Exploring uses of maritime surveillance data for marine spatial planning: A review of scientific literature

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Abstract

Maritime Spatial Planning (MSP) has become of key interest in many countries around the world in the last decade, leading to an increased need to inform the historical spatial and temporal footprint of maritime activities. If this knowledge was still recently considered a blind spot, recent developments of maritime surveillance systems (e.g. AIS, VTS, VMS) have allowed to fill some of these gaps by generating significant amounts of spatial data on ships at sea. In this paper, the use of these maritime surveillance data for planning purposes is explored through the lens of the international scientific literature. A first set of 2030 articles dealing with maritime surveillance data and collected through the Web of Science collection was explored to determine the type of data used, the maritime activities addressed and the main objective of each paper (technical developments, safety and security, environmental protection, MSP). This allowed to highlight the growing interest on maritime surveillance data in the scientific literature over the past decades, predominantly towards AIS data and shipping. Over the 2030 papers, only 63 dealt specifically with MSP. These were extracted and explored, allowing to highlight the potential of these data to feed in MSP processes, with a specific focus on fisheries. Nevertheless, the description of actual uses of surveillance-based information within MSP processes remained particularly rare. If this can be seen as a result of a science-policy delay, we suggest that it is mostly related to issues of accessibility, acceptance by economic stakeholders and appropriation by decision makers.

Keywords: bibliographic review; maritime surveillance data; Maritime Spatial Planning (MSP); Automatic Identification System (AIS); Vessel Monitoring System (VMS); marine radar.

1. Introduction

1.1. Marine Spatial planning: Project and/or Protect.

Recent decades have been characterized by a growing importance of maritime issues in different spheres of modern societies (political, economic, environmental). This is the result of an increasing awareness of the human pressures on marine resources and ecosystems, highlighted among others at global level by Halpern et al. in 2008 [1], but also of the hopes placed in the future maritime economy: job creation, response to the depletion of terrestrial resources, energy or food production [2]. Sustainable development at sea, formalized in Europe by the concept of Blue Economy, is nowadays caught in the middle between these conservative and utilitarian visions [3].

While sectoral, local or specific policies and regulations have allowed to manage individual environmental impacts and conflicts between activities until the end of the last millennium - with varying degrees of success - they no longer seem sufficient to meet the current diversification and intensification of maritime activities, as Cicin-Sain et al. already pointed out in 1998 [4].

The new challenges of a greater whilst sustainable exploitation of the seas and oceans have led to the implementation of increasingly integrated and forward-looking approaches, first on the coasts (Integrated Coastal Zone Management – ICZM [5]) then further offshore, with the international development of so-called "integrated maritime policies" [6].

In this context, several States, NGOs and scientists have in recent years perceived the need for strategic and spatial planning of seas and oceans, essentially public if not common [7]. Qualified as *Marine* or *Maritime Spatial Planning* (MSP), this spatially explicit approach constitutes an integrated framework to support the sustainable development of historical and new activities, while increasing efforts to preserve the marine environment [8]. In 2017, 67 countries around the world had launched MSP initiatives [9].

Thereafter, MSP is considered in the broadest sense, as defined in the European MSP Directive [10], as a "*public process by which authorities analyse and organize human activities in marine areas to achieve ecological, economic and social objectives*".

In Europe, these objectives are defined either by European directives (e.g. MSFD[11]) or by national ones, and mostly relate to either environment (e.g. achieving the good environmental status or implementing MPAs) or Marine Renewable Energies (MREs). As well as on land, these objectives often collide, and result in decision and governance issues, as extensively documented in the scientific literature [12–14]. In this context, information on current maritime activities can have a significant impact on the outcomes of planning processes.

To establish the initial status and analyse maritime activities, a wide range of information is required, e.g. on activity areas, individual and cumulative environmental impacts, economic production as well as social aspects [15–17]. While comprehension of marine ecosystems is building up, knowledge of maritime activities was still recently considered an almost blind spot [18], shaped by the "*freedom of the seas*" [19]. In particular, apprehension of the spatial and temporal distribution of activities at sea remains fragmentary, and sometimes subjective [20].

1.2. Setting the scene with maritime surveillance data?

In recent years, *maritime surveillance* has greatly improved, in response to growing maritime security issues, intensified by an increasing density of sea uses, and to associated international regulations and national policies (e.g. [10,21]).

According to the European Commission [22], maritime surveillance is a mean to "*understand, prevent wherever applicable and manage in a comprehensive way all the events and actions related to the maritime domain which could impact the areas of maritime safety and security, law enforcement, defence, border control, protection of the marine environment, fisheries control, trade and economic interests*". It essentially focuses on ships' positions and dynamics, even though environmental maritime surveillance, such as sea-state monitoring, have also developed significantly [e.g. 24–26]. Maritime surveillance is mainly designed for instantaneous *maritime situational awareness* [26] and short-term reactions: collision avoidance, Search and Rescue (SAR), police operations, detection of dangerous or illegal events. Accordingly, it is essentially carried out by states services such as navy, customs, police, but also by port authorities or shipping companies, and even by marine users themselves at a local scale.

This "*multi-faceted*" surveillance [22] involves a wide range of systems : on-board transmission devices (Automatic Identification System – AIS [27]; Vessel Monitoring System – VMS [28]), recording systems (Voyage data recorder [29]), marine radars (frequencies ranging from HF to X-band [30–32]) or imagery (in situ observation, aircraft, drone, satellite [33]), each with its specific characteristics in terms of spatial and temporal coverage and resolution, existence and precision of associated metadata, format, fleet coverage.

State services and port authorities surveillance systems, often operated by shore-side Vessel Traffic Services (VTS [34]), produce tremendously large amounts of data, and its uses in delayed time open new perspectives to inform the spatial and temporal footprint of activities (e.g. [18]) particularly because of their continuous and systematic nature.

Contributions from these data to Marine Spatial Planning have started to be scientifically documented in a few cases [18,35], and could *a priori* be diverse: for environmental purposes, to apprehend, avoid, reduce or compensate impacts of activities, as well as for economical ones, to anticipate and mitigate conflicts of use, to find space for new activities or for activities to assert their interest, for instance.

If Le Tixerant et al. (2018) [18] have already studied some contributions of AIS data for MSP, the contributions of *maritime surveillance data* as a whole for planning purposes has yet to be assessed on a global scale.

Using the scientific literature as a proxy, this paper aims at drawing up the state of the art of maritime surveillance data uses for planning purposes. A first global analysis of maritime surveillance data-based researches is conducted to highlight the attention given to certain types of maritime data or specific activities, and to the current technical and methodological developments in terms of data acquisition and processing. A more detailed analysis is then conducted on papers linking maritime surveillance data to their potential uses for MSP, in order to identify standard or common practices and specific knowledge gaps.

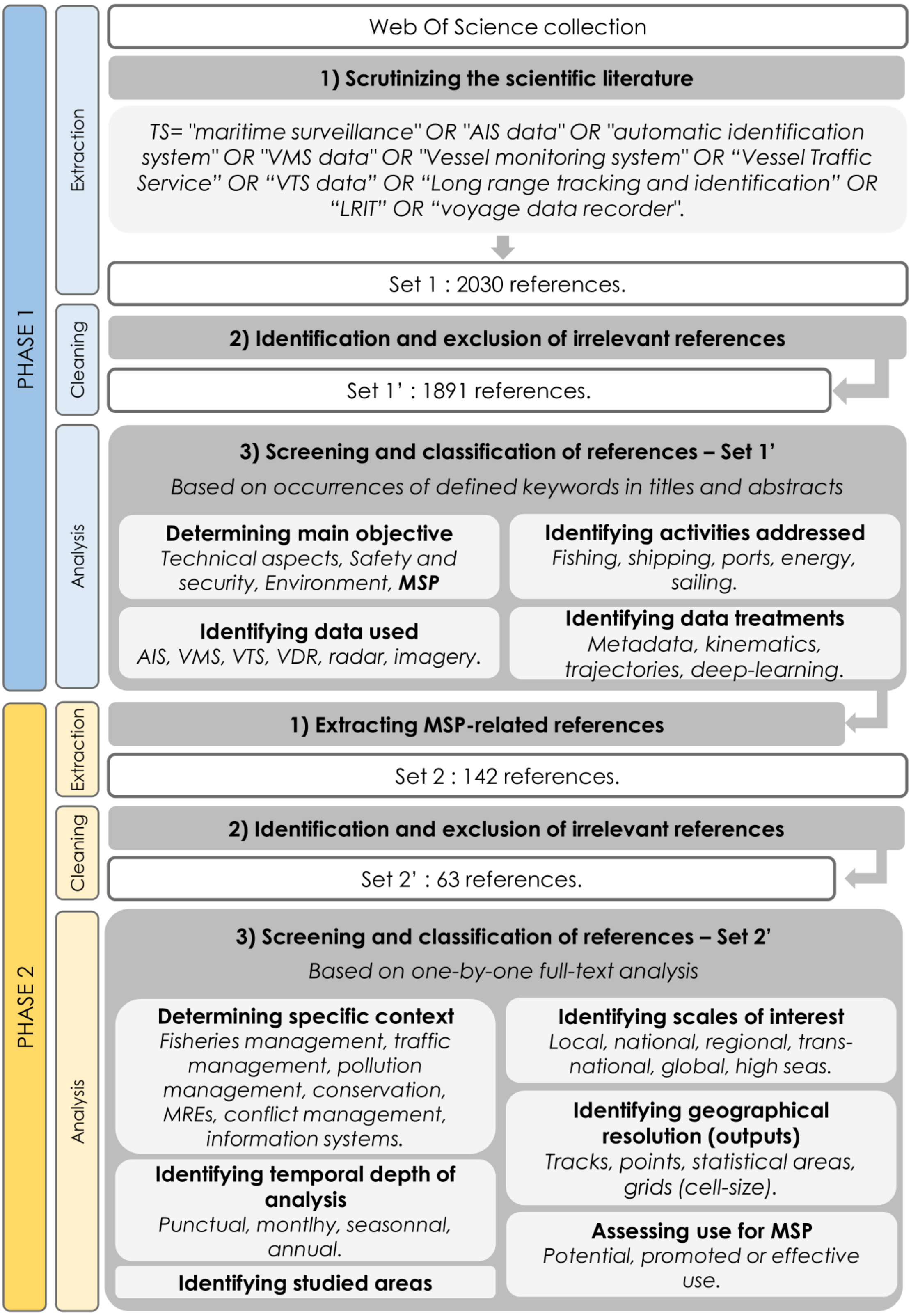
2. Methodology: Reviewing the scientific literature

For this literature review, the *Web of Science* was considered the most exhaustive collection of international scientific literature, despite its indexation delays. The overall methodology consisted of two phases, both divided in 3 major steps: 1) identification and extraction of relevant references, 2) cleaning and exclusion of bycatch and 3) screening, classification and analysis.

Phase 1 focused on a global corpus of references dealing with maritime surveillance data broadly (Set 1 and 1'). Classification was based on occurrences of a set of keywords in *Titles* and *Abstracts*. Phase 2 then focused on a subpart of the global corpus, dealing with uses of maritime surveillance data for MSP (Set 2 and 2'). In this case, full-text were explored one-by-one for classification.

The methodology is summarized in **Erreur ! Source du renvoi introuvable.** and detailed in the following paragraphs.

FIGURE 1. OVERALL METHODOLOGY - LITERATURE REVIEW



2.1. **Phase 1: Maritime surveillance data-based references**

2.1.1. Scrutinizing the scientific literature

The Web of Science was explored with the following query, designed to include all maritime surveillance systems and sensors as defined by the European Union [36]:

> TS= "maritime surveillance" OR "AIS data" OR "automatic identification system" OR "VMS data" OR "Vessel monitoring system" *OR "Vessel Traffic Service" OR "VTS data" OR "Long range tracking and identification" OR "LRIT" OR "voyage data recorder*"

The "TS" equation enables exploration in both titles, abstracts, author keywords and Keywords Plus®. "*Radar*" and "*imagery*" were excluded from the equation as they do not specifically refer to maritime subjects. This research equation led to the collection of n=2030 papers, published from 1980 to 2019 in over 800 scientific journals.

2.1.2. Identification and exclusion of irrelevant references

7% of the corpus was considered irrelevant and excluded from following analysis. These references were spotted iteratively through:

1) Exclusion of previously identified bycatch: military strategy, geopolitics.
2) Manual inspection of references with low responses to the keyword's exploration used for analysis and detailed in the next section;
3) Manual identification of clear "misunderstanding": medical AIS, RFID tags, and automatic exploration of the corpus with corresponding keywords (e.g: patient, disease, injuries, RFID, etc.); manual exclusion of identified references.

After cleaning, Set 1' comprises 1891 references.

2.1.3. Screening and classification of references

Literature reviews have become in the last decades a more and more frequent aspect of the research process, in response to a constantly increasing scientific literature [37]. Bibliometrics methods are abundant, and most of them rely on statistical lexical analysis and on detailed exploration of identified references [38,39]. In this paper, due to the consequent size of the identified corpus, the screening and classification of references was automated, based on the detection of a set of selected keywords in both title and abstract of each paper, following the fundamental logic of literature identification in most search engines. Full texts exploration was not considered necessary except for a few cases.

Four aspects were analysed for each of the collected papers: 1) the main objective of the paper, 2) the maritime activity(ies) explored, 3) the type of data used and 4) the treatments applied to raw data.

For each of these aspects, defined *a priori*, a set of subcategories was defined. For 1) *data used*, were considered: AIS, VMS, VTS, radar, imagery and VDR; For 2) *maritime activities addressed*, were distinguished: shipping, fishing, port activities, marine renewable energies (MREs), oil and gas, and sailing. For 3) *main objective*, four subcategories were defined: safety and security, environmental protection, MSP and technical aspects. Finally, for 4) *data treatments* were spotted: trajectory analysis and artificial intelligence techniques.

Keywords were defined from a previous manual analysis on 100 randomly selected references and adapted iteratively during the analysis, resulting in the selection of keywords presented in ***Erreur ! Source du renvoi introuvable.***.

TABLE 1. KEYWORDS DEFINITION FOR TITLES AND ABSTRACTS INSPECTION

Category	**Subcategory**	**Keywords**
Main Objective	MSP & resource management	Planning, management, policy, governance
	Safety	risk, collision, accident, security, threat, near-miss, encounter, rescue, surveillance, cybersecurity, safety
	Environment	Noise (pollution), sound (pollution), emissions, discharge, poisoning, discard, protect, pressure, footprint, bio, anchoring, environment, illegal fishing
	Technical aspects	*Articles not matching with any other objective**
Maritime activities addressed	Fishing	Fishing; trawling
	Shipping	Shipping; traffic; navigation; cargo; container; transport; tanker; cruise; ferry
	Port activities	Terminal; harbour; port, dredging
	MREs	Renewable; wind; tidal; energy
	Oil and gas	Oil and gas
	Sailing	Sail
Data used	AIS	AIS, automatic identification system
	VMS	VMS, vessel monitoring system
	Radar	radar
	VTS	VTS, Vessel traffic service
	Imagery (sat, aerial, video)	Image, optical, sentinel, lapan, SAR (synthetic aperture radar), remote, video
	VDR	VDR, voyage data recorder
Data Treatments	Trajectories	Trajectory, pattern, course, behaviour, voyage, event, recognition, kinematic, velocity, movement, speed
	Artificial Intelligence	Neural, mining, heuristic, learning

** It is assumed that articles not matching with either safety, environment or MSP objectives focus on technical aspects. This assumption was confirmed through a 200 references manual check (10% of the corpus), with an accuracy of 95%.*

In some cases, keywords spotted in abstracts leaded to clear over-estimations, as precision of words decreases in comparison with titles. Ex: “Noise”: when “noise” appears into an article’s title, it refers to marine noise pollution in 80% percent of cases (*28 out of 34)*, which was considered as a suitable proxy. However, due to its ambiguous meaning, especially with regards to “noise” in radar signal processing, this ratio comes down to 25% when “noise” appears in abstracts (*29 out of 117*). In other words, abstract exploration only led to the identification of one relevant paper out of 83 responses to “noise”. In that sense, “noise” was excluded from the analysis of abstracts. Other cases were spotted through aberrant (Title)<(Abstract) ratios (>6 fold) and led to the exclusion of 9 keywords from abstract research (***Erreur ! Source du renvoi introuvable.***).

TABLE 2. KEYWORDS EXCLUDED FROM ABSTRACT INSPECTION

Category	**Subcategory**	**Keywords excluded for abstract research**	**Justification**
Activities	Port activities	port	becomes technical (e.g. usb port)
	MREs	Wind	Relates to meteorological conditions
Objectives	MSP	management	too broad in abstract
		Policy	too broad in abstract
	Safety	threat	redundancy with environment
		surveillance	too broad as part of the initial research equation
	Environment	Noise	relates to signal processing (noisy radar)
		sound	relates to acoustics broadly (e.g. marine mammals communication)
		environment	becomes technical (e.g. software environment)
Data	Imagery	SAR	also stands for Search and Rescue

Duplicates resulting from both (1) titles and abstract redundancy and (2) occurrences of multiple keywords for the same subcategory were deducted before any analysis

2.2. Phase 2: references linking maritime surveillance data to MSP

2.2.1. Extracting MSP-related references

In order to assess current uses of *maritime surveillance data* for MSP purposes, references from Set 1' with mentions of "*Marine Spatial Planning and resource management*" associated keywords were extracted and a subset of n=142 papers was isolated.

2.2.2. Identification and exclusion of irrelevant references

Due to limitations of the keywords approach, and more precisely to the multiple meanings of most MSP associated keywords (*planning*, *management*, *policy*), a significant portion of bycatch remained, dealing with route and navigation planning (at individual ship's level), operation and safety management (in real-time) as well as data management and policy. A one-by-one manual validation was conducted to avoid over-estimation, bringing the subset down to n=63 papers (Set 2').

2.2.3. Screening and classification of references

To overcome the limits of the approach deployed in phase 1, based on an automated detection of keywords in titles and abstracts (over-estimation, over-interpretation) [40], full texts were considered for each of these 63 papers, to explore the following characteristics:

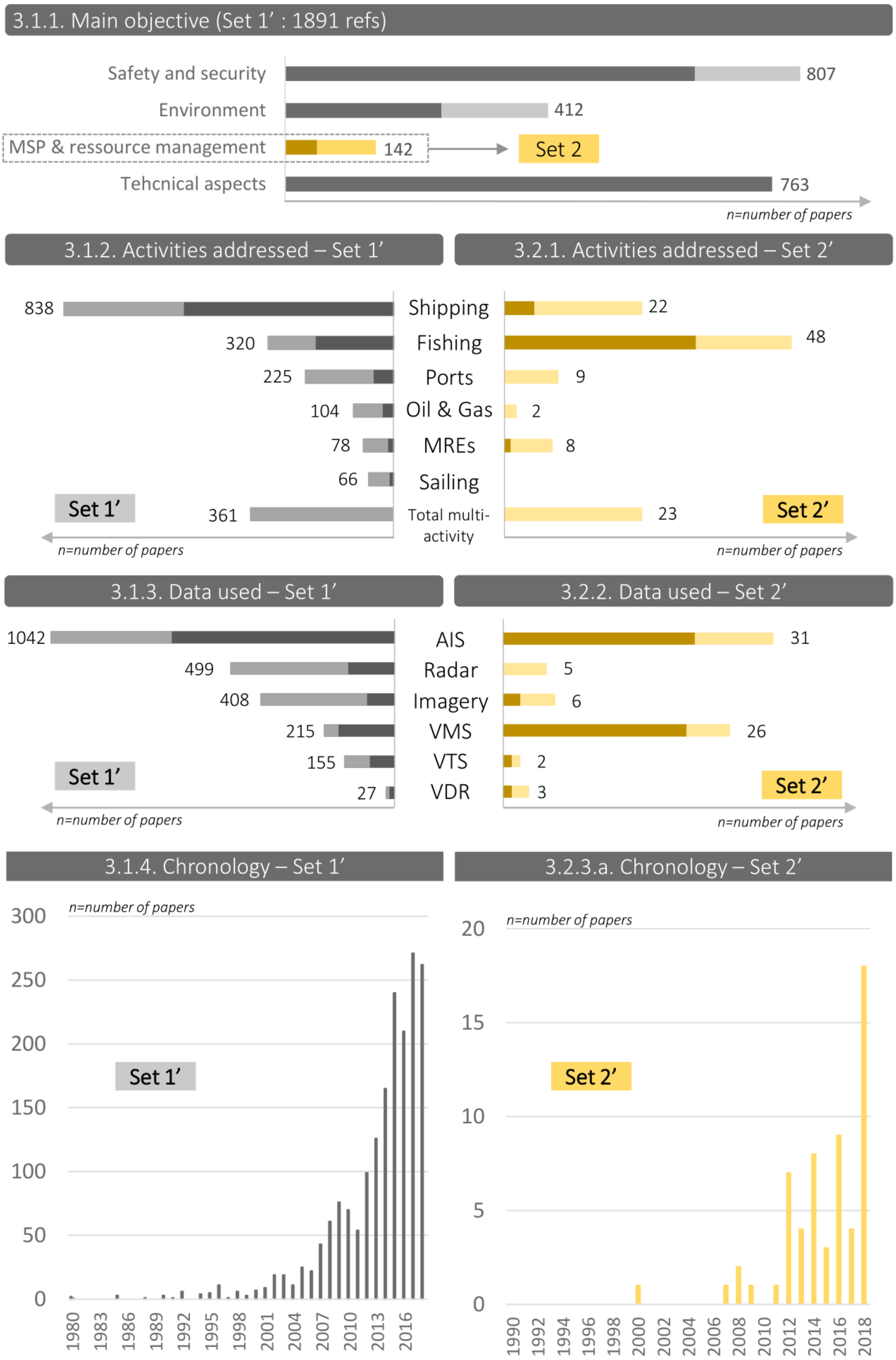
- The specific context of each study. If all relate to uses of maritime surveillance data for MSP, most deal with specific aspects of this general process: fisheries management, traffic management, noise and air pollution management, conservation, development of marine renewable energies (MREs), conflict management or information system implementation.
- The scale of interest of each study: from local level (Marine Protected Areas, MREs projects, specific fisheries management zones) to national or regional one and up to global level.
- The geographical resolution of produced surveillance-based datasets, from raw tracks and points to density maps with grids units sorted in 5 categories: <0.25km^2; 0.25-1km^2; 1-25km^2; 25-225km^2; >225km^2.

- The temporal depth of analysis, which may or may not provide information on the seasonality of some maritime activities (e. g. fishing or pleasure boating): annual, seasonal, monthly or punctual.
- The treatments applied to raw surveillance data to extract information: from metadata alone to kinematic analysis (speed) or involving deep-learning and other artificial intelligence approaches.
- The degree of support to MSP: from the identification or the promotion of potentials for MSP applications, to the description of effective data use for MSP.
- The location of studied areas across the globe, highlighting the geographical distribution of surveillance-based MSP research.

3. Results

The first phase of the analysis, conducted on the global corpus of papers (Set1'), provides an overview of the distribution of articles according to their main objective, the activities they address and the surveillance data they focus on. **Erreur ! Source du renvoi introuvable.** summarizes the results obtained during this phase, both for the global corpus (Set1') and for the sub-corpus specifically dealing with MSP (Set2').

FIGURE 2. RESULTS (1/2) MAIN OBJECTIVE, ACTIVITIES ADDRESSED, DATA USED AND CHRONOLOGY OF PUBLICATIONS FOR SET 1' (PHASE 1 – IN GREY) AND 2' (PHASE 2 – IN YELLOW).



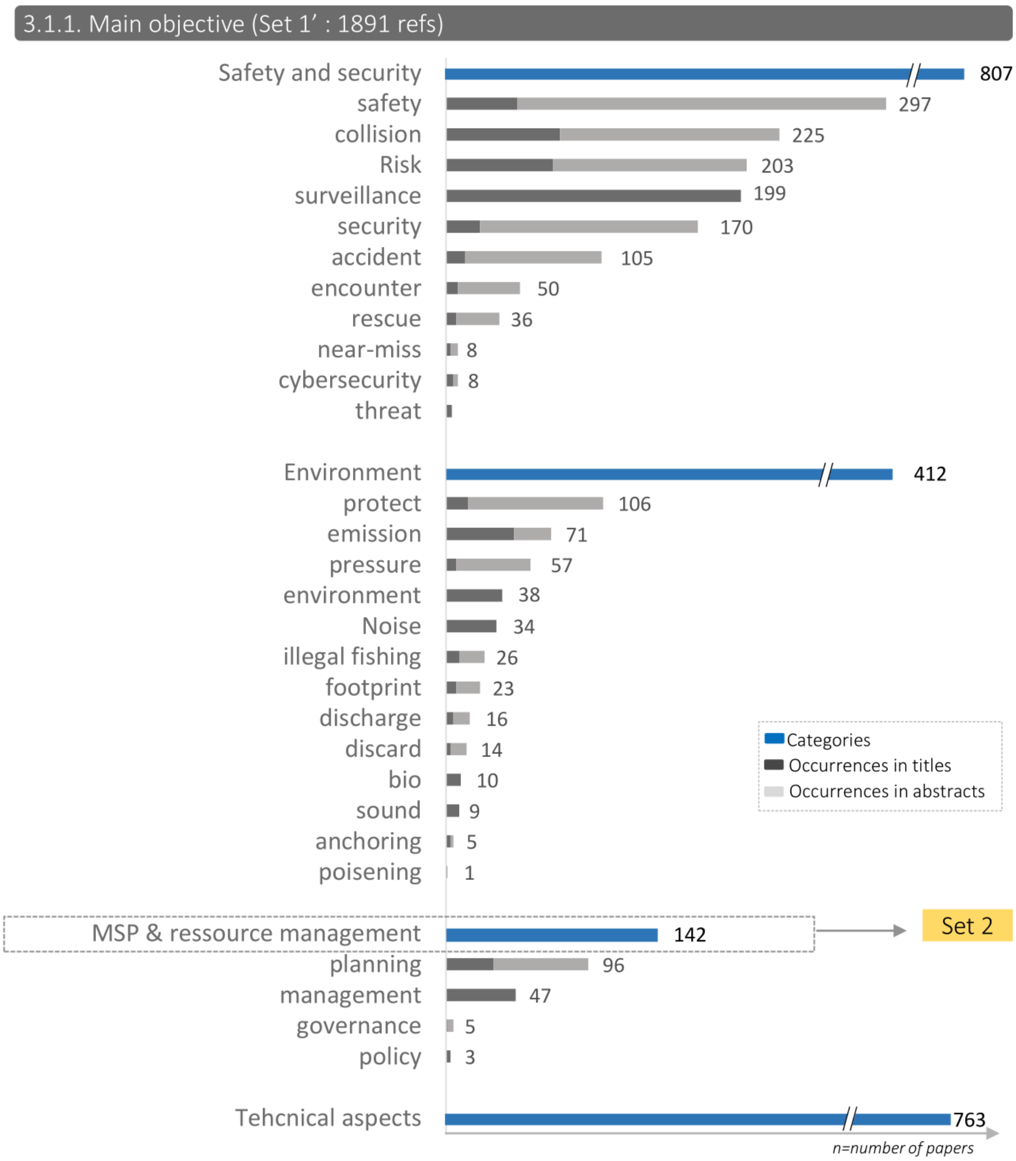
3.1. Phase 1: Analysis of maritime surveillance data-based references

3.1.1. Main objectives

The most significant portion of Set 1' deals primarily with uses of maritime surveillance data for safety and security issues (42%), and about 20% of these make explicit links to associated environmental or planning issues.

40% (n=763) of the 1891 references were identified as mainly dealing with technical aspects of maritime surveillance, focusing on surveillance systems themselves, in terms of geolocation capabilities, transmission technologies or signal processing for instance, and do not address planning issues at all. Uses of maritime surveillance data for environmental objectives are addressed in 18% of references, with focus ranging from detection of illegal fishing to assessment of marine noise pollution for instance. Finally, only 7% of references from Set 1' were identified as dealing with MSP and marine resources management. The number of papers spotted with each specific keyword per category of objective are detailed in **Erreur ! Source du renvoi introuvable.**, where occurrences in titles and in abstracts are distinguished.

FIGURE 3. DISTRIBUTION OF PAPERS ACCORDING TO SPECIFIC KEYWORDS SPOTTED FOR EACH CATEGORY OF OBJECTIVE (SET1'). THE NUMBER OF PAPERS FOR EACH CATEGORY APPEARS IN BLUE, AND KEYWORDS OCCURRENCES IN DARK GREY FOR TITLES AND IN LIGHT GREY FOR ABSTRACTS.



3.1.2. Maritime activities addressed

There is a clear predominant interest on *shipping* in Set 1', addressed in 838 papers (44%). These papers focus mainly on uses of maritime surveillance for navigational safety, but also for optimisation of routes and related consumptions (fuel, energy) and emissions (air pollutants, Green House Gases, sound).

The second most addressed activity is fishing, mentioned in 17% of the corpus (320 refs). These papers focus on uses of maritime surveillance data to assess fishing effort and pressure as well as to detect illegal fishing for instance.

Other maritime activities are much less frequently discussed. References to port activities were spotted in 12% of the corpus, Oil and Gas activities in 5%, marine renewable energies in 4%, and sailing in 3%.

Total percentages exceed 100% because 20% of the papers address multiple activities simultaneously.

690 papers did not respond to any of the *Activities* keywords, most of them also identified as dealing with technical aspects of maritime surveillance.

3.1.3. Maritime surveillance data used

AIS data appears as the most widely used or studied surveillance data, spotted in 1042 papers (55%). In about a third of cases, AIS is not used alone but in combination with other data (366 refs).

Radars also appears as a significant area of interest for research, spotted in 499 papers (26% of Set 1') and most often addressed along with other surveillance data (combinations in 70% of cases).

Uses of Imagery (spatial, aerial or terrestrial) are also abundant (408 refs, 21% of Set 1') most often combined with other data (80% of cases).

VMS data are used or studied in 215 papers (11 %), with a very small combined fraction (20%). VTS are addressed in 155 papers (8%) and mentions of VDRs remain anecdotic (1%).

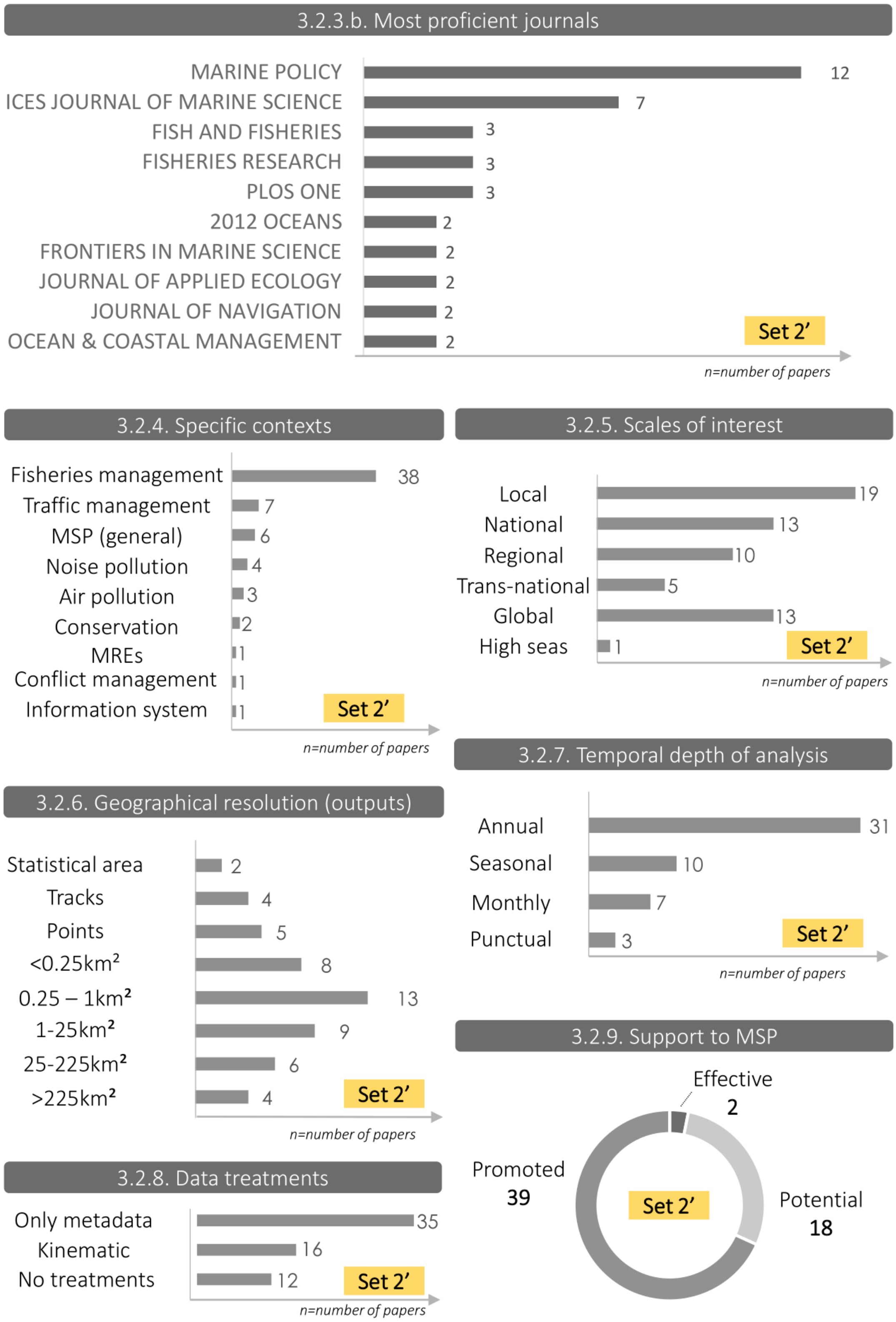
3.1.4. Chronology of publications

Papers from Set 1' were published from January 1980 to April 2019 in over 800 different journals. A significant majority of the corpus was published after 2010 (84%), and most of it after 2000 (98%). Maritime surveillance appears as a recent subject of interest for scientific research, with a significant growth rate (mean annual growth rate = 36% between 2000 and 2018, and 18% since 2010). The most represented journals in Set 1' are: The Journal of Navigation (63 papers), Ocean Engineering (35 papers), the ICES Journal of Marine Science (35 papers) and Marine Policy (27 papers).

3.2. Phase 2: references linking maritime surveillance data to MSP

Results presented hereafter only concern Set 2', composed of 63 references linking maritime surveillance data to its MSP applications (**Erreur ! Source du renvoi introuvable.**).

FIGURE 4. RESULTS (2/2) – CHARACTERISTICS OF REFERENCES LINKING MARITIME SURVEILLANCE DATA TO MSP.



3.2.1. Maritime activities addressed

When shipping was the most addressed activity in Set 1', uses of maritime surveillance data in Set 2' mainly concern fishing activities (76%) (**Erreur ! Source du renvoi introuvable.**). Shipping is only addressed in 35% of references, followed by Marine renewable energies and port activities, respectively in 14% and 12% and Oil and Gas activities in 3%. Total percentages exceed 100% because over a third of the papers address multiple activities simultaneously.

3.2.2. Maritime surveillance data used

As for set 1', *AIS* is the most used data in Set 2' (49%) (**Erreur ! Source du renvoi introuvable.**). *VMS* is much more represented than in set 1' (41%). For both, combinations with other data are relatively low (respectively 29% and 19%). *Imagery*, *VDR* and VTS are anecdotic, respectively 9%, 5% and 3%, and *radar* is never used or studied alone.

3.2.3. Chronology of publications

Publications on this specific subject started a few years later than for Set 1' but have undergone a significant mean annual growth of +120% since 2000 (**Erreur ! Source du renvoi introuvable.**). The 63 references were published from 2000 to 2019 in 45 different journals. *Marine Policy* and the *ICES Journal of Marine Science* are the most prolific, with respectively 12 and 7 references.

3.2.4. Specific contexts

Only 6 papers from Set 2' deal with MSP as a whole, others addressing specific subparts of the global MSP process. An absolute majority (60%) targets fisheries management, when only a few targets traffic management (11%), noise (6%) and air (5%) pollution management, conservation (3%), MREs development (3%), conflict management (2%) and information systems implementation (2%) (**Erreur ! Source du renvoi introuvable.**).

3.2.5. Scales of interest

Most of the studies focus on the local (i.e. sub-national) level (30%), but also a lot on the national (20%) and global level (20%). The regional and transnational levels account for 16% and 8%, and high seas only for 2%. (**Erreur ! Source du renvoi introuvable.**).

3.2.6. Geographical resolution (outputs)

12 papers were broad reviews of maritime surveillance data potentials or of other studies, but 51 studies produced spatiotemporal descriptions of activities. Most produced density maps, with cell-sizes ranging from 50*50m to 1*1°. The most common unit appears to be between 0.25 and 1km^2 (20%), but other resolutions are almost evenly represented. Respectively 5 and 4 papers only provided raw points or tracks data (**Erreur ! Source du renvoi introuvable.**).

3.2.7. Temporal depth of analysis

Most studies used or produced data aggregated over a year (31 papers). 10 papers addressed seasonal variability, and 7 monthly variability. 3 studies only used punctual data (a few days or weeks) (**Erreur ! Source du renvoi introuvable.**).

3.2.8. Data treatments

To distinguish activities and ship's types, most studies used metadata from AIS and VMS (35 papers. A few studies used vessel's speeds to derive information on activities (16 papers), to differentiate between transit and fishing phases of a fishing vessel for instance, or to estimate actual consumption and emission of ships. Deep-learning and other data mining techniques were only addressed in 2 papers. Ten studies were based on raw data without any kind of treatments (**Erreur ! Source du renvoi introuvable.**).

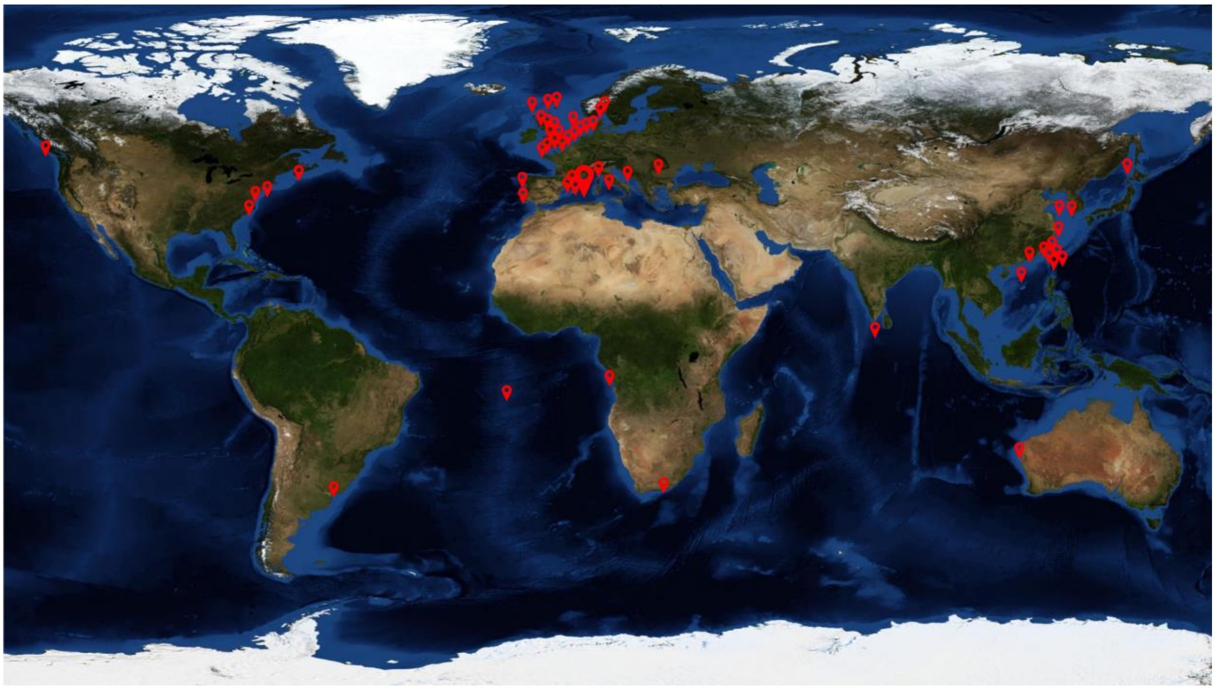
3.2.9. Support to MSP

Of the 63 papers from Set 2', only 2 described actual use of maritime surveillance data in MSP initiatives: as a way to manage fisheries in the Ascension Island [41] and to take into account shipping activities in European MSP initiatives [18]. Others either promoted its use (43 papers) or identified a potential for usage (18 papers).

3.2.10. Most studied areas around the globe

Areas studied in Set 2' are not evenly distributed around the world, with a significant predominance in European waters (27 papers), and mostly around the North Sea (17 out of 27). East-Asia has also been frequently studied (12 papers) (**Erreur ! Source du renvoi introuvable.**) Other parts of the world are studied in a more anecdotic way. Only 50 studies are depicted, as some broader papers either deal with no specific area or with the entire world.

FIGURE 5. GEOGRAPHICAL DISTRIBUTION OF PUBLICATIONS – SET 2'



4. Discussion

4.1. Maritime surveillance data as a significant input for scientific research

Maritime surveillance data have increasingly been used in the scientific literature over the last decade, mostly for studies aiming to improve *maritime situational awareness* and safety and security at sea, but also to a growing extent to map shipping density in different areas of the world [41,42] to assess fishing effort [43–45], to serve as a basis to extrapolate noise [46] and atmospheric pollutions [47], to assess risks and conflicts between activities [48,49] as well as cumulative environmental impacts [50,51].

The significant 36% mean annual growth rate of Set 1' appears as corelated to the global development of maritime surveillance, resulting from IMO's resolutions concerning Vessel Traffic Services and the requirement for AIS carriage (formalized in the revised version of the SOLAS 19 convention in 2000 [21]) and to the emergence of new data sources for national and regional regulation (e.g. VMS requirements in Europe in 2011 [52]) . As a result, most of the identified literature deals with safety and security issues. In these cases, there is a specific interest in real-time data acquisition to improve *maritime situational awareness* [26]. Numerous papers also study potential uses of data in delayed times to improve instantaneous detection of abnormal situations and dangerous behaviours by analysing past events [53,54]. Another significant portion of Set 1' focuses on technical aspects of maritime surveillance, illustrating the constant progress of maritime surveillance systems and the potential for improvement in terms of equipment [55–57], data acquisition and fusion [56,58,59], pre-processing and exploitation [60–62]. A large share of these papers focusses on event and activity recognition based on trajectory analysis [63,64], sometimes relying on artificial intelligence (deep-learning, data mining) [65,66]. A minor but non-negligible share of papers focuses on uses of maritime surveillance data to serve environmental objectives, either in real-time to ensure compliance with environmental regulations and detect offenders [67–69], or in delayed-time to assess impacts on ecosystems and marine and atmospheric pollutions [46,70,71]. In comparison, explicit references to MSP are still rare, despite an increasingly recognized potential to address the diversity of planning issues.

AIS is by far the most used maritime surveillance data, certainly as a result of its availability through official bodies or private companies -depending on areas and countries- , its temporal and spatial resolution, its coverage of the fleet and the richness of the associated metadata [18]. As a result, shipping is clearly the most studied activity in the collected literature. Radars, as essential tools for maritime surveillance in real-time, also emerges as a significant input for maritime research, mainly addressed from a technical point of view (e.g. calibration, noise-filtering, single ship tracking)(e.g. [72,73]) or to assess physical and biological parameters (e.g. [32,74,75]). Imagery data also appear as a non-negligible input with associated remote sensing techniques (e.g. [76,77]). Radar and imagery data-based studies often do not focus on a specific activity, but on objects moving at the sea-surface, be it *ships*, *boats, vessels* or *mobiles.* As a result, occurrences of *Activities* keywords mostly arise from more sectoral based data such as AIS and VMS. VMS data are used to a smaller but still considerable extent, to support fisheries management [44] or to assess the carry-over induced by marine protected areas [78] of offshore windfarms implementation [28] for instance. VMS strengths (metadata and coverage of the fishing fleet) are still probably being hampered by its low accessibility. Data coming from VTSs are addressed in more than a hundred papers. It should be noted that the importance of VTS in providing surveillance data may be underestimated, as VTSs involve various monitoring systems (mainly AIS and radars) ([79]) and their contributions may therefore be diluted in the other data categories. In addition, the storage of data produced by VTS is not systematic, and access to it by the scientific community remains limited ([35]). Finally, VDR data, initially designed for accident replay, are hardly ever used for research, probably because these data are rarely collected or available. The analysis of co-occurrences of different data in single papers illustrated the interest of combinations of different data sources, mainly when using metadata-less data (radar and imagery) (e.g. [80,81]). It also points at the -yet- very isolated use of VMS data.

4.2. Maritime surveillance data as an emerging input for MSP

Uses of maritime surveillance data for Maritime Spatial Planning only represent a little fraction of Set 1'. Papers linking maritime surveillance data to MSP are rare and recent, in correlation with the international development of MSP in the last decade (see [9]). If these uses for MSP remain particularly limited in the scientific literature, Set 2' however shows an impressive mean annual growth rate of 120%. Comparable to the growth rate of set 2' in the early 2000, this stresses out an emerging interest on the subject and could indicate the premises of a steeper slope in the coming years, along with the development of MSP initiatives.

Santos et al. [9] highlighted that about 70 percent of the MSP initiatives undergoing in 2017 took place in Europe (37%) and in North and central America (29%). Surprisingly, very few studies on uses of maritime surveillance data for MSP were conducted in North and central

America. However, European waters appear to be the most studied worldwide, quite clearly linked to the effect of European regulations, especially MSFD [11] and MSP directive [10] in 2008 and 2014, that force member states to both reach a "good marine environmental status" and to develop marine spatial plans for their EEZ. European waters are also very intensively used, be it in the English Channel [82], in the North Sea [83] and the Baltic Sea [84] as in the Mediterranean, and have therefore been the cradle of numerous transnational initiatives leading to improvement in maritime surveillance data production, archiving, centralization and sharing, with high stakes in terms of standardization, both for safety and security issues (CISE-EMSA-[85]) and for MSP itself (e.g. EmodNet -[86]; SIM projects – see [87])

In the MSP context, AIS and VMS data seem to be the most fitted. The use of imagery data remains anecdotic, probably because of their discontinuous temporal coverage, a little more fitted to identify punctual abnormal activities (e.g. illegal fishing, pollution) than to generate exhaustive information on maritime activities over time, but also because their processing appears to be more difficult to automate. Stand-alone radar data are yet never used in the MSP context, but mentioned in few cases as potential complements to other data sources. If radars are commonly used for coastal surveillance and the detection of punctual abnormal activities, their uses in delayed time to assess overall maritime activities patterns and footprint are still embryonic research subjects, mostly treated from a technical point of view (e.g. [88,89]). The collection and use of radar data produced at ships-level, which could significantly increase the spatial coverage of such system (through an extensive and collaborative surveillance) remains at this stage completely unexploited, certainly due to the countless sources (each equipped vessel) and the associated technical challenges (storage, collection, aggregation and over-lapping, harmonisation).

In Europe and elsewhere, AIS and VMS data proved to be relevant at all scales, from international to national, and even more at local level. Density maps seem to be the most relevant form of visualization, and their geographical resolutions are very much dependent on the scale of interest, with bigger grids used at international levels than at local ones. However, a trend seems to be emerging in favour of cell-sizes about 1*1km. Despite the great temporal variability of maritime activities [18] and its implications for planning -because different activities can operate in the same zones at different time of the year or of the day-, aggregation of activities over a year are the most commonly used.

Complex trajectory analysis based on deep-learning technics were frequently discussed in Set 1', with lots of developments in the recent years. However, they remain anecdotic when addressing MSP, maybe as a result of a still latent need for improvement in terms of robustness. In Set 2', most studies based their analysis solely on metadata associated to surveillance data. Metadata from AIS and VMS are quite rich (see [18] and [52]) and allow to easily derive information on specific types of ships or activities. Nevertheless, a significant share of papers also uses ship's speed thresholds as indicators of specific activities, especially in the case of fishing to distinguish transit from active fishing phases.

In about half of the identified papers, despite the integrated vocation of MSP, a single activity is explored, either to document it for MSP or to analyse its position within MSP processes. When shipping was the most explored activity in Set1', there is a clear shift of interest towards fishing when discussing MSP. This is probably the result of various factors including: the existence of a specific monitoring system -VMS- and associated data; the importance of fisheries management in the MSP context, as an historical and widespread activity of which arise most space-related conflicts, especially in more and more coveted coastal waters; the remaining information gaps about fisheries, resulting from both the complexity and diversity of these activities [90] and from a certain culture of secrecy [91].

4.3. Perspectives: maritime surveillance data as a standard MSP input?

It should be noted that, if all papers from Set 2' make explicit links between maritime surveillance data and their uses for MSP, most of them only promoted these uses (i.e. these data/this research "should support MSP") or identified it as a potential (i.e. this "could support MSP"), and only 2 described effective uses for MSP.

For maritime surveillance data to become a standard input for MSP, some limitations might have to be overcome.

One remaining limitation with mostly used AIS and VMS data is that they are not required for smaller ship (<300 gross tonnage for AIS, and <12m for VMS in Europe). As a result, information extracted from these data do not offer exhaustive depiction of maritime activities spatiotemporal footprint, especially in coastal areas where most ships are below these size limits. A few attempts have been made to fill this gap, either by introducing cooperative data collection (interviews [90,92], GPS on specific fleets,[93,94]) or by mobilizing the potential offered by coastal radars, much less dependent on ship's size [32,95,96]. The extension of requirements for VMS on smaller ships is currently discussed in Europe within the Common Fisheries Policy (CFP, [97]) and could contribute to reducing these gaps.

Another significant issue lies in data accessibility. As a result of the multi-faceted dimension of maritime surveillance, both in terms of supervisors and of objectives, data is not necessarily archived, and remains scattered and rarely shared [98]. Improving data exchanges between states and services has been identified as a crucial issue in Europe, which is currently developing a *Common Information Sharing Environment* (CISE) to *"give all concerned authorities access to the information they need for their missions at sea"*. This collection of information is however taking place in a fuzzy legal context [18,91] and is being hampered by strategic (defence secrecy) and economic aspects(confidentiality, commercial secrecy)[98]. This is mainly the case for data produced in a military context, but also for sectoral data such as VMS data. AIS data seem to be more easily made available, while it could also have strategic implications from both economic (e.g. competition) and security (e.g. piracy) point of views. However, public AIS data are only available in few countries (e.g. USA, Denmark) and most of data acquisition relies on commercial distributors (e.g. Marine traffic, Fleetmon, amongst many others).

The acceptability of such derived uses of surveillance data -out of the safety and security spectrum- by economic sectors and related administrations is probably another reason for data unavailability. In the complex context of MSP development -as marine space becomes finite- activities with expansion strategies (MREs, aggregate mining, aquaculture, but also conservation in a way) start to compete with historical ones. These ones, managed through sectoral regulations up to now, are progressively compelled to engage in broader and more integrated governance mechanisms [14,91,99]. While information on their spatiotemporal footprint can contribute to their better consideration, it might as well be the basis for fully informed decisions that have an impact on them [12,13,100]. In that sense, a certain opacity is probably desired by some stakeholders, considering surveillance data as interfering with an already complex establishment of effective integrated maritime governance scenes, with a strong top-down approach.

Despite these limitations, the coming years will most probably call for a constantly increasing need to inform the spatiotemporal footprint of existing activities, and thus for more and more uses of maritime surveillance data. As an evidence, 132 new scientific papers matching the research query used for this paper were indexed on the Web Of Science since analysis were conducted. It will probably be the case especially in Europe, be it in response to environmental protection objectives (MSFD, [11]) and more specifically to address the issue of cumulative impacts, but also to prepare the ground for a *decarbonized* Europe [101] for which MREs capacities should be multiplied by 4 in 2030, and by 20 in 2050. Presumably, conflicts for space will only increase, and surveillance data could help setting the scene into which wind farms and other MREs will take place.

5. Conclusion

Recent developments in maritime surveillance systems, such as the automatic identification system (AIS), the vessel monitoring system (VMS) or vessel traffic services (VTS) have led to the generation of significant amounts of data, strongly improving the m*aritime situational awareness*. This literature review allowed to highlight the growing interest on maritime surveillance data in the scientific literature over the past decade, predominantly towards AIS and radar data. Within the frame of Maritime Spatial Planning, these data have more recently gained interest from the scientific community, eager to address the knowledge gaps on the spatial and temporal dynamics of maritime activities, especially on fishing and shipping. This is particularly the case in European seas and oceans, where MSP has been a hot topic, and will probably continue to be considering the European objectives for MREs development.

Nevertheless, if numerous papers highlighted the potential of maritime surveillance data to feed in MSP processes, the description of effective uses of surveillance-based information within actual MSP processes remains particularly rare in the scientific literature. Apart from technical limitations of these data, especially when considered separately, this lack of concrete examples can be seen as a result of a science-policy delay that could be overcome by exploring grey literature and political documents (see [102]), even in other languages (Chinese, French, Spanish). However, we suggest that it might as well illustrate the tensions generated by MSP, and that it could mostly be related to issues of accessibility, of acceptance by economic stakeholders and of appropriation by decision makers.

6. References

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