls from a resource (i.e. total area trawled, without considering possible overlaps between trawls) and habitat (i.e. area swept from the seabed, discounting overlap) point of view for the 2012-2021 decade.

METHODS

I conducted all analyses using the information that each vessel's captain records for each fishing set (see above). For the analyses described below, I focused on those tows that took place between 2012 and 2021 both inclusive. Although previous year's information is available, it still needs to be checked for inconsistencies, cleaned and incorporated to the database (see "Bases de datos de la pesquería de vieira patagónica: estructura, limitaciones y prestaciones"). All functions, packages and analyses described below were performed using R (R Core Team 2022).

The basic procedure to estimate the area swept by each tow was performed as follows:

1. The initial and final position of each tow were connected with a straight line (*sf_linestring* function from package *sfheaders*; Cooley 2020).
2. As that line marks the vessel's fishing path, the line was displaced 10.5 m starboard and/or port depending on the net/s used (parallel to the first line; the precise distance displaced varied depending on vessel's structure; custom function, see here).
3. If both nets were used, one of the two nets was extended 30 m in length at both the beginning and the end of the tow (custom functions; see here).
4. Swept area was estimated calculating a 7 m buffer for each line belonging to each tow to represent the 14 m opening of the nets (*buffer* function from the *terra* package; Hijmans 2022).
5. Each tow was assigned to a management unit (or outside management units) using the *st_intersects* function based on the centroid position of each tow (*st_centroid* function; both from the *sf* package; Pebesma 2018).
6. The area of each tow was calculated using the *st_area* function from the *sf* package.

Based on this information, I performed several calculations. First, I evaluated the cumulative swept area per calendar year without considering overlaps between tows. This is related to fishing effort but likely overestimates the impact on the seabed surface. If two tows close in time sweep the same area, they likely affect less the seabed surface that if those two tows occurred in different locations (i.e. a larger seabed area remains undisturbed in the first scenario). To make this more informative, those areas are expressed as a percentage of the (1) Argentine continental shelf (i.e. 1'530'000 km^2; Koutoudjian 2011), (2) overall management units' area, and (3) most frequently used management units' area (i.e. all except "1", "H", "I" and "J"). Management units "H", "I" and "J" are relatively large and were barely fished, and management unit "1" is quite new and was not wished before 2019.

Afterwards, I analyzed the temporal and spatial distribution of fishing tows. To achieve this, I summed the area of all tows occurring within a calendar year and a given management unit. Then, the area of those tows was expressed as a percentage in relation to the corresponding management unit's area. Again, spatial overlap was not taken into account.

To have a visual overview of the locations where fishing tows occurred, I created an animation for each management unit. These animations were created using the packages *ggplot2* (Wickham 2016), *gganimate* (Pedersen and Robinson 2022) and *cowplot* (Wilke 2020), and were then integrated into a web page using *shiny* (Chang et al. 2022).

From a seabed's perspective, the preceding analyses can be overestimating the amount of surface disturbed by fishing tows, given that each tow not necessarily occurs in a previously undisturbed area (see APPENDIX, **Fig**. A1 for an extreme overlapping situation). Thus, I quantified the percentage of each management unit's area swept across all years. I made this calculation not considering tow overlap (as above) and also considering annual overlap (i.e. seabed perspective). To achieve the latter, I aggregated all fishing polygons occurring within management unit F, and then calculated the area of the resulting geometry using *st_union* and *st_area* functions from the *sf* package.

Finally, and only for management unit F (the one with the largest proportion of its area swept, either considering tow overlap or not) due to time and computer limitations, I calculated the amount of tow overlap occurring within a calendar year. Thus, I calculated seabed surface swept per management unit by joining all tows within each management unit, and then calculating the overall area (*st_union* and *st_area* functions from the *sf* package). APPENDIX, **Fig**. A2 shows an example of how the unified area swept during a given year looks like, as well as how I quantified the undisturbed (i.e. not towed area). This analysis gives and idea whether most tow overlaps occur over short or long time frames. For a more in-depth analysis see "Esfuerzo pesquero: análisis espacial de la pesquería de vieira patagónica entre 2012 y 2019".

RESULTS

Cumulative fishing area per year

After summing per year the area of all individual tows that took place between 2012 and 2021, it became evident that a tiny proportion of the seabed is swept by the Patagonian scallop fishery each year (always less than 0.15 %). Moreover, it is even a small fraction of all management unit's area (<1 %). If only the area of most actively used management units was considered, the total swept area never exceeded 3.3 %. All these estimations (see **Fig**. 1) are conservative, as there is some overlap between tows (see below), which obviously leads to a higher proportion of the seabed undisturbed.

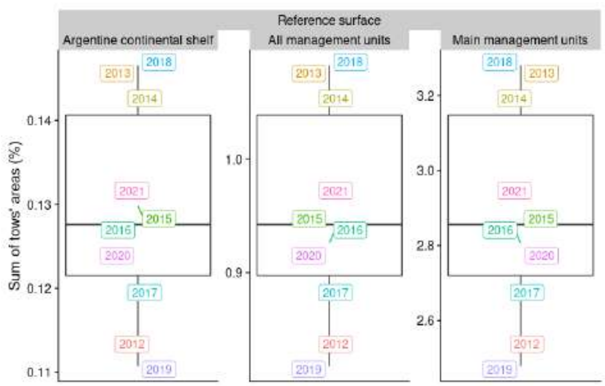

Fig. 1. Box-plots showing total area swept annually by the fleet as a percentage of the Argentine continental shelf, the area of all management units and only those management units that are frequently visited by fishing vessels. The box represents data values between percentiles 25 and 75, whiskers highlight min and max values and the horizontal lines represents the median value. Each data point represents the area fished in a different year (highlighted with colored labels).

Temporal variation in fishing effort

When the area swept was expressed as the percentage of each corresponding management unit, some interesting patterns emerged. The highest value (13 %) occurred on management unit E during 2014, with values above 10 % also in management units 1 (2020), D (2012) and F (2013). Interestingly, peaks in the remaining management units also occurred in distinct years (B: 2017, C: 2019, G: 2015; **Fig**. 2).

Although some fishing occurred outside management units, so far not considered in this subsection, it was a relatively minor proportion. On average, 7.7 % of the swept area occurred outside management units, ranging between 0 % during 2016 and 2017, to a maximum 19 % during 2021 (see APPENDIX, **Fig**. A3).

Considering overlap between tows

First, I created an animation to show the temporal variation on the spatial distribution of tows along the most important management units. The animation can be found here, and it reveals that year after year, there is a clear movement of the areas most intensively fished.

However, although visual representations are great tools to have an idea of the general patterns, they are not enough to make conclusive statements. Thus, I calculated the total seabed surface towed per management unit not considering tow's overlap (as I have reported so far), and also taking account that some tows could have swept areas that were already swept by previous tows. As expected, for all management units, seabed's area swept considering overlaps between tows was smaller that the arithmetic sum of all tows' areas (**Fig**. 3). Mostly fished management units exhibited nearly 45 % overlap along the 2012-2021 decade, ranging between 60.9 % (management unit F) and 24.1 % overlap (management unit A). Indeed, after accounting for the spatial overlap between tows, only two management units (E and F) exhibited swept areas >20 %, being 23.3 % the maximum value.

From the seabed point of view, a higher overlap between tows implies that a larger proportion remains undisturbed, but at the same time it could imply frequent disturbances on fished areas. However, the analysis for management unit F (the one with the largest amount of overlapping areas) reveals that 62.2 % of the overlapped surface occurred within a calendar year (i.e. the overlapped area during 2012 + the overlapped area during 2013 + ... + the overlapped area during 2021). This analysis likely underestimates overlap within a one year time frame, given that for example, it is leaving out overlaps taking place between December of a given year and January of the following year (several fishing trips occurred between two calendar years). Due to time and computer limitations it was not possible to extend this analysis to other management units or across different time frames. However, a previous report ("Esfuerzo pesquero: análisis espacial de la pesquería de vieira patagónica entre 2012 y 2019") analyzing the temporal pattern of overlapped fishing tows' areas revealed that the pattern described above holds for all the main management units; most overlaps occur within the same year, with relatively few overlaps taking place in longer time frames (i.e. not frequent disturbances on the same areas).

DISCUSSION

The results shown here illustrate that only a minor proportion of seabed is swept annually while fishing Patagonian scallops. The great majority of fishing tows occurred within management units, with relatively constant overall fishing effort (estimated as the total area of all tows of a given year) but with strong spatial variability in locations across time (i.e. the most fished management unit differs between years, as well as the location of tows within a given management unit). Finally, after accounting for overlaps between tows (that mainly occur within a given year), it emerges that on average 15 % of each management unit's surface was swept during the last decade.

There is a great concern on how bottom trawl fisheries could be affecting benthic ecosystems (Thrush and Dayton 2002; Pitcher et al. 2022). Estimations of trawling footprint on the continental shelves worldwide reveal large

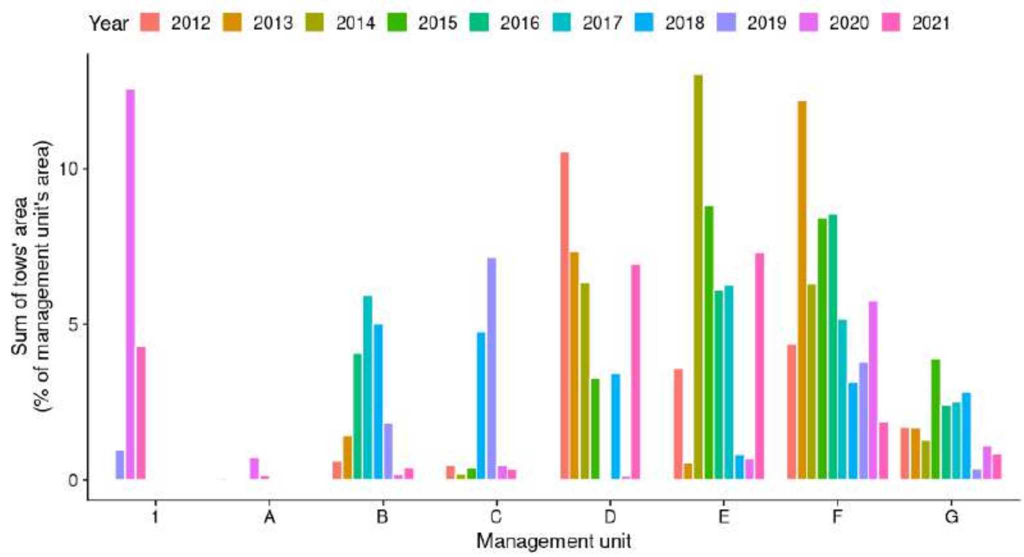

Fig. 2. Sum of all tows' areas aggregated by management unit and year, and expressed as a percentage of the corresponding management unit.

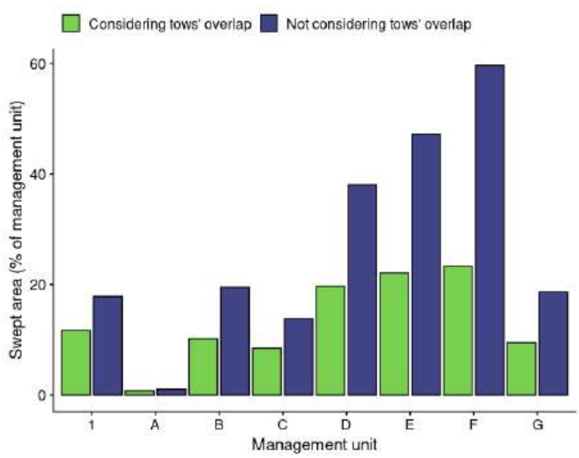

Fig. 3. Seabed's area swept between 2012 and 2021, considering and not considering overlap between tows, as a percentage of the corresponding management unit's area. Some management units are not shown because the swept areas were negligible.

differences between regions, with the Argentine shelf far less impacted than some regions of Europe, but certainly most impacted than other regions such as Australia or southern Chile (Amoroso et al. 2018; Pitcher et al. 2022). Due to the worldwide extension and the limitations of available data, those studies were based on the information from vessel monitoring systems which. Here I explored an extremely rare dataset with high precision information for the entire set of tows from the whole Patagonian scallop's fishery fleet, which allowed very accurate estimations. In any case, these or previously cited estimations (for all bottom trawl fisheries) suggest a relatively low use of the continental shelf.

The relatively low overlap between tows occurring in different years can be explained by different factors. Several forces, mainly oceanographic, determine where the highest abundances can be found (Orensanz et al. 2006). Particularly, Patagonian scallop aggregations are associated to frontal systems (Bogazzi et al. 2005), and indeed the width of these aggregations matches the seasonal variability in front position (Mauna et al. 2008). However, irregular stocks (see Caddy and Gulland 1983), as it was argued to be the case for the Patagonian scallop ((Campodónico et al. 2019), are characterized by sporadic events of massive recruitment that can extend the population into *a priori* suboptimal areas (Caddy 1989). Thus, either unexpected changes in the front location, atypical events of successful recruitment or a combination of both could lead to varying local high densities. This could explain, for example, why high densities appeared on management unit 1 (leading to the creation of this management unit). In addition to these potential oceanographic drivers that could explain varying high-density patches of scallops, management decisions might also play an important role by banning different areas along the years (see resolutions here, and the previous report "Evolución temporal de la producción de callo de la vieira patagónica ponderada por el esfuerzo pesquero" for a map until 2019). When considering only overlapped tows, it is interesting that most of it occurs within the same year. Although a different and more in-depth analysis would be needed to make more conclusive statements, one possibility could be that net efficiency is relatively low and thus it is necessary to sweep the surface a couple of times to catch most of the scallops.

This spatially explicit approximation identifying tows' overlapping areas has been proven to be useful for different applications that extend beyond the analyses performed here. For example, the explicit distribution of fishing tows was used to quantify gear efficiency and even stock assessment models (Rago et al. 2006; Northeast Fisheries Science Center 2010; Hennen et al. 2012; Poussard et al. 2021). Hopefully, the growing possibilities of obtaining and storing high precision data, along with the increasing tendency to make data publicly available (Weerakkody et al. 2017; SEDIA 2021), will soon contribute to a better understanding of the fishing impacts on seabed ecosystems, and also to feed decision making, ultimately contributing to the sustainable use of marine resources.

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APPENDIX

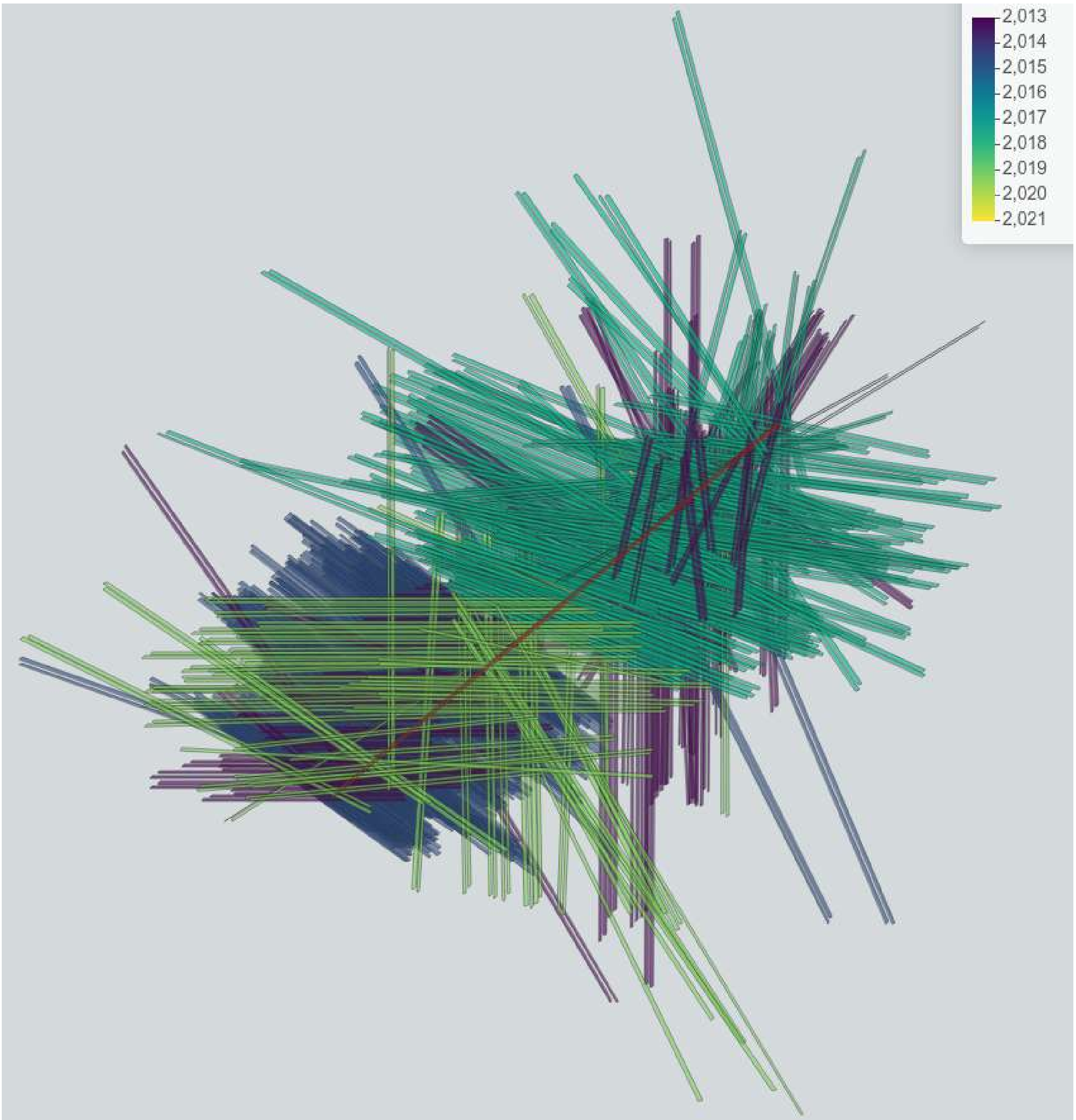

Fig. A1. One particular tow (in red) from 2021, with all its overlapping tows (shown in different colors representing different years). This figure represents an extreme overlapping situation. Note that the different widths of fishing tows are the result of rendering glitches rather than true differences in width or erroneous calculations.

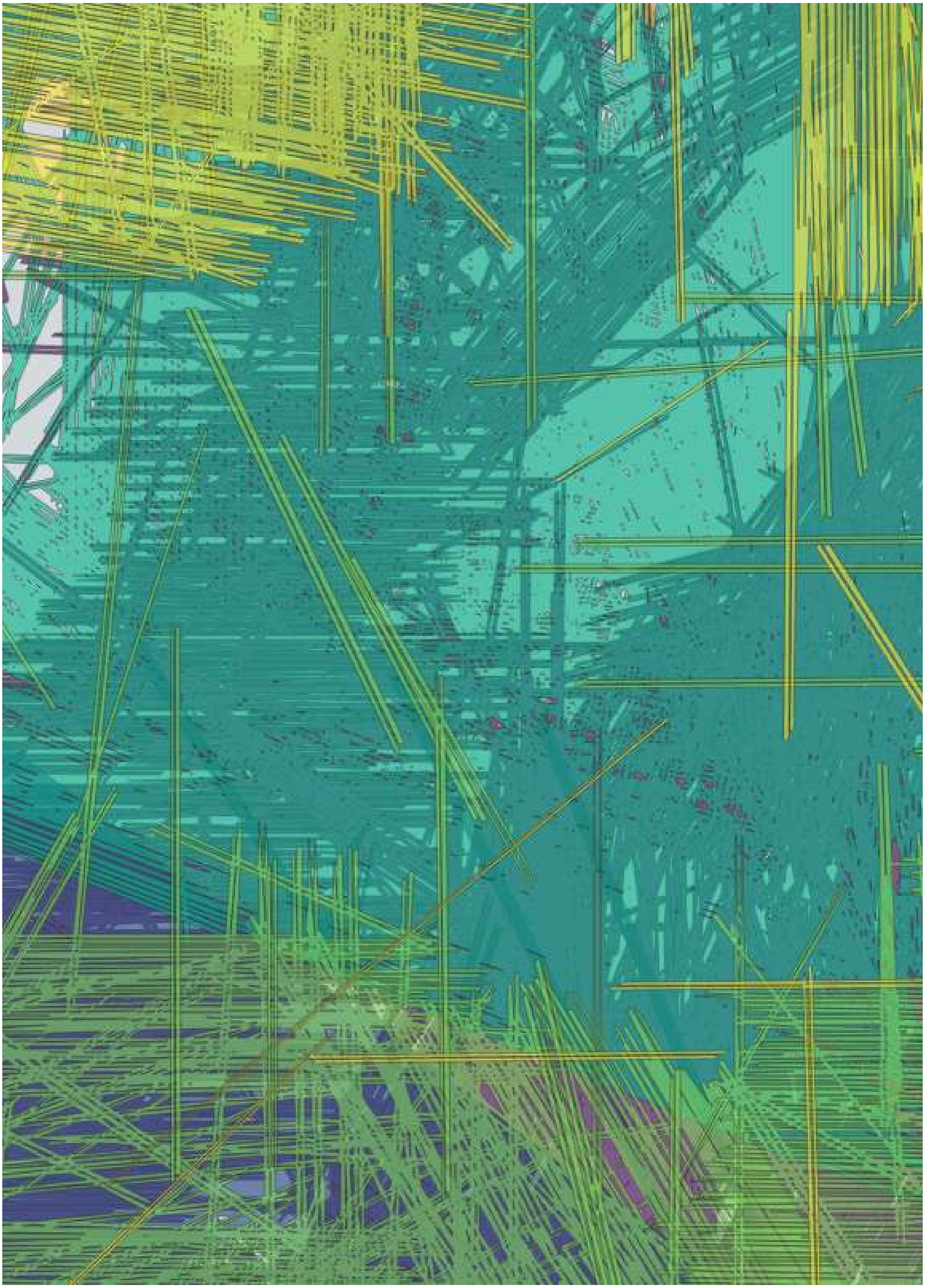

Fig. A2. The area represents a 0.1 x 0.1 degrees area with intensive fishing in management unit F to illustrate how tows were grouped within a given year (different colors represent different years). The gray areas between colored polygons represents the seabed surface that was not fished between 2012 and 2021. This is one of the most intensively fished areas during the studied decade.

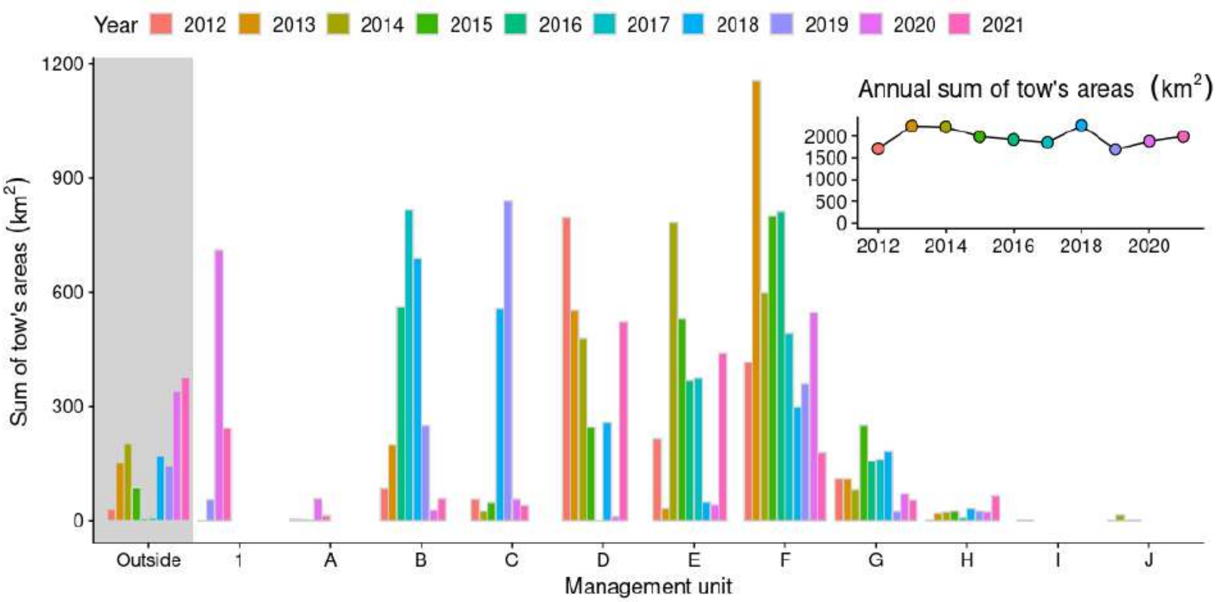

Fig. A3. The main panel shows the sum of all tow's areas aggregated by management unit and year. Swept areas are expressed as a percentage of the corresponding management unit's area. The inset shows the annual sum of all tow's areas.