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FISH and FISHERIES WILEY

Toward a better use of fisheries data in spatial planning

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Abstract

In the search for protecting biodiversity, enhancing sustainable resource use, and minimizing conflict among users, spatial planning is now ubiquitous around the globe. Acquiring maps of fishing activity is critical to account for the interests of fishers, but fisheries are generally underrepresented in spatial plans. We conducted a quantitative systematic literature review on how fisheries data have been included in spatial planning. 145 research articles were reviewed. Most studies (99%) assessed marine ecosystems. A kaleidoscope of data sources has been used to map fisheries, from vessel tracking data (11%) to surrogates (17%). Most articles (43%) have focused on mapping fishing effort, but other variables might be more relevant for spatial planning. Stakeholder groups are generally aggregated together (84%), but to achieve socially equitable outcomes, differences in relative importance or vulnerability should be included in the analyses. There ought to be a shift in spatial and temporal scale so that the scale in which fishing activity is recorded matches the scales needed for relevant management. At the planning stage, fishing data have been incorporated mostly to avoid conflict (97%). However, when stocks are overfished, ensuring some areas remain open to fishing and including fisheries in alternative ways to "cost" (which incorporates the economic and social impact of spatial closures) might be necessary. The use of inappropriate fisheries data has produced spatial plans that lead to poor management decisions, social conflict, and lack of compliance. Based on these results, we offer a set of suggestions on how to develop fisheries spatial planning research that will promote environmental and social sustainability.

KEYWORDS
fisheries data, fisheries management, fishing, spatial scale, systematic conservation planning, temporal scale

1 | INTRODUCTION

Globally, increasing demand for aquatic goods and services has led to increased pressure on aquatic ecosystems, which are being used simultaneously by multiple stakeholders (Halpern et al., 2008). Whenever multiple stakeholders use the same location for different purposes, conflicts can arise. The goal of spatial planning is to partition a region into various uses, minimizing conflicts, and providing better outcomes both for the environment and people. Chief among the stakeholder groups using aquatic systems is capture fisheries, which is the group most studied and targeted during research and management efforts (Liquete et al., 2013), and the one that generally suffers most from planning, as planning tends to focus on objectives such as biodiversity conservation.

Spatial planning aims to improve management in regions where conflicts among users are clear by optimizing the use of the area. The criteria for doing so include (1) achieving planning objectives while (2) minimizing environmental impact and (3) reducing costs to users (e.g., ensuring that areas providing large benefits are still available), ideally (4) promoting equity in social outcomes; thus, promoting environmental and social sustainability (Saunders et al., 2019). Successfully minimizing costs to users, competition and conflict require a clear understanding of the potential effects of proposed plans on various stakeholder groups. Consequently, spatial planning requires spatially explicit data (maps) of the various uses.

Although of primary economic importance in many cases, fisheries are currently underrepresented in spatial plans (Gurney et al., 2015; Janßen et al., 2018). In a review of 43 marine spatial planning initiatives around the globe, Trouillet et al. (2019) found that only half considered fisheries explicitly. Producing maps of human uses is generally perceived to be of secondary importance in spatial planning, where more effort is placed in obtaining an accurate spatial representation of biodiversity (Grantham et al., 2009; Janßen et al., 2018). Acquiring appropriate data on the spatial patterns of fishing is however critical to reach management decisions that ensure local livelihoods, conservation, and resource sustainability goals (Janßen et al., 2018).

Fishing activity can be quantified using multiple tools and metrics, from highly accurate vessel tracking data linked to logbooks that detail the position and catches of multiple vessels in a fishery (Bastardie et al., 2015) to rough surrogates such as distance to port that are used as proxies for fishing activity (Martin et al., 2009). There is, however, no guidance on how to best represent the fisheries sector in the spatial planning process, nor much awareness of the consequences of omission or misuse of the different metrics, nor of associated temporal or spatial scales.

Here, we carry out a quantitative literature review on the use of spatially explicit fishing data in spatial planning. Our goal is to provide researchers, managers, and planners with a state-of-the-art list of resources to evaluate the socioeconomic impacts of fisheries closures. First, we give an overview of research reviewed in terms of its temporal, geographic, and ecosystem patterns. We then describe the types of fisheries analyzed, sources of data, and metrics used. An issue commonly overlooked, we describe the temporal and spatial scales addressed, and then detail how fisheries data have been used in spatial planning. We finish the review with a compendium of recommendations on how to provide spatial plans in the future that promote social sustainability. This review is based on advances published in peer reviewed literature, and not on spatial plans themselves; therefore, they reflect the current state of knowledge and progress in the field and not necessarily approaches actually implemented by management bodies. A review tackling this issue is necessary and timely because the field has progressed quickly over a short time. Spatial planning is increasingly being used to prioritize spatial management actions (Álvarez-Romero et al., 2018), and recent technological developments allow automatic tracking of vessels, producing a wealth of data that can be useful in the planning process (Kroodsma et al., 2018).

2 | DATASET: FISHERIES DATA IN SPATIAL PLANNING

We carried out a quantitative review on the use of spatially-explicit fisheries data in spatial planning. Articles were selected by means of a structured literature search in Web of Science, one of the largest and most complete literature repositories available, in September 2021. The Web of Science record spans from the year 1900 to the present day. Search words were combinations of “fishing” or “fisheries” and “spatial planning” or “conservation planning” within the title and keywords (both author keywords and keywords plus). The search contained a total of 625 unique records from the years 1984 to 2021. These studies were summarily assessed and were incorporated in this review if they included spatially-explicit information on fishing. Many articles had a theoretical focus, were qualitative, did not include fisheries information, were not spatially explicit, or their methods lacked enough detail, and were excluded from further analysis. A total of 145 studies met the criteria and were fully analyzed as described below.

Publications on the topic started in 2005 (Figure 1a), and have increased in frequency since, with a notable maximum in 2015, when 20 articles were published on the subject. A close

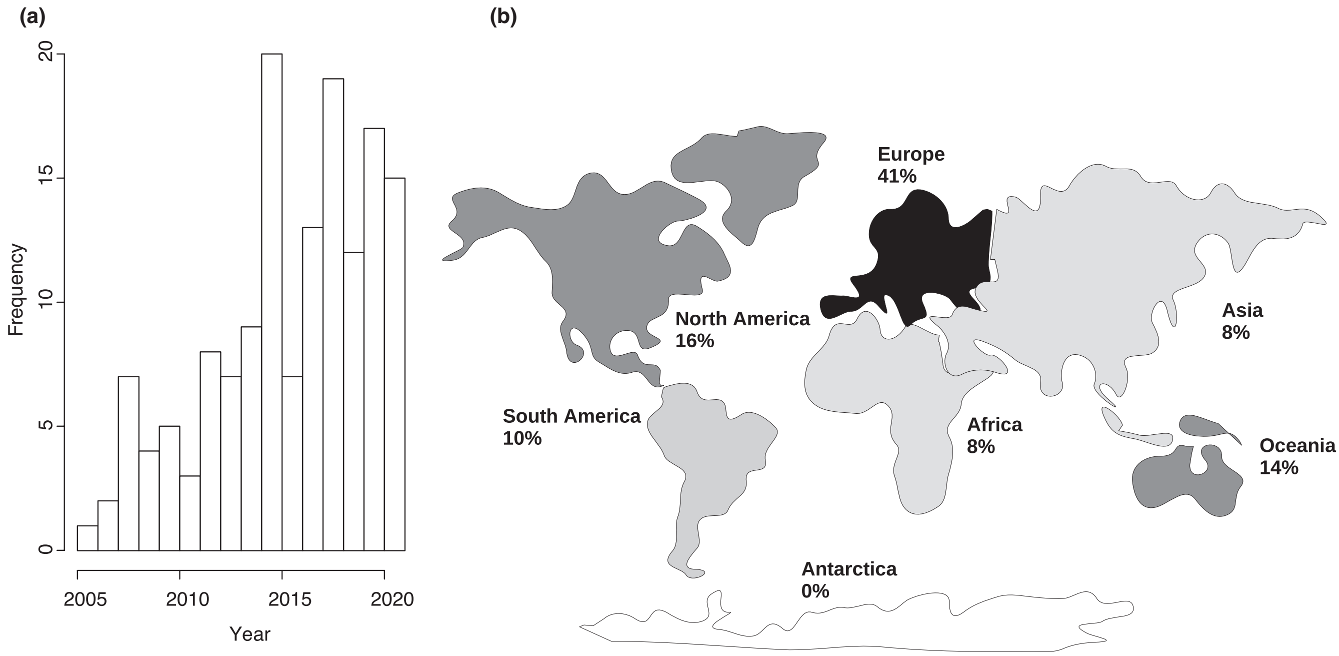

FIGURE 1 Summary of papers reviewed. (a) Temporal trend; (b) Spatial trend. Shade of gray proportional to relative frequency

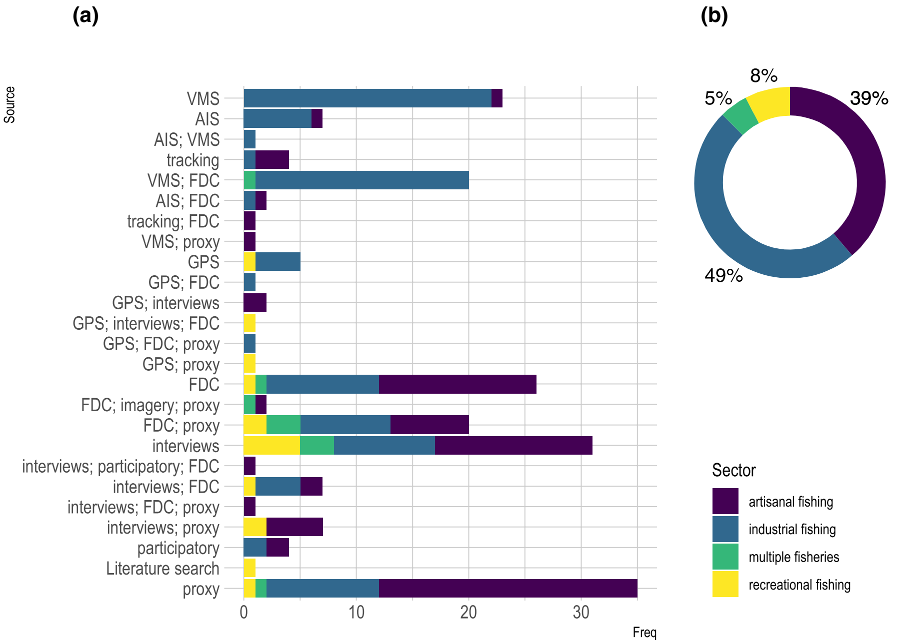

FIGURE 2 (a) Studies enumerated according to sources of data. "VMS" = Vessel Monitoring System; "AIS" = Automatic Information System; "FDC" = Traditional Fisheries Data Collection; "tracking" = other vessel tracking technology; "GPS" = Global Positioning System; "imagery" = satellite imagery; "participatory" = participatory mapping; (b) Studies enumerated according to type of fishery. "Multiple fisheries" include a combination of industrial and either artisanal or recreational fishing

examination of the data did not provide insight as to the cause of this peak, and authors, regions studied, and objectives were heterogeneous that year. The overall increase in the number of research papers dealing with our subject might be related to the growing need of spatial data fostered by the development of spatial planning in the last two decades and the technological progress and increase in fishing data availability (Trouillet, 2019). Most studies were located in Europe (41%). North America (16%) and Oceania (14%) were also well represented. Africa, Asia, and South America less so, and Antarctica has never been the subject of research (Figure 1b). Below we address different aspects of the research that has been produced, and we present our findings grouped under eight thematic headings.

2.1 | Fisheries data are underused in freshwater systems

Most studies were carried out in marine environments and only two studies assessed fishing in freshwater ecosystems, both riverine (Chiaravalloti, 2017; Xie et al., 2019). The lack of representation of freshwater systems might be related to two separate issues: the general lag of freshwater conservation science relative to marine science and the perception that fishing is not a main threat activity in freshwater systems (Reid et al., 2019).

Systematic conservation planning has been generally underutilized in river systems which, despite being among the most threatened ecosystems on Earth, have received little attention (Reid et al., 2019). The paucity of studies in spatial prioritization in freshwater systems has been attributed to the need of incorporating unique and difficult-to-depict processes, such as environmental connectivity and the propagation of threats along river networks (Linke et al., 2019).

Inland fisheries have been poorly studied and are rarely included in spatial planning exercises although fishing in inland waters is an important sector of the economy, particularly in many underdeveloped regions of the world (FAO, 2020; Lynch et al., 2016). The lack of study of fisheries in inland aquatic systems is due in part to the perception that other threats such as habitat degradation and flow modification are more relevant to these ecosystems (Reid et al., 2019). It is also possible that the lack of inclusion of inland fisheries in spatial plans is related to the type of fishery that takes place in these systems. Island fisheries are mostly carried out by small operations, anglers, and recreational fishers. The dispersed nature of these stakeholders makes this sector challenging to study, harder to reach, monitor, and engage in fisheries management actions (Hyder et al., 2020). Inland fisheries might also be under-assessed because the harvest of inland capture fisheries is considered small relative to the capture of marine fisheries (Deines et al., 2017). In 2020, for example, global catches in inland fisheries accounted for only 12.5% of total capture fisheries production (FAO, 2020). Official statistics, however, might provide a misleading picture. Inland fisheries harvest is often under-reported or unrecorded and recent estimates indicate inland fishing could exceed the official numbers by more than 60% (Fluet-Chouinard et al., 2018). Given their large contribution to the economy and their potential impact on ecosystem health, a larger effort should be placed to routinely incorporate inland fisheries into spatial planning and resource allocation decisions.

3 | TYPES OF FISHERIES, SOURCES OF DATA, AND METRICS USED

3.1 | Industrial and artisanal fisheries are both well represented in the literature

Most research that included fisheries in spatial planning focused on industrial fisheries (49%), but artisanal fisheries are also well represented in the dataset (39%) with recreational fisheries being the sector least studied (8%, Figure 2b).

3.2 | A wide diversity of methods have been used to collect fisheries data

To map fisheries, analysis of existing literature found that researchers have relied on Vessel Monitoring Systems (VMS), Automatic Information Systems (AIS), and other vessel tracking data (17%), traditional fisheries data collection data (13%), or used qualitative methods such as interviews and participatory mapping (17%), many times aided with ancillary data or proxies (Figure 2a). Other creative sources of data include a thorough web search of recreational angling sites in Wales (Monkman et al., 2018) or counting fishing vessels in Google Earth imagery (Appolloni et al., 2018; Magris et al., 2016).

Vessel tracking technologies have been increasingly used for fisheries management across the globe, and are required in most commercial domestic and high seas fisheries worldwide (Lee et al., 2010). VMS was developed for vessel monitoring, control and surveillance, and its use is mandatory in participating fisheries. It is sometimes linked to logbooks recording fishing metier (gear and target species) and catches. On the other hand, AIS was designed as a collision avoidance system, and vessels can turn it on and off at their discretion. There is no explicit link to the type of activity of the boat, limiting its use as a fisheries management tool (Le Tixerant et al., 2018). VMS and AIS were mostly used to assess industrial fisheries (93%), but they have also been used, with other vessel tracking technologies, to assess the spatial footprint of artisanal fishing. In our compilation, the most commonly used technology to map fishing activity using vessel movement data was VMS, used either in isolation (11%) or with other data, mostly fisheries logbooks (10%, Figure 2b). AIS data were less-often used to depict fishing patterns, featuring in only 3% of articles (Figure 2b). Other vessel tracking technologies included the use of small Global Position System (GPS) devices attached to the boat (Dosell et al., 2021; Metcalfe et al., 2017; Zaykoski, 2016) or on-board observers recording GPS locations at fixed time intervals (Mendo et al., 2019).

When tracking data were unavailable, some studies used GPS locations to identify fishing grounds or even quantify fishing effort, either by themselves (2%) or with other data sources (5%). Studies have used onboard observers (De Freitas & Tagliani, 2009; Leathwick et al., 2008), shore-based observers (Schmiing et al., 2015), boat observers (Griffin et al., 2021), time-lapse photography (Parnell et al., 2010), GPS trackers deployed on gear (Flower et al., 2020) or locations from fisheries enforcement patrols through vessel, land, or aerial surveys (Breen et al., 2015; Cabral et al., 2017).

Traditional fisheries data collection, including logbooks and different at-port collection schemes, have been used by themselves (13%) or to supplement other approaches when depicting fishing spatially (Figure 2b). Generally, “statistical areas” used in fisheries management are too coarse to be directly used in spatial planning. For example, the International Council for the Exploration of the Sea areas used in Europe measure 0.5 by 1 degree (roughly 55 × 55 km at 60°N). Many times, information on the location of fishing activities is estimated using other methods such as proxies, and then linked to fisheries data to provide estimates of catch or fisheries value.

Interviews are the most common source of information used, and 15% of the studies used interview data only to depict fishing patterns (Figure 2b). Qualitative methods such as interviews and participatory mapping, where stakeholders are gathered in a meeting to map fisheries in collaboration, have been used mostly to assess artisanal fisheries. Fishers' local knowledge can be profound and detailed, and offer crucial information for spatial planning (Silvano & Valbo-Jørgensen, 2008). However, the representation of all stakeholder sectors is rarely achieved during consultation processes, particularly when the sector is heterogeneous (Teixeira et al., 2018).

Additionally, gathering local knowledge requires trust between data gatherers and fishing communities, and this relationship needs to be ensured to obtain an accurate depiction of fishing activity in a region (Baker & Constant, 2020). Finally, some studies have shown that there can be a large mismatch between fisheries value recorded in the field (e.g., using at-port surveys) and as perceived by the fishers (recorded using interviews and participatory mapping), therefore, caution needs to be exercised when interpreting fishing activity maps from qualitative methods (Hamel et al., 2018; Turner et al., 2015; but see Mason et al., 2019).

When spatially explicit information on fishing activity was not available, many articles mapped fishing using only proxies (17%). Researchers tend to use proxies or surrogates when there are no funds, expertise, or time to acquire new data (Grantham et al., 2009). Proxies are either extracted from local databases, databases available online, or calculated using spatial analyses for the region of study. These include factors that determine the proximity of the fishing ground (e.g., distance to port or to fishing village, Hamel et al., 2018), measures of human pressure (e.g., population density, size of nearest settlement, Weeks et al., 2010a), competing activities (e.g., other types of fishing, maritime traffic, Kavadas et al., 2015), spatial management (e.g., distance to areas closed to fishing, Brown et al., 2015), topography (e.g., depth, shoreline steepness, Stamoulis et al., 2018), environmental factors (e.g., wave exposure, sea temperature, Harborne et al., 2018), or proxies of fishing pressure (e.g., parrotfish mean size, a surrogate of fishing pressure in coral reefs, Harborne et al., 2018: Figure 3). Using proxies is more common when depicting artisanal fisheries (Figure 2b). Proxies have been used by themselves or in combination. Areal extent, for example, has been used as a measure of fishing intensity, under the simple assumption that fishing is equally distributed across the seascape (Brown et al., 2015; Hamel et al., 2018). Another commonly used single proxy is distance to port or fishing settlement, under the assumption that closer areas have easier access, involve consuming less fuel, and are preferred. However, the utility of such a simple proxy has been contended (Hamel et al., 2018), and studies have shown the relationship between fishing activity and distance is not always linear and depends on the level of depletion of the resource, with areas closest to port showing lower fishing effort when they have been already depleted (Chollett et al., 2014; Silvano et al., 2017).

When multiple variables were used to depict fishing activity, they have been linked by relatively simple numerical relationships or complex modeling (e.g., multi-criteria decision analysis: Giakoumi et al., 2012; boosted regression trees: Harborne et al., 2018). Many times, values of revenue or catch available at a regional level are distributed in space using proxies (Baker-Médard et al., 2019; Mazor et al., 2014, 2021).

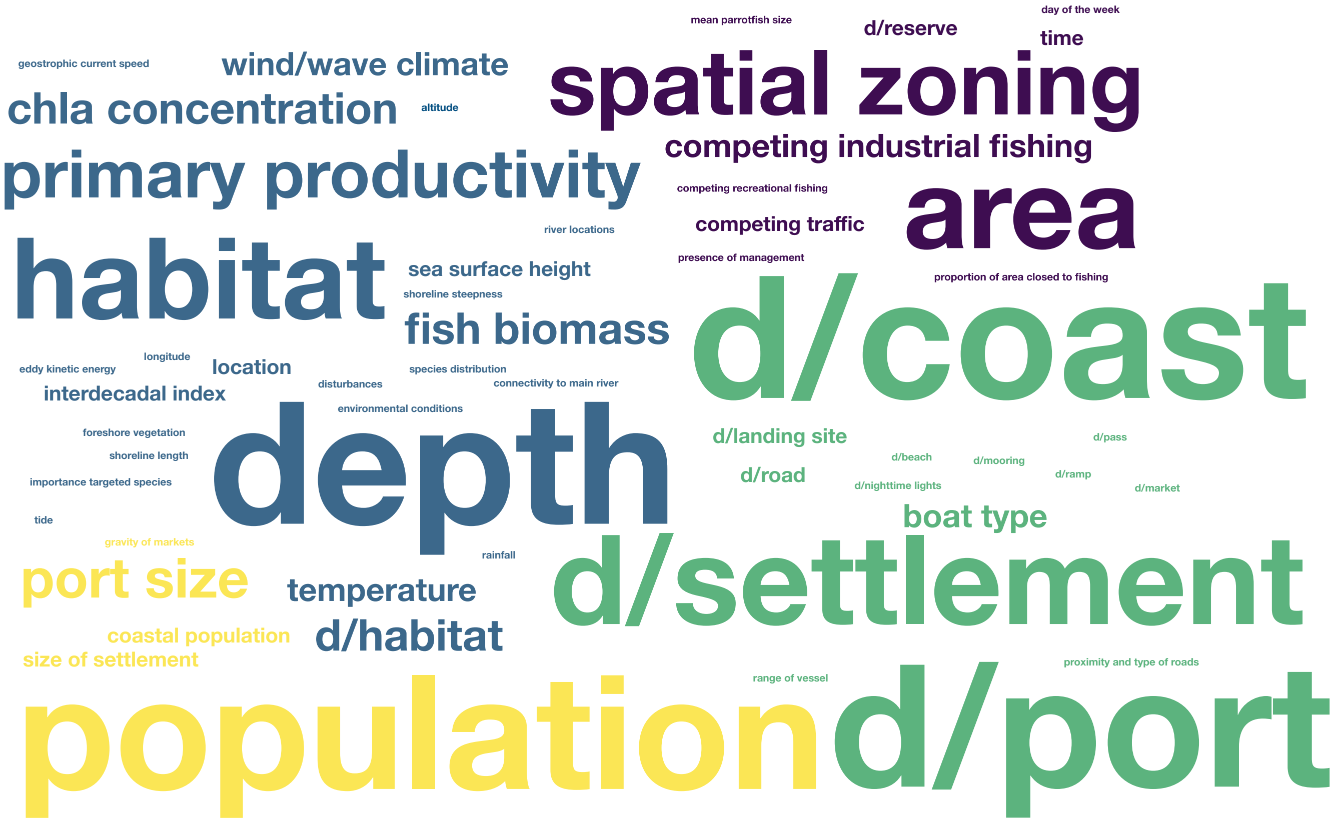

FIGURE 3 Proxies used to map fisheries. In blue are environmental and biological proxies. In yellow are proxies related to population size. In green are proxies related to fishing access. In purple are other proxies. Size of font refers directly to the frequency of times each proxy was referred to in the literature (maximum = 21). "d/" means distance to

Numerous studies include many variables when modeling fishing activity using proxies, but a few articles have compared model performance against direct observations to find the best predictors. Weeks et al. (2010a) compared spatial patterns of fishing effort gathered with four different proxies against empirical data on spatial distribution of fishing effort collected through interviews. The proxies considered were distance (from fishing location) and size of settlement, distance and size of coastal population, distance to settlement and number of fishers, number of vessels per settlement according to the distance range of the different metiers. They found that none of the proxies was able to accurately predict fishing activity. However, proxies based on population data were considerably worse (Spearman's rank correlation <0.2) than proxies based on number of fishers (correlation between 0.5 and 0.6; Weeks et al., 2010a). Soykan et al. (2014) found that a small set of variables was sufficient to explain industrial fishing effort patterns using drift gillnet and albacore troll with reasonable model performance (59% and 66% explained deviance). For the drift gillnet fishery year, longitude, latitude, and month were the best predictors. Sea temperature was the most important predictor for the albacore troll fishery, corresponding to the environmental preferences of the primary target species. Harborne et al. (2018) looked at the relative contribution of proxies in explaining fishing activity in an artisanal reef fishery, and found modest model performance (36% of variance explained), with human population density and distance to port as the best spatial predictors. From our review, it seems clear that when used, proxies need to be tailored to the fishery, region, and target species. Including a metric of travel costs such as fuel use or a proxy (e.g., distance to port), linking use patterns to number of users (fishers) instead of numbers of people, and considering that the relationship between these variables and fishing activity is not linear, has shown to be particularly relevant in artisanal fisheries (Adams et al., 2011; Chollett et al., 2014; Harborne et al., 2018; Weeks et al., 2010a).

All data sources have benefits and limitations. Spatially-explicit sources of information are the best at providing an accurate picture of fishing location patterns. Although vessel tracking data are preferable, they are generally not available for artisanal and recreational fleets, they represent only a fraction of industrial fleets in many countries, and their setup and maintenance are costly. Alternative ways of obtaining locations of fishing activity (e.g., through time lapse photography or GPS devices attached to fishing gear) can be valuable when assessing small operations. However, these methods provide restricted geographic coverage and limited temporal coverage, which has shown to be key in depicting stable patterns of fishing activity, in particular when assessing temporally variable resources (Trouillet et al., 2019, see section “Temporal and spatial scales” below). Logbook data often have good industrial fleet coverage but the spatial resolution of fishing areas is too coarse to be applied in spatial management decisions directly. Supplementing these data with proxies for a finer spatial distribution has shown to be a useful avenue (Teixeira et al., 2018). When the deployment of accurate, quantitative data gatherers is not possible, obtaining information on fishing activity through interviews and participatory mapping has been a useful approach, particularly when assessing historical fishing patterns (Selgrath et al., 2018). Additionally, including fishers in the mapping process has benefits beyond accuracy, and makes them part of the planning process which has been related to higher levels of compliance (Weigel et al., 2014). The use of proxies on its own has shown mixed success, and should be tailored to the region of study to ensure relevance.

3.3 | Fishing effort is the most commonly used variable

Different articles mapped different aspects of fisheries. 8% just delineated fishing grounds. Most studies (43%) assessed fishing effort. 7% of the studies mapped catch and 6% went one step further and mapped catch per unit effort (CPUE). 13% of the articles related catch to monetary value, using either gross or net revenue, or contribution margin. 23% of the studies used proxies to produce a map of surrogate fishing activity, effort, or catch (Figure 4).

Hamel et al. (2018) compared fishing activity patterns using simple distance proxies, fishing effort, catch and CPUE measured through at-port surveys, as well as perceived fishing importance of each site through interviews. They found different metrics had significantly different spatial patterns, echoing results found by others (Deas et al., 2014; Weeks et al., 2010a). Different variables also produced different spatial plans when used in spatial planning exercises (Deas et al., 2014; Hamel et al., 2018; Weeks et al., 2010a), even when input variables showed high similarity (Teixeira et al., 2018). A badly chosen metric can actually increase the cost of a plan when compared to a null scenario of no socioeconomic data included (Deas et al., 2014).

The choice of variable to map is many times determined by data already available in the region. When many options are available, or it is possible to gather new data, it is important to take into account that different variables depict different aspects of fisheries. Many consider that when effort, catch, and revenue information are available, revenue measures are preferred as a metric for depicting relative importance of an area for fishing, given that effort measures cannot gauge how effective vessels and gears are at capturing fish, and catch fails to capture the difference in value across species (Jin et al., 2013). In any case, the variable used should match closely the objectives of the planning exercise, to ensure the social sustainability of the resulting plan.

3.4 | Data from different fisheries are often combined simplistically

When handling multiple gears or fisheries sectors, most articles (84%) merely added up the values. A small number of studies (1%) added standardized values for each sector (to give each equal weight) and some (5%) used weights to give more importance to sectors or gears that had more vessels, catches, or associated stakeholders.

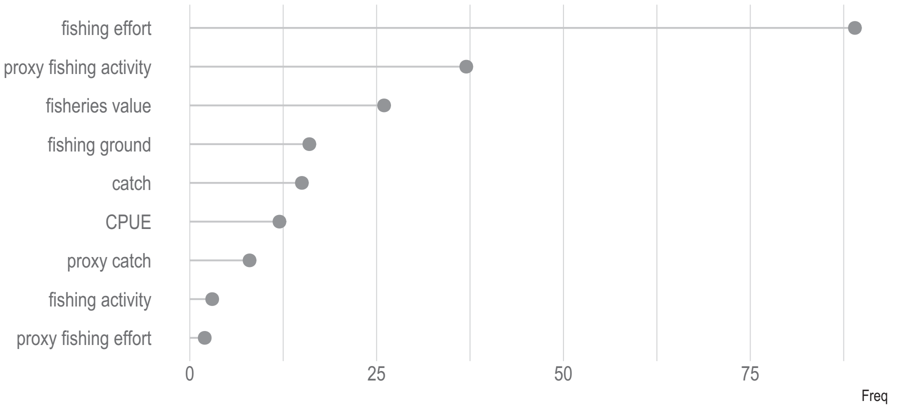

FIGURE 4 Variables mapped

Although mostly overlooked, the decision on how to combine multiple sectors is important when producing information for planning. Simply adding values of effort, catch, or revenue gives all fisheries sectors the same importance, which might be desirable in many instances. However, when handling fisheries management processes with stakeholders, it might be desirable to lead a more equitable process, where each stakeholder is given equal weight, or uneven weights when particular stakeholder groups are more important or vulnerable (Giakoumi et al., 2012; Klein et al., 2008). So far researchers have assigned weights to stakeholders groups based on importance, such as larger weights to sectors with more boats. No article considered weighting stakeholders as a function of their perceived vulnerability to management, an issue we consider should be a priority to ensure equitability in management outcomes. Such an approach would acknowledge that individuals and social groups have different advantages and abilities to cope with change, and the planning process can address this by giving more importance to disadvantaged or vulnerable stakeholders, so to achieve socially sustainable outcomes (Saunders et al., 2019). We acknowledge, however, that gauging the relative vulnerability of stakeholder groups is challenging. Gurney et al. (2015) and Kockel et al. (2020) circumvented this issue altogether by setting individual objectives (targets) for each stakeholder group, showing that this approach produced spatial plans with the least severe trade-offs between biodiversity and fishery objectives.

4 | TEMPORAL AND SPATIAL SCALES

4.1 | Short-study periods and lack of temporal variability are the norm

When recorded, the average time assessed in the different studies ranged from 2 months to 60 years with a median of 3.5 years. The duration of the study and data gathered varied significantly with the fisheries sector (ANOVA, *p*-value = .05). Artisanal fisheries had the shortest periods assessed, and a median of 1 year. A notable exception is the study by Selgrath et al. (2018) who, using interviews, reconstructed artisanal fishing effort in the Philippines through an impressive period of 60 years. In general, studies including industrial fishing, which could be recorded with government-led, long-term fisheries monitoring tools such as VMS, logbooks, and at-port fisheries data collection, had longer time frames.

A quarter of the articles assessed had an undefined timescale. These were generally the products of qualitative data gathering methods where the assessment of fishing activity was performed without an explicit time frame, limiting the usefulness of the results, given that is not possible to know if their results refer to fishing areas recently used or used during a lifetime.

Most studies (88%) did not include any temporal variability in fishing patterns. Some, however, included variability in decadal (Selgrath et al., 2018), annual (Stelzenmüller et al., 2008), seasonal (Stelzenmüller et al., 2008) monthly (Mason et al., 2019) patterns or before and after effects (Lagasse et al., 2015). Mason et al. (2019) mapped shark fisheries at monthly time steps showing a marked seasonality in Peru. Conversely, Stelzenmüller et al. (2008) found no seasonal differences in trawls and dredge fishing patterns in the United Kingdom, although inter-annual differences were significant. Selgrath et al. (2018) mapped 20-fold increases in fishing effort in artisanal fishing in the Philippines over 60 years. Lagasse et al. (2015) mapped landings using two temporal scales, 15 years and 7 years, and showed temporal changes in the distribution of landings, which produced different spatial plans, and suggested using recent fishing patterns to build meaningful spatial plans.

García-Barón et al. (2021) looked at the influence of timescale of input data (trawl and gillnet fishing maps) on spatial plans. They developed 10 scenarios integrating different amounts of data, and determined that plans based on one year of data were highly variable, and scenarios that considered more than 4 years of data provided consistent results. This study demonstrated that the use of a snapshot as input data can lead to an inadequate selection of priority conservation areas, and a robust time coverage is crucial for relevant spatial planning. The monitoring period needed to ensure the appropriate depiction of fishing activity is likely dependent on the temporal variability of the distribution of the resource and the users. Highly mobile target species, species that have strong seasonal or inter-annual variability of recruitment and abundance and/or fisheries that switch gears and targets frequently will need longer time frames (García-Barón et al., 2021; van de Geer et al., 2013).

4.2 | The spatial resolution of fisheries data reflects opportunistic gathering and does not agree with management scales

The spatial resolution of the fisheries data varied widely among the studies, ranging from 25 m^2 to 6160 km^2, with a median of 1 km^2. Spatial resolution varied according to which fisheries sectors were included (Figure 5b). Studies tended to have a finer spatial scale when tackling artisanal or recreational fisheries (Figure 5b) and assess smaller areas (Figure 5c). There is large variability among studies, however, and differences among groups are non-significant (ANOVA, *p*-value = .2). The spatial resolution of the data was in many cases opportunistic and dependent on what was at hand. For example, the spatial resolution was the largest in studies that used the raw ICES rectangles to assess patterns of industrial fishing.

There is a mismatch of spatial scales between the fisheries data and the units used during spatial planning (linear model between spatial resolution used to depict fisheries data and used for planning, *p*-value = .3). The choice of spatial resolution should reflect a compromise between the size of the area that needs to be mapped and computational feasibility (Kafas et al., 2017; Stelzenmüller et al., 2008). The spatial resolution of fisheries data was, however, not significantly related to the size of the study region (linear model, *p*-value = .1), but the spatial resolution of the management unit used during spatial planning was significantly related (linear model, *p*-value <.001). This indicates that the spatial resolution of the spatial planning units was related to a trade-off between representation and feasibility, while the spatial resolution of fisheries data was more variable and unpredictable, denoting opportunistic gathering.

In many cases, the spatial resolution of the fisheries data is too coarse to fulfill the requirements for spatial planning. Jin et al. (2013) suggested a grid system with a maximum sized cell of 10 minutes (about 340 km^2 at the equator) to value marine space. Marchal et al. (2014) recommended 3′ (about 30 km^2) to analyze the interactions between fisheries and other human uses. These seem, however, still too coarse and unable to match the spatial scale of many features that need to be mapped when dividing the seascape among users. 65% of marine protected areas, for example, are smaller than 10 km^2 (https://mpatlas.org/zones/, accessed November 2021), offshore aquaculture pens occupy a few dozens of square meters (Chu et al., 2020) and offshore wind turbines require about 0.3 km^2 of space (van Grieken & Dower, 2017).

The choice of spatial resolution influences the results when mapping fishing activity. Coarser maps lead to larger spatial footprints, increasing the amount of overlap, and, therefore, perceived conflict among users (Breen et al., 2015; Hamel et al., 2013; Mendo

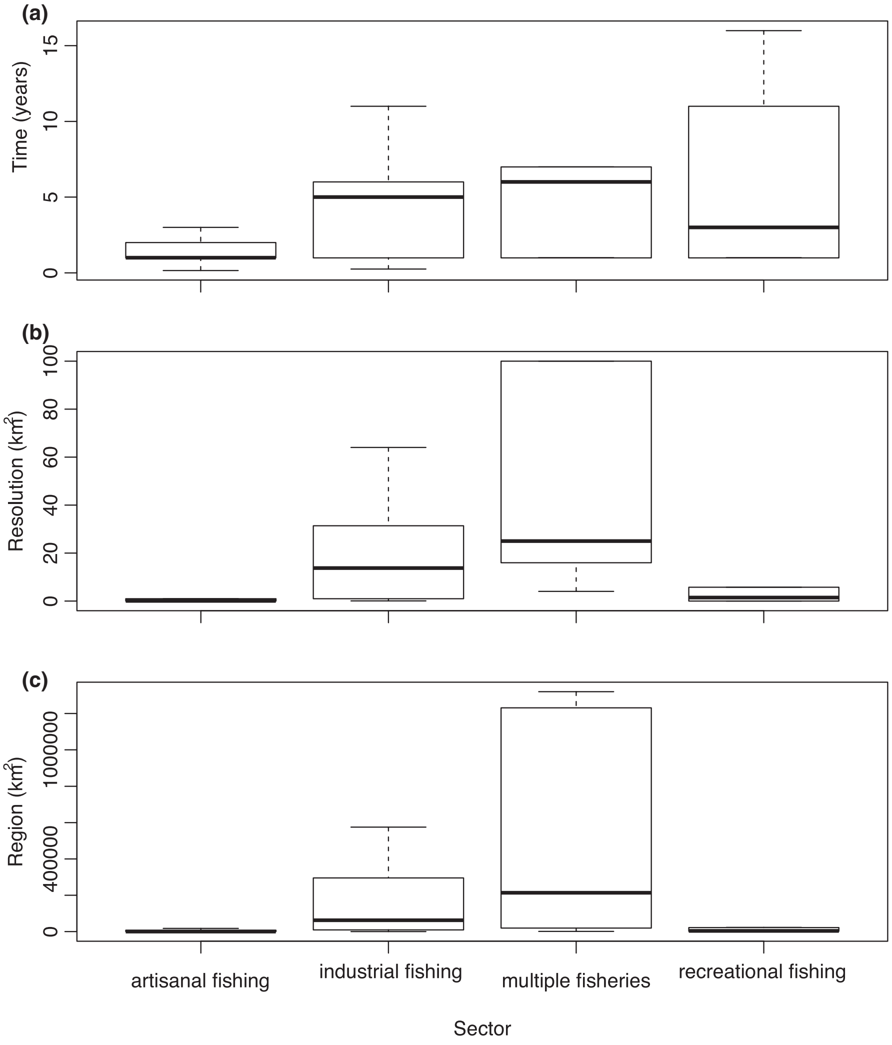

FIGURE 5 Temporal and spatial scales according to fisheries sector. (a) Time frames of the studies; (b) Spatial resolution of fisheries maps; (c) Approximate extent of the region assessed in each study. In boxplots, the bold line indicates the median, boxes the interquartile range (IQR, 25th, and 75th percentile) and whiskers show the highest and lowest value excluding outliers (1.5*IQR)

et al., 2019; Richardson et al., 2006). Richardson et al. (2006) compared spatial plans when including coarse fisheries-data-collection inputs at ICES resolution versus fine-scale survey data, and showed that plans produced using coarse data were not much better than plans depicted without socio-economic considerations. When considering an artisanal fishery deploying static gear, Mendo et al. (2019) found that increasing the spatial scale of fishing maps from 100 m to 200 m in grid size resulted in a twofold overestimation of the fishing area. These studies highlight that whenever possible, the spatial resolution should be kept detailed to decrease conflict and produce better plans. This idea clashes with the requirements of many managers which consider fisheries data as secondary and available data as an excellent resource. The Marine Spatial Planning Directive in the European Union, for example, requires planning processes to use the best available fisheries dataset rather than collecting new data (Directive 2014/89/EU Art. 10), making it extremely difficult to produce spatial plans that are representative and useful for management.

The spatial resolution of the data is also limited by the precision of the technique used for data gathering (Trouillet et al., 2019; Turner et al., 2015) and the level of aggregation needed so as not to reveal individual fishing areas and ensure confidentiality and willingness from fishers to share their data (Kafas et al., 2017; Trouillet et al., 2019; Zaykoski, 2016). Overall, there should be a shift in spatial scale so the spatial distribution of maps of fishing activity matches the scales needed for relevant management, while considering the characteristics of the study system and the needs of the stakeholders. That shift might facilitate the integration of fisheries data in the spatial planning process, increase relevance of the resulting plans and decrease conflict (Hamel et al., 2013; Janßen et al., 2018).

5 | USE OF FISHERIES DATA IN SPATIAL PLANNING

About 43% of the assessed articles included planning, but 41% focused on producing data for further use ("inventory") and 15% in assessing changes in use before and after spatial planning took place ("assessment," Figure 6a). Of the articles carrying out spatial planning, most of them used publicly available software for grid-based, large-scale spatial conservation prioritization. Different software differs in the underlying algorithms used. Most articles used the software *Marxan* (53%) or its relatives, *Marxan with Zones* (19%) or *MarProb* (1%, Figure 6b). Other speciality software such as *Zonation* and *prioritzr* were also used but much less frequently (6% of the studies). About 12% of the studies used either population or bio-economic population models to assess and choose among different spatial plans. Allnutt et al. (2012) used categorical classification, and Szalaj et al. (2018) used a multi-criteria decision-making method. Five studies used qualitative methods to identify spatial plans.

Most planning was done as a research exercise and only three articles explicitly indicated that their spatial plan was actually implemented (Dosell et al., 2021; Flower et al., 2020; Johnson et al., 2020). Interestingly, only one of these three real-world cases used a quantitative method (*prioritizr*) to develop a spatial plan, albeit heavily edited by local stakeholders (Flower et al., 2020). In the other two examples, zoning was carried out considering different layers of information but based on decisions of local stakeholders. It is worth noting that these three studies are all recent, which may reflect a shift in objectives from desk studies to actual plans.

Spatial planning is always an exercise of balancing conflicting objectives. The vast majority of the studies (91%) compared fisheries and conservation activities, while a minority considered planning that balances other uses. Spatial planning exercises documented by our review included planning for aquaculture (Maina et al., 2021), renewable energy (Yates et al., 2015), maritime shipping (Dosell et al., 2021), spatial fishery management areas (such as fishery refuges or locally managed areas: Maina et al., 2021; Morzaria-Luna et al., 2020) or assessed hypothetical closures without an explicit objective (Bastardie et al., 2014).

5.1 | Inclusion during spatial planning depends on the condition of the resource

When using quantitative methods to define spatial plans, fisheries data can be used in different ways. Most researchers include fishing

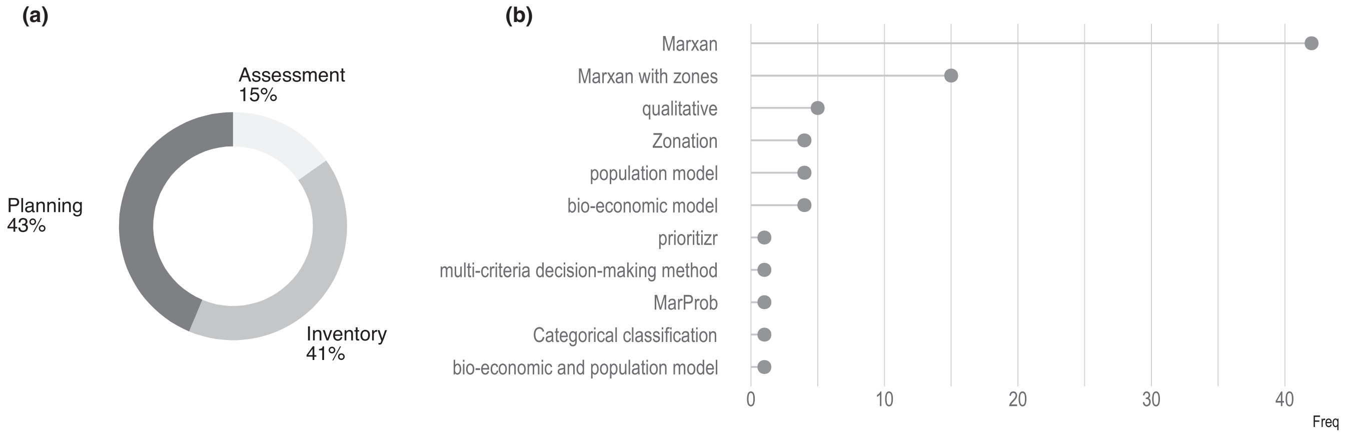

FIGURE 6 Use in management. (a) Objective of the study; (b) Method used during spatial planning

patterns as a cost (85%). Fisheries information, however, has been included also as the inverse of cost (1%), targets (11%) or as a feature that needs to be locked out (3%) of the design (for definitions on these terms, read below). While "costs" and "targets" define quantitative values for characterizing areas that might be selected across the seascape, "locked-in" and "locked-out" areas are necessarily included in/excluded from spatial plans. "Costs" define areas that need to be avoided so to minimize the economic cost and social impact of spatial closures, and conflicts with resource users (Ban & Klein, 2009). "Locking out" key fishing grounds from the spatial plan is the most secure way of ensuring fishing areas are accessible for fishers and minimizing social conflict, but can produce inefficient designs that require larger areas to satisfy targets (Weeks et al., 2010b). Including fishing areas as targets in a plan with multiple zones, that is, ensuring a fixed proportion of fishing grounds or fishing effort is used for fishing, has also been used as a way to protect fishers (Gurney et al., 2015).

Few articles have done the opposite, namely using fishing data to ensure important fishing grounds are not used for fishing (3%). This might seem counter intuitive, but it has been applied to promote sustainable fisheries by allowing the recovery of fishery resources and the spillover to other areas (Baker-Médard et al., 2019). This has been done either by setting fishing areas as a target to protect important fishing grounds (Yates et al., 2015), or by including the inverse value of the fishing activity layer as a cost (Baker-Médard et al., 2019). In theory, the same objective can be achieved by locking in some key fishing grounds and ensuring they are excluded from fishing, but this was not recorded in any of the studies assessed.

The choice on how to include fisheries information during spatial management has utmost importance for the resulting spatial plans (Gurney et al., 2015; Jones et al., 2018), and has shown to be more relevant than the spatial planning software used (Delavenne et al., 2012). Selecting how best to include fisheries data in planning is likely to be a balance between the way of dealing with conflict and the condition of the resource. If conflict with fishers needs to be avoided, then fishing areas are better included as cost, or as a target to represent fisheries in open areas, or locked out. On the other hand, if the resource is overfished, ensuring recovery areas by setting fishing as a target to prevent fishing in important fishing areas, then inverse cost or locked-in area might be the only way forward to guarantee the sustainability of the resource and the recovery of intensely harvested stocks (Baker-Médard et al., 2019). Few researchers have used mixed approaches. An exception is Yates et al. (2015), who used fishing data as a cost and also as a target for including and protecting fisheries, minimizing conflict, but also ensuring key fishing areas were available and set aside for recovery.

An additional issue that needs to be kept in mind when considering how to include fisheries data in spatial planning is that including fishing as a cost (or its inverse) allows only including one variable. However, if including fishing patterns as a target, it is possible to set multiple objectives for each fishery or stakeholder group, thus ensuring a more equitable outcome (Gurney et al., 2015).

6 | CONCLUDING REMARKS

The selection of the appropriate data to represent fishers' rights is key to ensuring social sustainability of spatial management plans. During the present review, we show that the default way of incorporating fisheries data in spatial plans, i.e., using opportunistic data, snapshots or rough proxies of fishing activity, is undesirable and results in costly management mistakes. To improve planning in the future, we synthesize our findings under the key themes that ought to be considered when incorporating fisheries into a spatial plan (Figure 7).

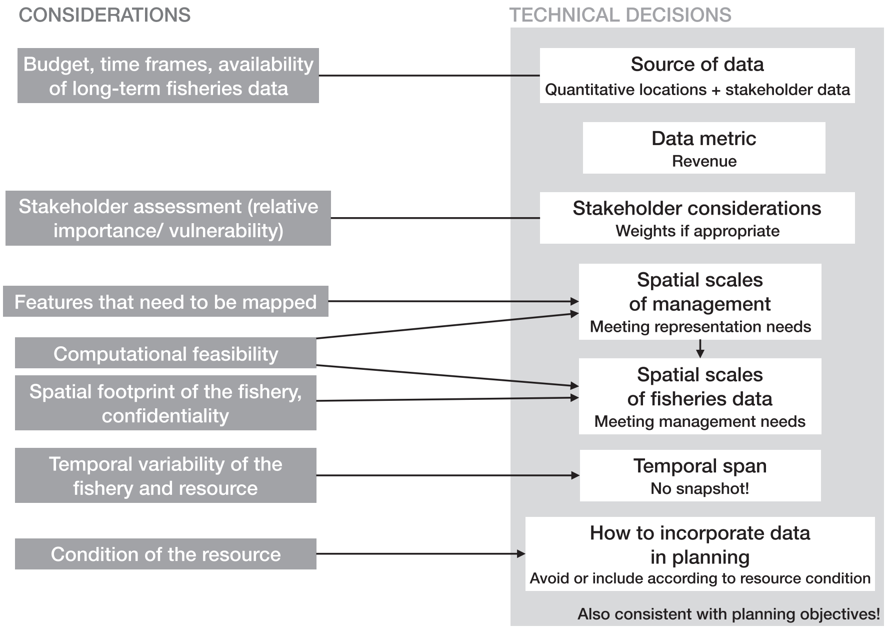

FIGURE 7 Aspects to be considered when including fisheries data in planning processes, and associated technical decisions with recommendations

- *Data sources*. Quantitative information on fishing activity, inferred either from vessel track movement data or GPS records, is preferable. However, stakeholder involvement should complement quantitative data gathering to ensure engagement of fishers in the planning process. Proxies should be avoided. If they need to be included they ought to be tailored to the specific region and fishery, including a measure of travel costs, focusing on users and not simply population indices, and considering non-linearities, so to better approximate patterns of fisheries use.
- *Data metric*. When effort, catch, and revenue information are available, revenue measures are preferred as a metric to depict relative importance of an area to fishing, given that effort is a poor metric for gauging how effective vessels and gears are at capturing fish, whereas catch metrics (e.g., landed weight) fail to capture the difference in value across species.
- *Multiple stakeholder considerations*. Different stakeholder groups should be given different weights if the relative importance of their activity is uneven and not captured by the data metric, or if some sectors are more vulnerable to management intervention than others. To that end, relevant stakeholders need first to be identified during initial spatial planning meetings, and a vulnerability assessment carried out to assign weights to each stakeholder group.
- *Temporal scales*. Snapshot data is unsuitable for producing plans that are robust, and some studies have found that at least 4 years of data should be included in spatial planning (García-Barón et al., 2021). Although the exact number of years required will depend on the particular fishery, at least 2 years of data gathering might be a good benchmark to buffer some inter-annual variability. A longer time series will be needed if a disturbance took place within the recorded timeframe. If gathering new data during this time span is not feasible, we suggest supplementing quantitative data with qualitative surveys that focus explicitly on more-recent patterns of fishing activity.
- *Temporal variability of the fishery and the resource*. If the resource or the fishery is highly variable, then this needs to be taken into consideration so to expand the temporal scales of data collection as mentioned above.
- *Spatial scales needed for management*. The spatial scales used during planning need to match the planning objectives, the features that are being planned for (e.g., marine reserves, aquaculture sites), while ensuring feasibility in data gathering and computational analyses.
- *Spatial scales for fisheries data*. Fisheries data should match the spatial scales needed for management. Maps built with coarser spatial resolution lead to larger spatial footprints of fishing activity, larger overlap of uses and a commensurate increase in perceived conflict (Breen et al., 2015; Hamel et al., 2013; Mendo et al., 2019; Richardson et al., 2006). The spatial resolution of the fisheries data should match the spatial footprint of the fishery. For example, mobile gear has a larger footprint than static gear (Mendo et al., 2019). The spatial resolution of the fisheries data should be the minimum that allows appropriate representation, while allowing computational feasibility and confidentiality.
- *Condition of the fishery resource*. This will help define the objectives of the management plan and how to incorporate fisheries data in planning decisions. If the resource is well managed and sustainable, objectives can focus on minimizing conflict among users, and data can be incorporated during spatial planning as a cost or target for protection. On the other hand, if the resource is overfished, explicit objectives should be set to rebuild the fishery, and fisheries data should be incorporated in spatial plans accordingly, either as the inverse of cost or as target for exclusion (Baker-Médard et al., 2019; Yates et al., 2015). If the status of the fishery is unknown, a precautionary approach should be applied that sets aside fishing grounds for protection.

We hope this review will put resource planners and fisheries scientists on the same page with respect to incorporating fisheries data into spatial planning, providing awareness of existing approaches and highlighting the repercussions of various decisions on management outcomes. Overall, we encourage better inclusion of fisheries data in spatial planning with a view to achieving true environmental and social sustainability in the future.

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DATA AVAILABILITY STATEMENT

All data produced in this review can be found in the Supporting Information (Data S1 and Appendix S1).

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