Vessel Tracking Datasets For Monitoring Canada's Conservation Effectiveness

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Identifying indicators for monitoring the effectiveness of Canada's conservation areas is a key next step following the recent expansion of marine and coastal protection. Levels of compliance with protected area restrictions and the extent and intensity of other ongoing human pressures are fundamental measures to include in monitoring programs as they facilitate interpretation of trends in ecological data and inform the need for adaptive management and regulations. Human pressures within Canada's marine conservation areas are often associated with vessel traffic through fishing activities or vessel-related impacts. The Government of Canada has been collecting a variety of vessel tracking data for several years that to-date have largely been used for real-time maritime awareness or compliance purposes. The benefits of such data for measuring long-term vessel impacts and monitoring conservation areas is becoming increasingly recognized worldwide. To take better advantage of these data in the future requires understanding what data are available, their access and use restrictions, how they are collected and stored, the spatial and temporal resolutions, and benefits and challenges associated with various data types. We provide these details for Automatic Identification Systems, Vessel Monitoring Systems, aerial surveillance, RadarSat II, and violation records as an initial step towards applying vessel tracking data as an indicator for monitoring conservation areas in Canada, with a focus on measuring fishing activities and fishing non-compliance.

RÉSUMÉ

Iacarella, J.C., Clyde, G., and Dunham, A. 2020. Vessel Tracking Datasets For Monitoring Canada's Conservation Effectiveness. Can. Tech. Rep. Fish. Aquat. Sci. 3387: viii + 31 p.

L'identification d'indicateurs pour surveiller l'efficacité des aires de conservation du Canada est une prochaine étape clé après l'expansion récente de la protection marine et côtière. Les niveaux de conformité aux restrictions des aires protégées et l'étendue et l'intensité des autres pressions humaines en cours sont des mesures fondamentales à inclure dans les programmes de surveillance car elles facilitent l'interprétation des tendances des données écologiques et éclairent la nécessité d'une gestion adaptative et de réglementations. Les pressions humaines dans les aires marines de conservation du Canada sont souvent associées au trafic maritime par le biais d'activités de pêche ou d'impacts liés aux navires. Le gouvernement du Canada recueille depuis plusieurs années diverses données de suivi des navires qui, à ce jour, ont été largement utilisées à des fins de sensibilisation maritime ou à but de conformité aux règlements. Les avantages de ces données pour mesurer les impacts à long terme des navires et surveiller les zones de conservation sont de plus en plus reconnus dans le monde entier. Pour mieux tirer parti de ces données à l'avenir, il faut comprendre quelles données sont disponibles, leurs restrictions d'accès et d'utilisation, comment elles sont collectées et stockées, les résolutions spatiales et temporelles, ainsi que les avantages et les défis associés à divers types de données. Nous fournissons ces détails pour les systèmes d'identification automatique, les systèmes de surveillance des navires, la surveillance aérienne, RadarSat II et les enregistrements de violation comme première étape vers l'application des données de suivi des navires comme indicateur de surveillance des zones de conservation au Canada, en mettant l'accent sur la mesure des activités de pêche et de la pêche non conforme aux règlements.

ACKNOWLEDGEMENTS

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INTRODUCTION

How to effectively monitor marine conservation areas is a pressing question for the Government of Canada following increased protection of marine and coastal waters to meet the international agreement to protect 10% of the ocean by 2020 (Aichi Target #11, Sustainable Development Goal #14) and calls for protection of 30% by 2030 in the Post-2020 Global Biodiversity Framework (Woodley et al. 2019). As of August 1, 2019, Canada has protected 13.8% of marine and coastal areas including 14 *Oceans Act* Marine Protected Areas (MPAs), three National Marine Conservation Areas, one National Wildlife Area, and 59 marine refuges. With a few exceptions, regulations within these conservation areas focus on fishing restrictions to protect and promote fish abundances and important benthic habitats.

A first step in developing monitoring plans for Canada's marine conservation areas is identifying key indicators of effectiveness. Compliance with regulations is the most fundamental component of protection effectiveness, as a conservation area that does not have regulations or compliance with those regulations will not function any differently than open areas. Surveillance and enforcement efforts led by the Conservation and Protection program (C&P) of Fisheries and Oceans Canada (DFO) are underway for many of the conservation areas. How often non-compliance occurs as encountered by surveillance programs, as well as estimates of unenforced non-compliance, are important pieces of information that contribute to understanding the effectiveness of protection. These measures can serve as indicators of compliance that in turn enable conservation area performance evaluation using ecological indicators such as fish abundance (Bloomfield et al. 2012; Campbell et al. 2012; Dalton et al. 2015; Kelaher et al. 2015). Without compliance indicators, it is difficult to understand whether trends in ecosystem indicators are related to effective or ineffective protection measures, or to other outside factors. However, many efforts to understand ecological performance in marine conservation areas do not include direct measures of non-compliance, but may allude to low performance because of known non-compliance (Lipej et al. 2003; Guidetti et al. 2008; Bergseth et al., 2015; Thiault et al. 2019). Human pressure monitoring in general, including unregulated activities, provides context that enables an understanding of how ecosystems are responding and whether regulations should be adapted (Bergseth et al. 2015; Dunham et al. 2020). As such, human pressure monitoring should be a primary focus of monitoring plans for conservation areas as these pressures may deter goals of protection (Vanderlaan and Taggart 2009; Cooper et al. 2014; Allard et al. 2015).

Many marine and coastal human pressures, as well as compliance with conservation area regulations, are associated with vessel traffic. In addition to extractive activities associated with vessel use such as fishing, vessels themselves produce impacts on marine species and ecosystems including noise, marine mammal strikes, habitat disturbance, pollution, and spread of invasive species through ballast and biofouling (e.g. Nichol et al. 2017, Putland et al. 2018, Iacarella et al. 2020). There are currently 74 conservation areas with static fishing closure regulations in Canada nationally, and an additional 162 static fishing closures in the Pacific region (Rockfish Conservation Areas). A few of Canada's conservation areas also regulate vessel traffic entrance and speed for the protection of seabirds (e.g. Scott Islands Marine National Wildlife Area) and whales (e.g. Saguenay–St. Lawrence Marine Park), as well as vessel anchoring for protection of benthic habitat (e.g. Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs MPA, Laurentian Channel MPA, Banc-des-Americains MPA). Vessel traffic datasets can be used to identify and estimate many of these pressures and thus serve as valuable resources for monitoring indicators.

GOALS

The Government of Canada collects a variety of vessel tracking datasets for real-time applications including maritime security, navigational safety, search and rescue, and enforcement. As such, these data may not currently be compiled and archived in a way that is readily available for retrospective and ongoing spatial and temporal analyses of vessel activities. We provide details of how the data are collected and their spatial and temporal resolutions to the best of our ability, with the aim to provide an initial resource for better understanding how these data may be applied for conservation and long-term monitoring purposes. In particular, we focus on how these data may be used to measure fishing activity and fishing non-compliance in conservation areas, and provide global examples of their application.

SCOPE

We provide details for different vessel tracking data types collected for Canada's Pacific, Arctic, and Atlantic oceans, with a focus on regions with more extensive data depending on the inherent differences in data collection. We identified the following data types for determining fishing activity and non-compliance: satellite Automatic Identification Systems (AIS), terrestrial AIS, Vessel Monitoring Systems (VMS), Electronic Monitoring, Long Range Identification and Tracking (LRIT), aerial surveillance, RadarSat II, violation records, and logbook records.

We focused on data sources that are currently available free of charge to DFO scientists and managers, as well as those that we deemed useful for monitoring efforts in the future. We did not include further details of Electronic Monitoring, Long Range Identification and Tracking, or logbook data. Though Electronic Monitoring includes video imagery and gear sensor data for commercial fishing events and has been employed in the Pacific region since 2000, it is not archived past a typical holding period of two weeks (Archipelago Marine Research Ltd, Victoria, British Columbia [BC], personal communication). LRIT devices transmit navigational information to satellites in real-time from ships required to carry the devices under the International Convention for the Safety of Life at Sea (SOLAS) maritime treaty, same as Class A AIS requirements (see ‘Automatic Identification Systems’ below). Information is reported every 6 hours unless tasked by the entitled country (i.e. within 1000 nautical miles of the country’s coastline) to report at a maximum of every 15 minutes. LRIT may fill gaps in AIS, which is limited by VHF signal transmission range, but its temporal resolution is too low for accurately detecting movements and vessel tracks (Koropatnick et al. 2012). Logbook data can also be used to estimate commercial fishing pressures, but given the higher resolutions and ease of using VMS data (Chang and Yuan 2014) we consider logbook records here only in the context of better understanding these data. Some data types, AIS in particular, have been used extensively and exclusively in studies of fishing pressure and vessel impacts (Robards et al. 2016). We compare these data sources as they all have benefits, challenges, and data gaps (Table 1), and identify their current and potential applications.

Table 1. Vessel tracking data extents, benefits, and challenges for identifying fishing activity and non-compliance for long term monitoring of Canada's marine conservation areas.

DATA TYPE	SPATIAL EXTENT	TEMPORAL EXTENT	BENEFITS	CHALLENGES
SATELLITE AIS	Global Maritime Area of Interest	2008 – ongoing	• Global coverage • Can be used to detect fishing activity • Publicly available	• Big data processing capacity needs • Not all vessels required to use AIS, particularly fishing vessels • Can be masked • Gaps in data based on satellite orbital pathways
TERRESTRIAL AIS	Canada's waters within 50 nautical miles of receivers	2012 – ongoing	• High resolution coverage nearshore • Can be used to detect fishing activity • Publicly available	• Big data processing capacity needs • Not all vessels required to use AIS, particularly fishing vessels • Can be masked • Some, infrequent data gaps when receiver goes offline
VMS	West and East coast Canada, more prevalent on East coast	2005 – ongoing	• Used by commercial fishing vessels	• Requirements vary greatly by region and fishery • Currently difficult to obtain data for large spatial or temporal extents • More costly for fishers and government • Privacy issues
AERIAL SURVEILLANCE	Canada's EEZ and international waters	1998 – ongoing	• Identifies fishing activity of vessels and use of AIS • Identifies non-compliant fishing events	• Limited by search effort and capacity of survey teams • Visibility affected by cloud cover
RADARSAT II	Global, used more extensively on West coast than East coast Canada	2007 – ongoing	• Detects vessels without AIS • Oil spill detection capability	• Swath width narrows with increased resolution. • Does not detect vessels < 8 m in length. • Low temporal resolution; passes same geospatial location every 3-4 days.
VIOLATION RECORDS	Canada's EEZ and international waters	2002 – ongoing	• Identifies non-compliant fishing events	• Limited by search effort and capacity of enforcement team

VESSEL TRACKING DATASETS

AUTOMATIC IDENTIFICATION SYSTEMS

Data details

AIS is a digital VHF radio-based transponder that relays navigational messages that are picked up by other AIS devices and by satellite and terrestrial-based antennas. The primary purpose of AIS is to help identify ships and to assist in search and rescue, target tracking, and situation awareness. AIS is also intended to aid in protecting the marine environment (IMO A 29/Res.1106). The International Maritime Organization (IMO) issued a requirement for certain vessels to carry AIS under the Safety of Life at Sea (SOLAS) maritime treaty as of 2002. Specifically, Class A AIS devices are required for vessels ≥ 300 tons on an international voyage or ≥ 500 tons not on an international voyage (fishing vessels exempt). In Canada, Class A devices are also required for vessels ≥ 150 tons carrying more than 12 passengers on an international voyage, and Class A or B devices are required for vessels voyaging outside of sheltered waters that are certified to carry more than 12 passengers or are ≥ 8 m in length and carrying passengers (Navigation Safety Regulations SOR/2005-134). Recreational vessels, fishing vessels, and warships may be voluntarily fitted with Class B devices for collision avoidance purposes.

Class A AIS devices comply with IMO carriage requirements and are given priority in signal transmission, whereas Class B devices do not meet the same performance standards and operate at a reduced reporting rate with less power (IMO A 29/Res.1106). However, Class B responders work on the same AIS network and can receive and transmit signals to Class A transponders on commercial vessels, facilitating collision avoidance. Class B+ devices became available in early 2019 and use the same Self-Organizing Time-Division Multiple Access (SOTDMA) technology as Class A, which provides the same priority in signal transmission (Digital Yacht 2018). They also have a greater frequency and transmission range owing to more transmission power (5 W from the 2 W of class B, compared to 12.5 W of class A). Class B+ devices are appealing to small vessel operators as they are relatively affordable and greatly improve collision avoidance compared to Class B (Digital Yacht 2018). Their increased use will improve the accuracy and current underestimation of vessel-related measures from AIS data.

AIS transmission rates vary by Class, vessel speed, and course changes, with more frequent reporting rates for Class A, at faster speeds, and during course changes. Class A devices have transmission rates of up to every 2 seconds, class B+ every 5 seconds, and class B every 30 seconds (Digital Yacht 2018). All classes of AIS transmit the vessel's static information every 6 minutes, but classes B and B+ do not transmit voyage-related information (Government of Canada 2019). Class A devices have an average transmission range of 40 nautical miles, whereas Class B transmissions have a maximum range of 10 nautical miles (Digital Yacht 2018; VT Explorer 2020). Transmitted information is provided to end users in the form of 27 ‘messages’ that include the static, dynamic, and voyage-related information (U.S. Coast Guard Navigation Center 2019) (Table 2).

Table 2. Vessel tracking information that is transmitted by Automatic Identification Systems (IMO A 29/Res.1106).

TYPE	ENTRY	INFORMATION
STATIC	Manually entered upon installation	• Maritime Mobile Service Identity (MMSI) • Call sign and name • IMO number • Length and beam • Type of ship
DYNAMIC	Automatically updated from position sensor	• Ship’s position (accuracy ~ 10m) • Position time stamp in UTC • Course over ground (optional) • Speed over ground (optional) • Heading • Rate of turn (optional)
	Manually entered and updated during voyage	Navigational status, e.g.: • Underway by engines / sail • At anchor / moored • Engaged in fishing
VOYAGE-RELATED	Manually entered at the start of the voyage	• Ship’s draught • Destination and ETA • Route plan • Hazardous cargo

Application

AIS is a powerful tool for detecting vessel activities owing to its high spatial and temporal resolution. Algorithms have recently been developed by Global Fishing Watch and collaborators that detect whether a vessel is fishing using convolutional neural networks (i.e. deep learning) that classify movement patterns tracked by AIS (McCauley et al. 2016; Kroodsma et al. 2018; Taconet et al. 2019). Six classes of fishing activity can be identified with 95% accuracy to obtain estimates of fishing effort (Kroodsma et al. 2018). These algorithms were applied to evaluate changes in longline and purse seine fishing following the enactment of the Kiribati’s Phoenix Island Protected Area and showed only one case of fishing activity in the six months post-closure (McCauley et al. 2016). AIS was similarly used to discover non-compliant bottom trawling covering over 70% of Italian Biological Protected Areas (Tassetti et al. 2019).

The primary challenge of using AIS to detect and quantify fishing activity, and illegal, unreported, and unregulated (IUU) fishing in particular, is the ability of vessel operators to mask signal transmission (e.g. by placing a bucket on top of the antenna, B. Gillard, C&P, Comox, BC, personal communication, 2019) or to falsify transmitted information. However, methods have been developed to find gaps in AIS data to identify when vessels may purposefully ‘go dark’ (Ford et al. 2018; Oceana 2019). Detection of long gaps in AIS transmission, particularly when close to boundaries of fishing closures or EEZs, can be used as a first-step approximation of IUU fishing (Oceana 2019; Rowlands et al. 2019).

Another challenge of using AIS is the lack of regulations for fishing and small vessels, though over 50 flag states have required more vessels to carry AIS in addition to IMO regulations. For instance, AIS is required for fishing vessels ≥ 15m in the European Union, ≥ 19.8m within US waters, and for all fishing vessels in Mauritius and Ecuador (McCauley et al. 2016). These additional EU requirements enabled an AIS-based study on commercial trawling effort that found higher trawling intensity on average inside EU MPAs than outside (Dureuil et al. 2018). In Canada, fishing vessels are not presently required to carry AIS. However, Global Fishing Watch identified 515 active Canadian fishing vessels using AIS in 2017 (ORBCOMM and Spire receivers), close to 75% of which were over 24 m in length (Taconet et al. 2019). Fortunately, AIS also captures a large number of recreational vessels and many small commercial fishing vessels that use the device voluntarily for collision avoidance (Iacarella et al. 2020). In 2016, 3,410 recreational and 776 fishing vessels transmitted AIS within Canada’s Pacific waters (including non-Canadian vessels, J. Iacarella unpublished data; Marine Traffic via ORBCOMM receivers). However, approximately 71% of vessels observed from flyovers of the Salish Sea of British Columbia did not use AIS, and of these 74% were recreational (Serra-Sogas et al. 2018). Challenges to mandating AIS carriage include lack of support from fishers who do not want to reveal key fishing locations to others or to facilitate enforcement monitoring capabilities. Additionally, AIS is regulated by Transport Canada, which complicates the implementation of new policies by DFO that would use AIS to support environmental and fisheries monitoring (S. Wheeler, C&P, Victoria, BC, personal communication, 2020). Other vessel tracking data sources, as detailed in this report, can be used to identify vessels that are not transmitting AIS to obtain a more complete assessment of vessel traffic.

Satellite AIS

Satellite AIS provides a global coverage that is based on the pathways of Low-Earth Orbiting (LEO) satellites. The satellites are often in polar (sun-synchronous) orbit and pass at a fixed time each day; others are in inclined orbits with overpass times that shift daily (Eriksen et al. 2018). LEO satellites typically make a complete revolution around the Earth every 90 minutes. The orbit type (e.g. polar, inclined, equatorial), altitude, and geospatial location of interest determine the frequency of passes, with polar orbiting satellites yielding gaps of up to 9 hours at the equator versus making 15 passes per day at the poles. The field of view of these satellites is around 5,000 km (Eriksen et al. 2018). Message collisions have been a primary challenge for satellite receivers to detect all vessels in high-density areas (> 1,000 ships). However, spectrum decollisioning processing has greatly improved high-density ship detection (exactEarth 2015a).

Satellite AIS technology and data collection is largely owned and developed within the corporate domain, with companies such as ORBCOMM and exactEarth (both Canada-based) launching and maintaining satellites and other companies such as Mareospace (Canada-based, data provided by ORBCOMM) and MarineTraffic (data provided by exactEarth, ORBCOMM, and Spire) supplying end-users with raw AIS data and data products. Satellite AIS technology and coverage is rapidly advancing; for instance, the launch of Iridium NEXT in 2017 included exactEarth AIS receivers on 58 satellites (an increase from 19 satellites; exactEarth 2015b), and ORBCOMM launched 17 next-generation satellites in 2016 that were each the equivalent of six first-generation satellites (ORBCOMM 2016). In 2016, the Government of Canada also launched the M3MSat within the exactEarth satellite constellation, with the primary objective of collecting AIS data for Canadian maritime zones. The satellite is owned by the Department of National Defense and operated by the Canadian Space Agency (CSA) (CSA 2017a). Discussions are currently in progress for Conservation & Protection and other DFO branches to be able to access these data (R.-M. Gionet, DFO, Halifax, Nova Scotia, personal communication, 2019).

CSA previously obtained AIS data from exactEarth (May 2012 – March 2017) and Maerospace (ongoing, April 2017 – October 31, 2020). These data are primarily from satellite AIS sources, but also include some terrestrial AIS (B. Banik, CSA, Saint Hubert, Quebec, personal communication, 2019). All data are archived and have some commercial use restrictions, but are otherwise available to DFO as a collection of .gnm, .nm4 (exactEarth), .nmea (Maerospace), and .csv (both) files. The data cover three phases of satellite coverage: ‘exactEarth enhanced’ starting with two satellites and increasing to eight (December 2012 – March 2016), ‘exactEarth reduced’ with three satellites (some noted data decimation, April 2016 – March 2017), and Maerospace with 15-17 satellites (April 2017 – October 2020) (P. Vachon, Defence Research and Development Canada, Ottawa, Ontario, personal communication, 2019). The time interval at which ships can be detected thus varies across years and latitudes (Figs. 1 & 2). For instance, Maerospace has better coverage at mid-latitudes than exactEarth as ORBCOMM (data provider for Maerospace) has more satellites in inclined orbit than exactEarth. However, exactEarth’s Iridium NEXT satellites provide the most advanced coverage currently available with a global minimum overpass frequency of every 11 minutes (0.18 hours; Fig. 1d).

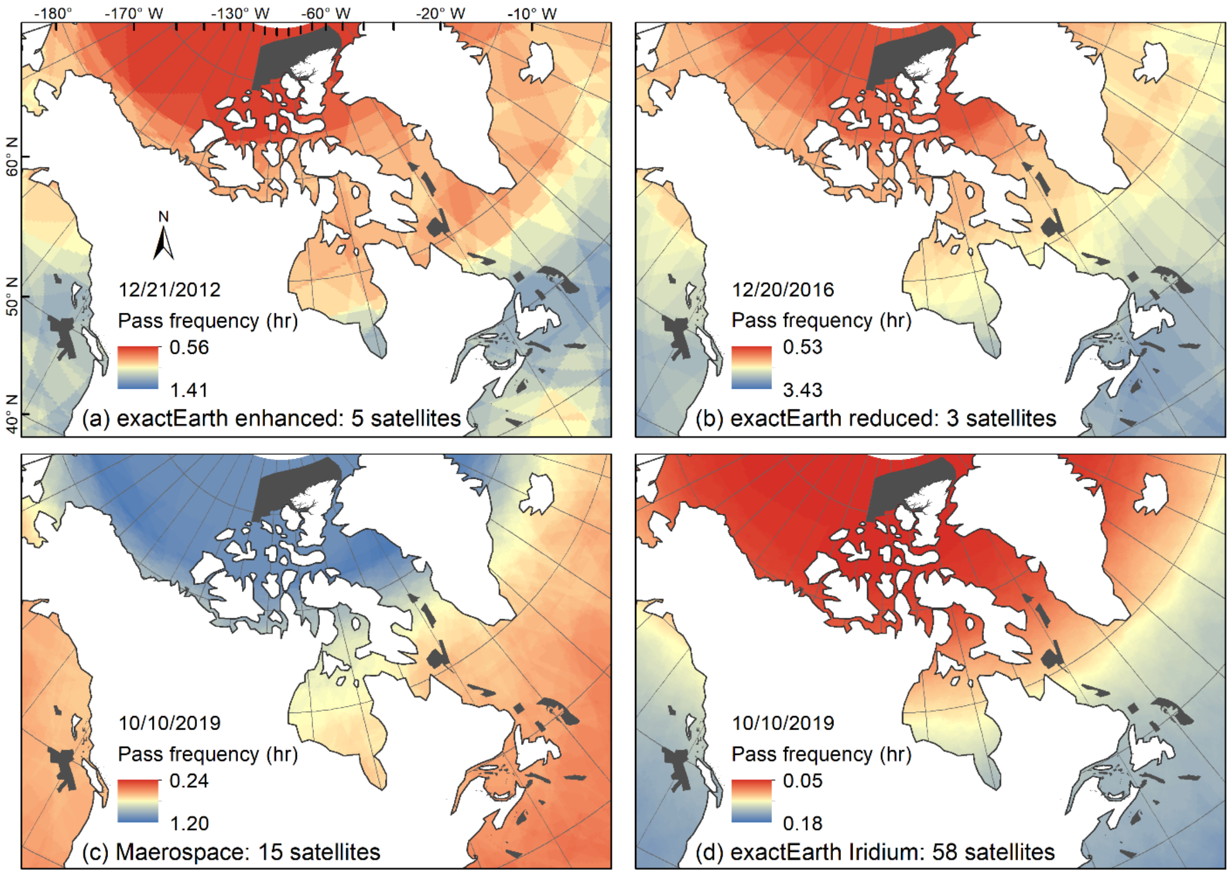

Figure 1. Frequency of satellite passes on example days for (a) exactEarth enhanced, (b) exactEarth reduced, (c) Maerospace, and (d) exactEarth Iridium. Satellite-received Automatic Identification Systems data are provided to the Canadian Space Agency from sources (a) – (c); (d) exemplifies state-of-the-art coverage. Frequency ranges differ for each panel; for instance, the most frequent coverage globally for exactEarth reduced is approximately every half hour and for Mareospace is every quarter hour. Canada's static fishing closures are shown in grey. Satellite layers were provided by P. Vachon, Defence Research and Development Canada.

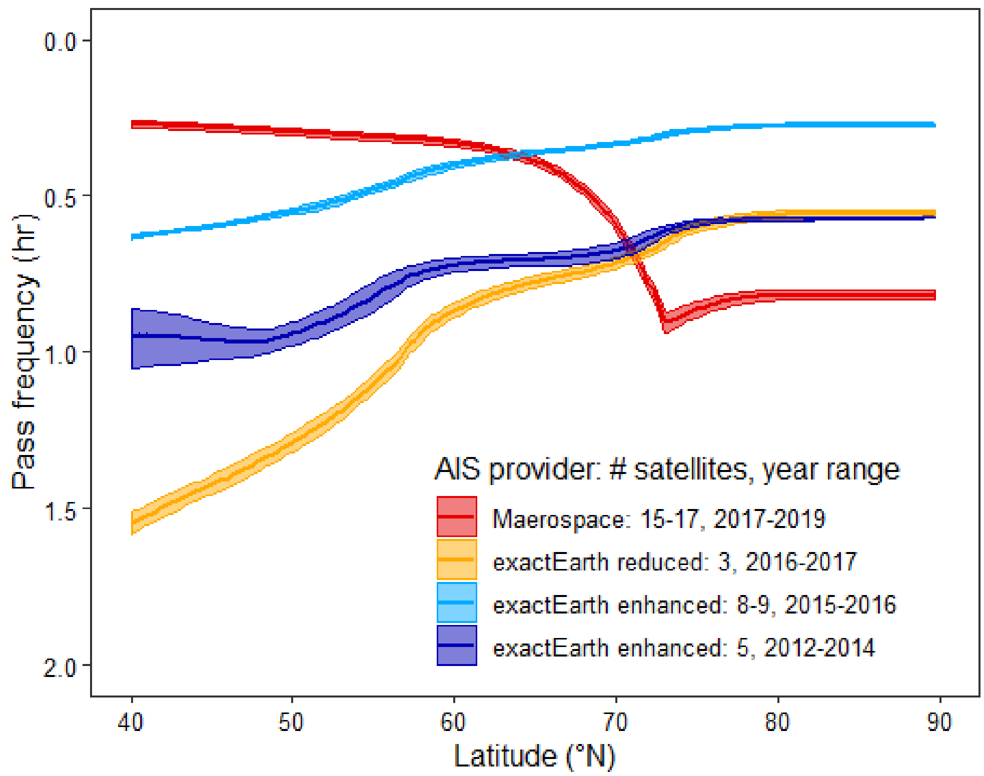

Figure 2. Frequency of Automatic Identification Systems (AIS) satellite passes for latitudes spanning Canada's waters. Solid lines are mean frequencies across global longitudes and sample days within the period of coverage (n = 5 for Maerospace and exactEarth reduced, n = 2 for exactEarth enhanced 2015-2016, and n = 3 for exactEarth enhanced 2012-2014). Shaded areas represent mean ± 1 SD across day samples. Data were provided by P. Vachon, Defence Research and Development Canada.

Terrestrial AIS

Terrestrial receivers are land-based stations that receive AIS transmission from vessels in their horizontal line-of-sight and within 50 nautical miles of the coast (Eriksen et al. 2018) (Fig. 3). Terrestrial AIS is higher resolution than satellite AIS as it receives constant transmissions, whereas satellite AIS is dependent on orbital passes. However, signals are lost when a vessel moves out of line-of-sight, for instance if an island or other vessels block the transmission. Spatial resolution is also dependent on the extent of land-based stations.

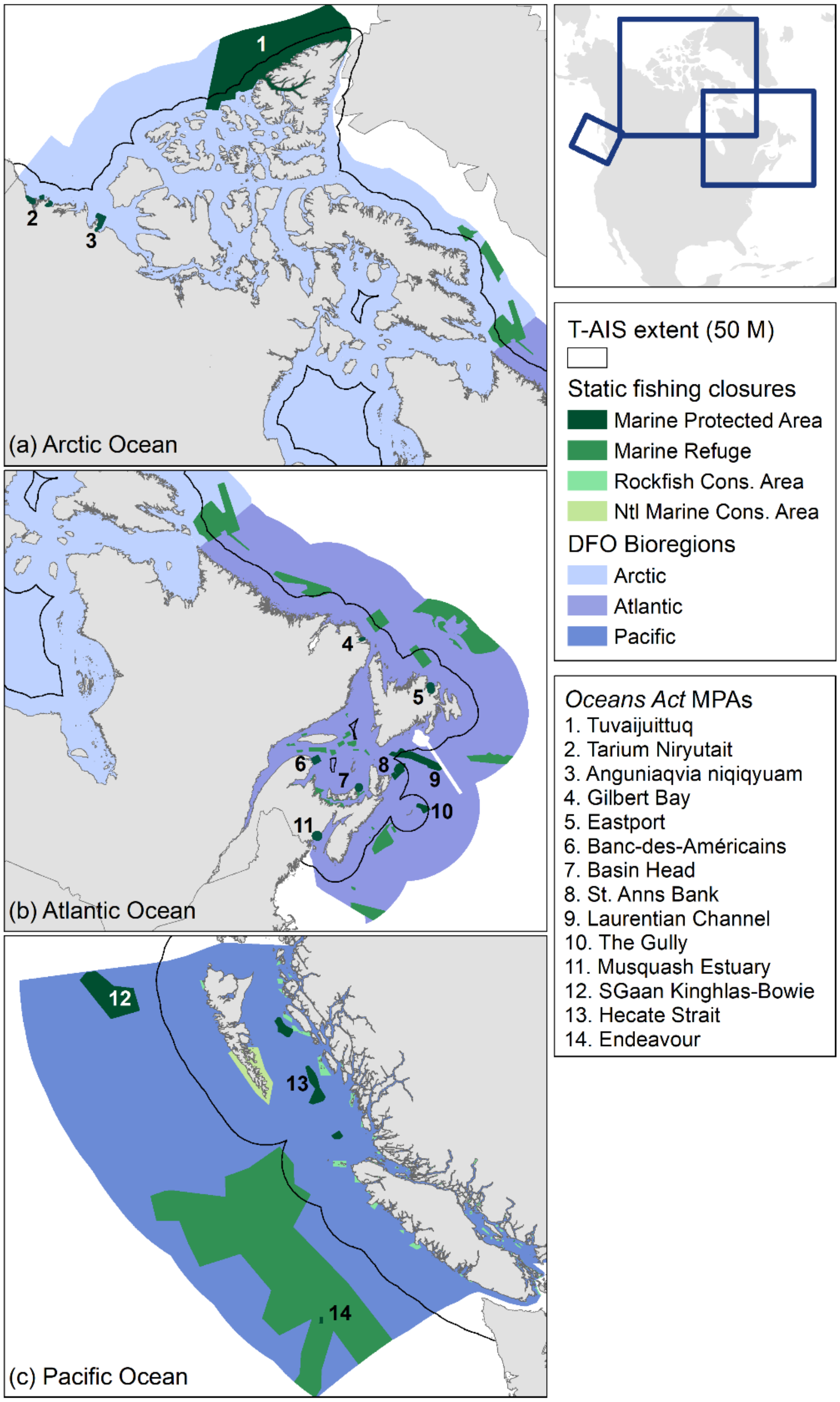

Figure 3. Terrestrial Automatic Identification Systems (T-AIS) full potential extent for Canada's *Oceans Act* Marine Protected Areas (MPAs) and other static fishing closures based on a 50 nautical mile (M) range for terrestrial receivers. All closures have satellite AIS coverage at a lower temporal resolution.

Terrestrial data are collected by the Canadian Coast Guard from operated receivers along the coastline and the Great Lakes interior waters (Fig. 4). Data collection began in earnest in 2012 and is ongoing, though some day-long data gaps have been noted occasionally when receivers have been non-operative. These data are fully archived and accessible to DFO, and have been used to create shipping traffic atlases for Canada's EEZ (Simard et al. 2014a; Simard et al. 2014b) and to identify shipping intensity in the Eastern Shore Islands Area of Interest to inform future MPA design (Konrad 2020).

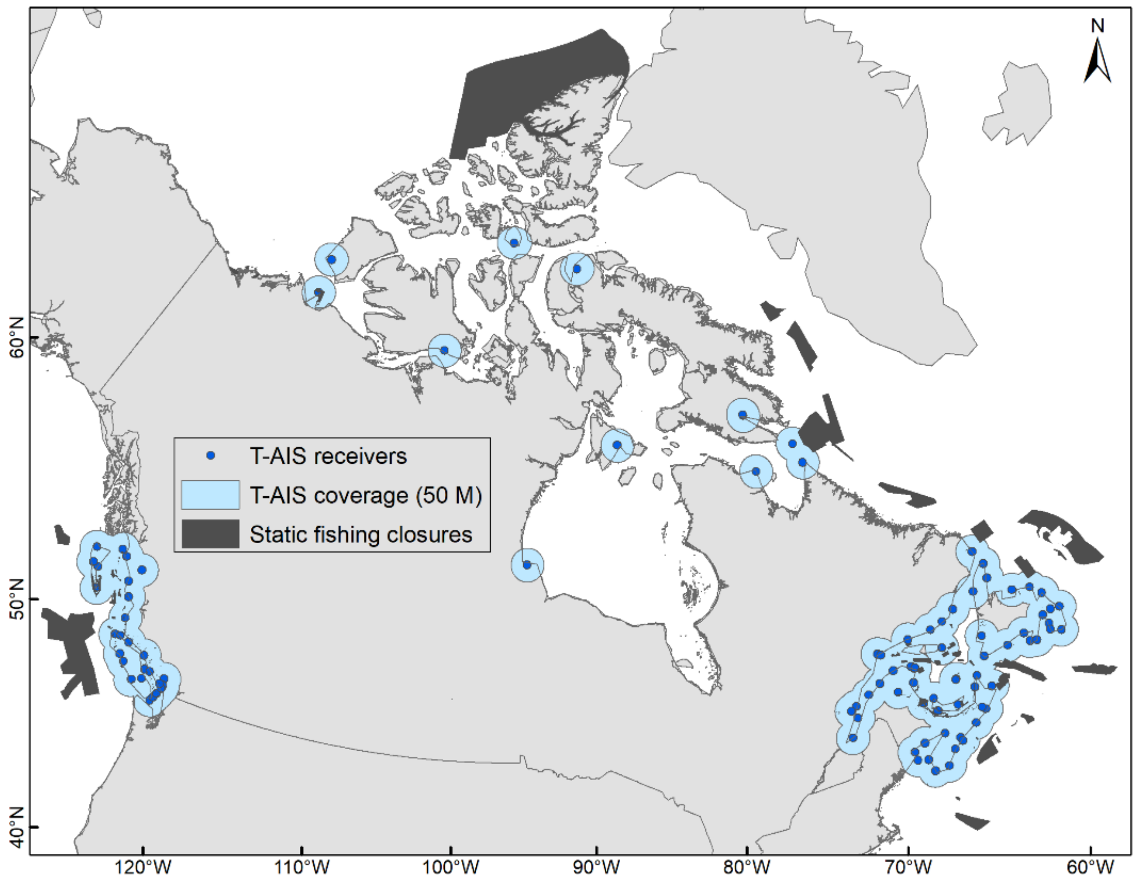

Figure 4. Locations of coastal terrestrial Automatic Identification Systems (T-AIS) receivers operated by the Canadian Coast Guard (provided by A. Ravanelli, CCG). The 50 nautical mile (M) extent around the receivers is the maximum coverage for T-AIS data based on current receiver locations.

VESSEL MONITORING SYSTEMS

<u>Data details</u>

The Vessel Monitoring System (VMS) is also a satellite-based vessel tracking system, but unlike AIS, it is carried only by commercial fishing vessels and the data are government-managed and not publicly available. The VMS program started in 2005 and is used within strict policies on data access and sharing by DFO for fisheries surveillance and enforcement, the Canadian Coast Guard for search and rescue, and by the Marine Security Operation Centres for responding to maritime security threats or incidents. The VMS program is currently changing governance and procedures, as well as updating the Data Access and Distribution Policy. The program is working to improve the functionality of VMS for management and enforcement of closed fishing zones (A. Williams, C&P, Ottawa, Ontario, personal communication, 2019).

Requirements for commercial fishing vessels to carry VMS vary by DFO region and fishery (i.e. by fish stock, gear type, and boat length), and are far more extensive on Canada's East coast than in the Pacific region (Table 3; Fig. 5). DFO's Integrated Fisheries Management Plans often specify which fishery management zone, gear type, and boat length requires use of VMS, when applicable. Integrated Fisheries Management Plans also include logbook reporting requirements and use of Electronic Monitoring for the Pacific region. The year in which each of the VMS regulations began varies greatly, and this information is not readily available for all fisheries. The frequency of transmission also varies by region and fishery. For instance, the snow crab fishery has a polling rate of five minutes in the Gulf and Quebec, whereas the Northern shrimp fishery has a polling rate of 30 minutes (VMS Centre of Expertise – DFO 2019); the Pacific requires VMS for the prawn fishery which polls every 15 minutes from May – June (M. Kattilakoski, DFO, Nanaimo, BC, personal communication, 2017). For Newfoundland and Labrador and the Maritimes regions, polling is generally every hour across fisheries (VMS Centre of Expertise – DFO 2019; S. Coffen-Smout, DFO, Dartmouth, NS, personal communication, 2020).

Vessel information provided by VMS includes the Vessel Registration Number (VRN), geospatial location, date, speed, and time, but does not include fishing activity type or license. To obtain this, studies have matched the VRN from VMS to licensing records, hail-out tables, or logbook data (Koen-Alonso et al. 2018; Butler et al. 2019).

Table 3. Commercial fisheries required to carry Vessel Monitoring Systems (VMS) as identified by Integrated Fisheries Management Plans and the VMS Centre of Expertise – DFO (2019). Note that there are many exemptions based on fisheries management areas and boat size within the regional requirements that are not detailed here. Gear types of the fisheries are provided as fishing closure restrictions are often gear-based; gear types noted in italics are not required to carry VMS.

DFO REGION	VMS REQUIRED (area and boat size exemptions apply)	GEAR TYPE
PACIFIC	Albacore tuna (pilot program)	Hook and line by troll
	Chum salmon (pilot program)	Purse seine, gillnet, hook and line by troll
	Prawn and shrimp	*Bottom trawl*, trap
	Red sea urchin (pilot program)	Dive
	Electronic Monitoring required (no VMS):	
	Dungeness crab	Trap
	Groundfish	Bottom trawl, midwater trawl, gillnet, hook and line by bottom longline, troll (Lingcod), trap (Sablefish)
CENTRAL AND ARCTIC	Greenland halibut	Bottom trawl, gillnet, hook and line by bottom longline
	Shrimp (Northern and striped)	Bottom trawl
QUEBEC	Capelin	Purse seine, *fixed seine, trap*
	Clams (offshore)	Dredge
	Groundfish	Bottom trawl, midwater trawl, gillnet, hook and line by bottom longline
	Herring	Purse seine, *bar/tuck seine, weir, gillnet, trapnet*
	Lobster (inshore)	Trap
	Mackerel	Purse seine, *tuck seine, gillnet, jigger, trap, handline*
	Scallop (offshore)	Dredge
	Sea cucumber	Drag
	Sea urchin	Dive
	Shrimp (Northern)	Bottom trawl
	Snow crab	Trap
NEWFOUNDLAND AND LABRADOR	Bluefin tuna	Angling, tended line, harpoon (inshore)
	Capelin	Purse seine, fixed seine, trap
	Clams (offshore)	Dredge
	Groundfish	Bottom trawl, midwater trawl, gillnet, hook and line by bottom longline
	Hagfish	Trap
	Herring	Purse seine, tuck seine, weir, gillnet, trapnet
	Mackerel	Purse seine, tuck seine, gillnet, jigger, trap, handline
	Scallop	Dredge
	Sea cucumber	Drag
	Seal	Firearm
	Shrimp (Northern)	Bottom trawl

	Snow crab	Trap
	Swordfish and other tunas	Pelagic longline, harpoon
GULF	Capelin	Purse seine, *fixed seine, trap*
	Groundfish	Bottom trawl, midwater trawl, gillnet, hook and line by bottom longline
	Herring	Purse seine, *tuck seine, weir, gillnet, trapnet*
	Lobster (inshore)	Trap
	Mackerel	Purse seine, *tuck seine, gillnet, jigger, trap, handline*
	Scallop (offshore)	Dredge
	Shrimp (Northern and Scotian Shelf)	Bottom trawl
	Snow crab	Trap
MARITIMES	Clams (inshore and offshore)	Dredge
	Groundfish	Bottom trawl, midwater trawl, gillnet, hook and line by bottom longline
	Hagfish	Trap
	Herring	Purse seine, midwater trawl, *weir, gillnet, trapnet*
	Lobster and Jonah crab (offshore)	Trap
	Mackerel	Purse seine, midwater trawl, *tuck seine, gillnet, jigger, trap, handline*
	Scallop (inshore and offshore)	Dredge
	Sea cucumber	Drag
	Shrimp (Northern and Scotian Shelf)	Bottom trawl
	Snow crab	Trap
	Swordfish and other tunas	Pelagic longline, harpoon
	Whelk (exploratory)	Trap

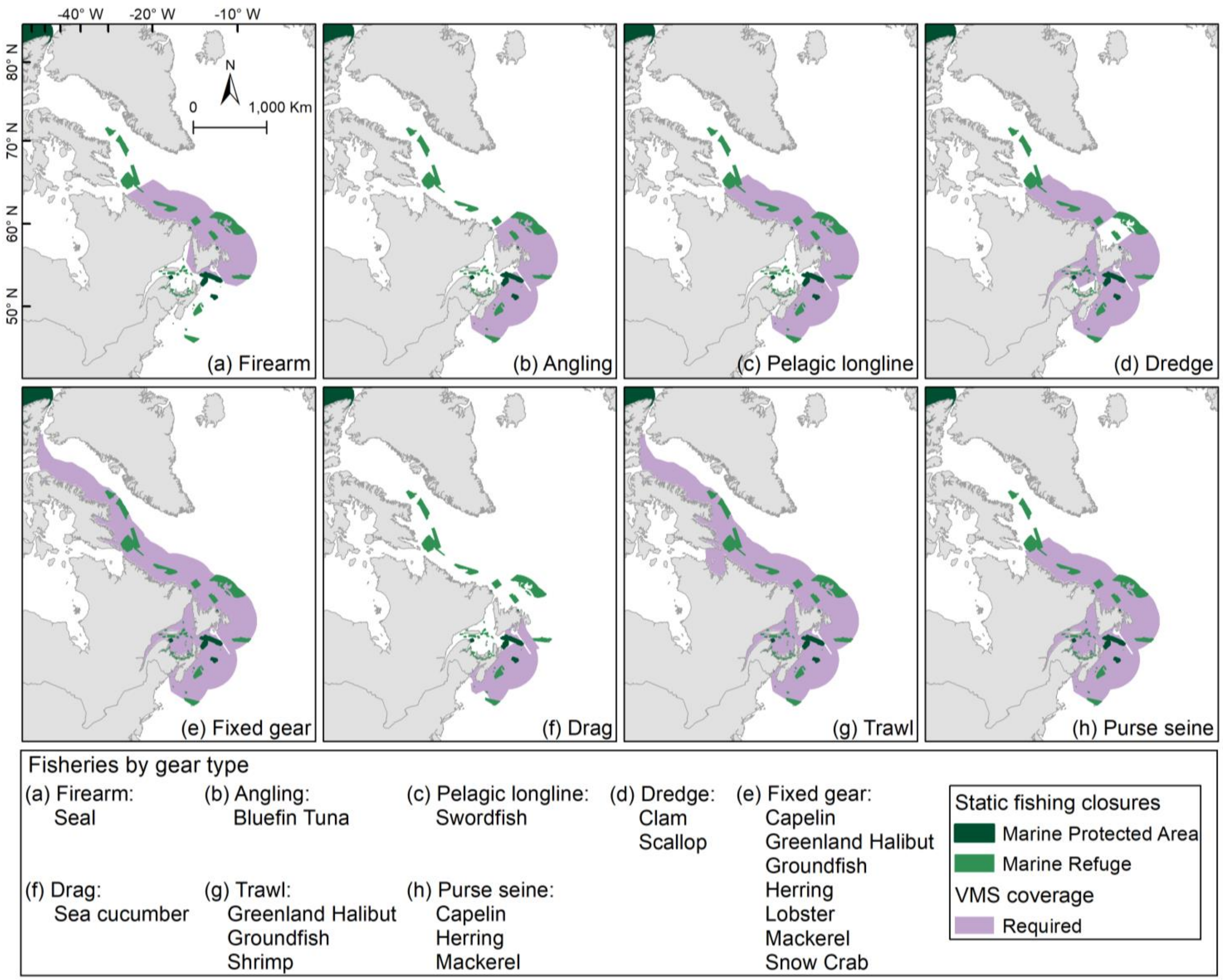

Figure 5. Management area footprints grouped by gear type for fisheries that are required to carry Vessel Monitoring Systems (VMS) by DFO on the Atlantic coast. VMS can be used to monitor fishing activity within closures where there are overlapping footprints.

Application

VMS locational records have been analyzed similarly to AIS to detect fishing activity by gear type (Lee et al. 2010; Chang and Yuan 2014; Watson and Haynie 2016; Butler et al. 2019), though applications of VMS data have been more limited than AIS given the closed access and data privacy restrictions (McCauley et al. 2016). VMS is subject to the Rule of 5 on data privacy, which states that fisheries data and data products cannot be shared without the fisheries' consent when there are fewer than five vessels per Northwest Atlantic Fisheries Organization (NAFO) unit area in Eastern Canada (Butler et al. 2019). The ongoing development of algorithms for quantifying fishing activity using AIS data can be applied to VMS data to estimate gear type and use based solely on movement patterns (e.g. McCauley et al. 2016; Kroodsma et al. 2018). However, VMS is predominately evaluated with algorithms that match logbook data to VMS data to obtain gear type, which is then paired with speed profiles to estimate gear use (Koen-Alonso et al. 2018; Butler et al. 2019). Despite significant spatial and temporal differences in VMS data availability, these data are a highly valuable addition to AIS datasets for measuring fishing activity as they capture the commercial fishing vessels that are specifically excluded from AIS-carriage mandates. As Canada's VMS program expands, these data will be important for measuring shifts in fishing activities, fishing displacement, IUU fishing, and other conservation and fisheries management issues.

AERIAL SURVEILLANCE

Data details

Aerial surveillance is conducted nationally by DFO's Conservation & Protection program, Transport Canada, Department of National Defense, and Canadian Coast Guard. The National Aerial Surveillance Program of Conservation & Protection (contract with PAL Aerospace) has been conducting flyovers since 2002, with more regular, dedicated flyovers since 2017 (B. Gillard, C&P, Comox, BC, personal communication, 2019). Conservation & Protection conducted 950 flyovers from April 2019 to March 2020, with the most surveillance time occurring in the Newfoundland and Labrador region (Fig. 6a). Monitoring, Control, and Surveillance plans are made in conjunction with the Marine Planning and Conservation program in the Aquatic Ecosystems Branch of DFO to patrol marine refuges and MPAs, and are implemented into Conservation & Protection work plans. For instance, a service level agreement was developed within Conservation & Protection to monitor and enforce Oceans Act MPAs in the Pacific region from September 1, 2014 to March 31, 2019. This entailed flyovers for SGaan Kinghlas-Bowie Seamount (up to 1-2 patrols weekly for up to 24 hours annually), Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs (up to 1-2 patrols weekly for up to 16 hours annually), and Endeavour Hydrothermal Vents (up to 1 patrol per month) (Fig. 6b). Flyover information is stored in an archived database and includes vessel on top reports, AIS reports, and intelligence briefs. Vessel on top reports contain information on visually observed vessels and includes the latitude/longitude and noted activity. AIS reports contain AIS transmissions received by the plane’s radar from vessels in the vicinity.

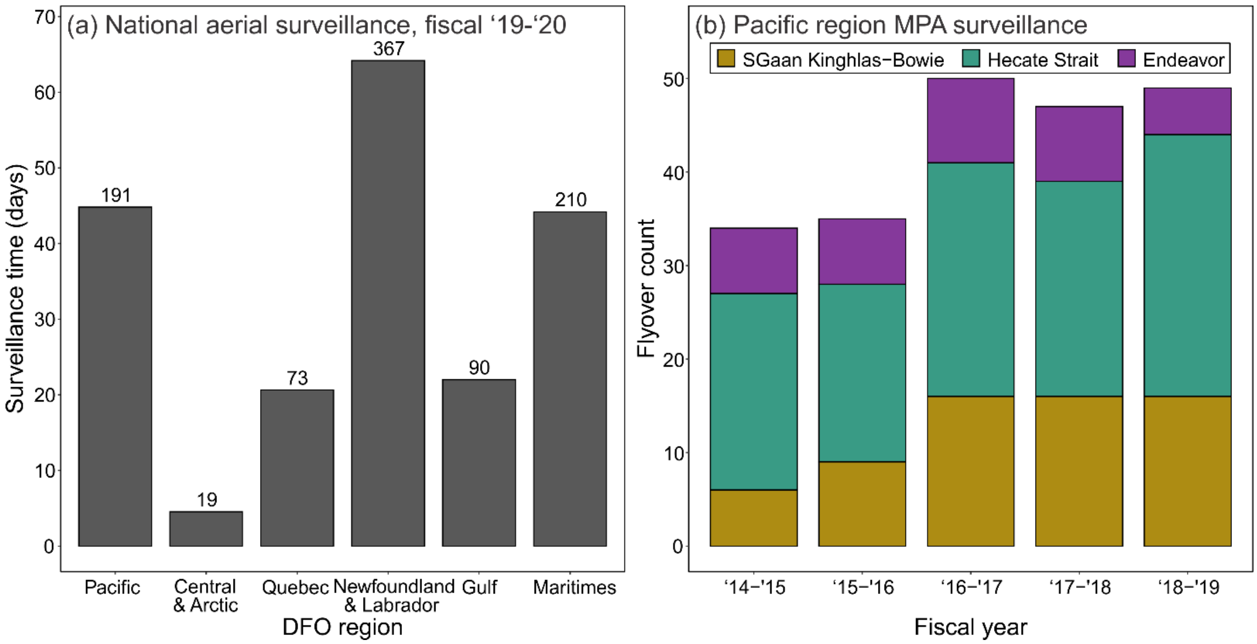

Figure 6. Aerial surveillance of fishing vessels conducted by the National Aerial Surveillance Program of Conservation & Protection, DFO. (a) Total surveillance time and number of flyovers (text above bars) from April 2019 to March 2020 in DFO regions from west to east. (b) Number of flyovers in the Pacific region from September 2014 to February 2019 for Marine Protected Areas SGaan Kinghlas-Bowie Seamount, Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs, and the Endeavour Hydrothermal Vents. Data provided by D. Browne and B. Marchant, DFO.

In the Pacific region, DFO previously contracted Aerospace Industries Association of Canada (AIAC) Pacific through a BC provincial agreement from April 2014 – April 2019 in addition to Conservation & Protection PAL flights. Transport Canada has now received the contract to conduct flyovers and report on the following MPAs: SGaan Kinghlas-Bowie Seamount (approx. once every 2-3 months), Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs (approx. once a week, weather dependent), and Endeavour Hydrothermal Vents (approx. once every 6 weeks) (O. Rusticus, TC, Vancouver, BC, personal communication, 2019). Email reports are provided from Transport Canada that note the number of vessels found within these MPAs and whether the vessels could be identified with AIS. Emails are not archived long-term, though flyover reports are stored in a database for 7 years; the database is proprietary and not set up to download historical data. Transport Canada may also conduct focused flyovers for specific monitoring needs; for instance, the Southern Resident Killer Whale Interim Sanctuary zones including Saturna, Pender, and Swiftsure Bank were reported on during initial enactment of the zones (June 1 – October 31, 2019) (O. Rusticus, TC, Vancouver, BC, personal communication, 2019). Additional support for Conservation & Protection aerial surveillance in the Atlantic and Arctic is provided by Canadian Coast Guard helicopters and Department of National Defense aircraft, with occasional patrols by Transport Canada in the Arctic.

The South Coast Creel Survey in the Pacific region also employs flyovers and dockside interviews to estimate fishing effort by recreational anglers. The objective of the South Coast Creel Survey is to evaluate fishing pressure on recreationally-caught species, not to enforce and monitor closures as for the National Aerial Surveillance Program. However, the data may be similarly applied to closures and estimates of non-compliance. Recreational fishing observations are counted during coastline flyovers in the Johnstone Strait and North Island Survey (Pacific Fisheries Management Areas 11, 12, 27, and 127), Strait of Georgia Survey (Areas 13-20, 28, and 29), and West Coast Vancouver Island Survey (Areas 20-26, 121-126). Surveys are conducted during the peak season of recreational angling, generally from April or June to September (Fisheries and Oceans Canada 2019). The creel surveys began in 1980 and expanded to their current spatial coverage by 1998. Spatial and temporal resolution varies annually depending on budgetary constraints (Fisheries and Oceans Canada 2019). Maps are annotated during the flyovers and must be digitized and geo-referenced for spatial analyses (Haggarty et al. 2016). In the Atlantic, recreational fishing effort is estimated during aerial surveillance by Conservation & Protection concurrently with enforcement patrols, particularly for the recreational groundfish fishery during summer and fall months (D. Browne, C&P, St. John’s, NL, personal communication, 2020).

Application

Aerial surveillance is one of the best methods for determining recreational and commercial fishing activity as small vessels and their activities can often be detected, and AIS use for these vessels is voluntary. Aerial creel survey data previously applied in the Pacific region found high levels of non-compliance by recreational fishers in Rockfish Conservation Areas with fishing effort detected in 61 of 77 of the studied conservation areas (Haggarty et al. 2016). In Ningaloo Marine Park, Australia, recreational fishing was observed from flyovers in over half of the sanctuary zones (Smallwood and Beckley 2012). Likewise, 32 illegal fishing events were noted during a year of aerial surveillance of the Tsitsikamma MPA, South Africa (Smith et al. 2015). A before-after comparison of fishing vessels identified by aerial surveillance monitoring of California MPAs found the number of commercial fishing vessels declined after MPA enactment to the same levels as non-fishing vessels (Zellmer et al. 2018). Such analyses enable a better understanding of ecological, social, and cultural responses to MPA establishment, which is critical information for guiding adaptive management.

RADARSAT II

Data details

RadarSat II is a Synthetic Aperture Radar (SAR) imaging satellite program that was launched in 2007 (CSA 2017b). The construction and launch of the satellite was funded by the Canadian Space Agency and the satellite is owned and operated by MDA (Canada-based company). RadarSat II is used for marine surveillance, ice monitoring, disaster management, environmental monitoring, and resource management. The satellite is in a polar (sun-synchronous) orbit that passes two times per day; every 24 days it passes over the exact same track, but covers similar areas every three to four days (P. Hagell, MDA, Esquimalt, BC, personal communication, 2019). RadarSat II has several imaging modes with different resolutions that are suitable for various purposes as higher resolutions tend to reduce the area that is captured (MDA 2018). Ship detection can be achieved in a range of modes including 'extra-fine', 'fine', and 'ship detection' (Detection of Vessels Wide Far beam, 'DVWF') modes; the extra-fine mode detects ships 5 m in length and has a swath width of 125 km, fine mode detects 8 m ships with a swath width of 50 km, and the ship detection mode detects 25 m ships with a swath width of 450 km (P. Hagell, MDA, Esquimalt, BC, personal communication, 2019; MDA 2018) (Fig. 7).

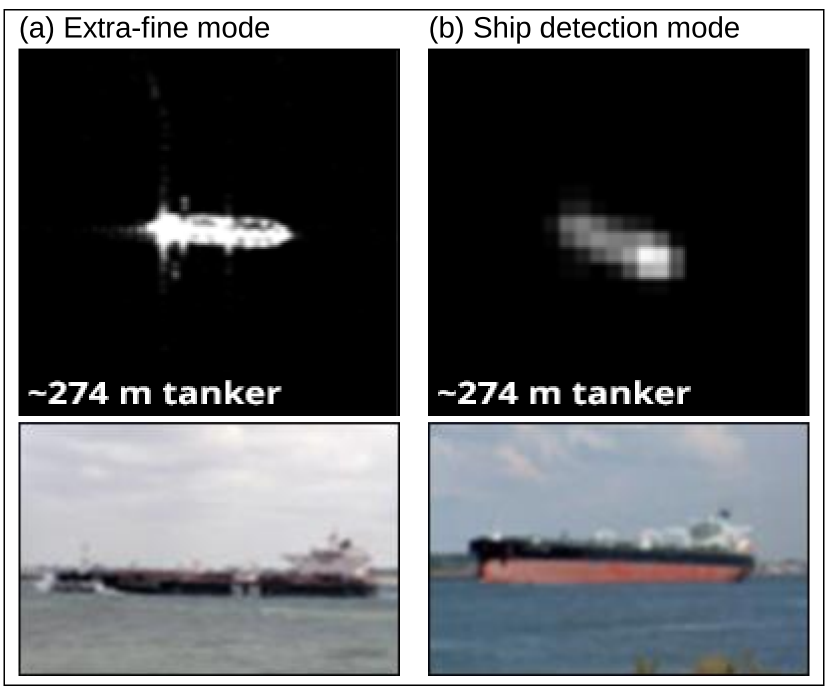

Figure 7. Synthetic Aperture Radar images from RadarSat II (top panel) using (a) 'extra-fine' and (b) 'ship detection' (DVWF) beam modes. Pictures are from MDA (https://mdacorporation.com/geospatial/international/markets/defence-and-security).

RadarSat II is used by the Department of National Defense in the Atlantic for surveillance of small vessels entering Canada's EEZ. DFO can access these data, and application of

RadarSat II for fisheries support is being assessed (J. Foote, C&P, Halifax, NS, personal communication, 2020).

It is currently used more extensively in the Pacific region by Conservation & Protection to identify potential non-compliance events that may then be investigated using aerial surveillance (B. Gillard, C&P, Comox, BC, personal communication, 2019). Conservation & Protection began receiving images in 2017 for surveillance of the following three MPAs: Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs, SGaan Kinghlas-Bowie Seamount, and seamounts within the Large Offshore Area of Interest. Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs are imaged using the fine mode, whereas the remaining areas (i.e. west of Haida Gwaii) are captured using ship detection mode as smaller ships are not observed that far offshore. These imaging modes are used as frequently as two times per day (one overnight pass and one daytime pass) over the Pacific EEZ, and on average three to seven times per month over each of the focal MPAs (Fig. 8).

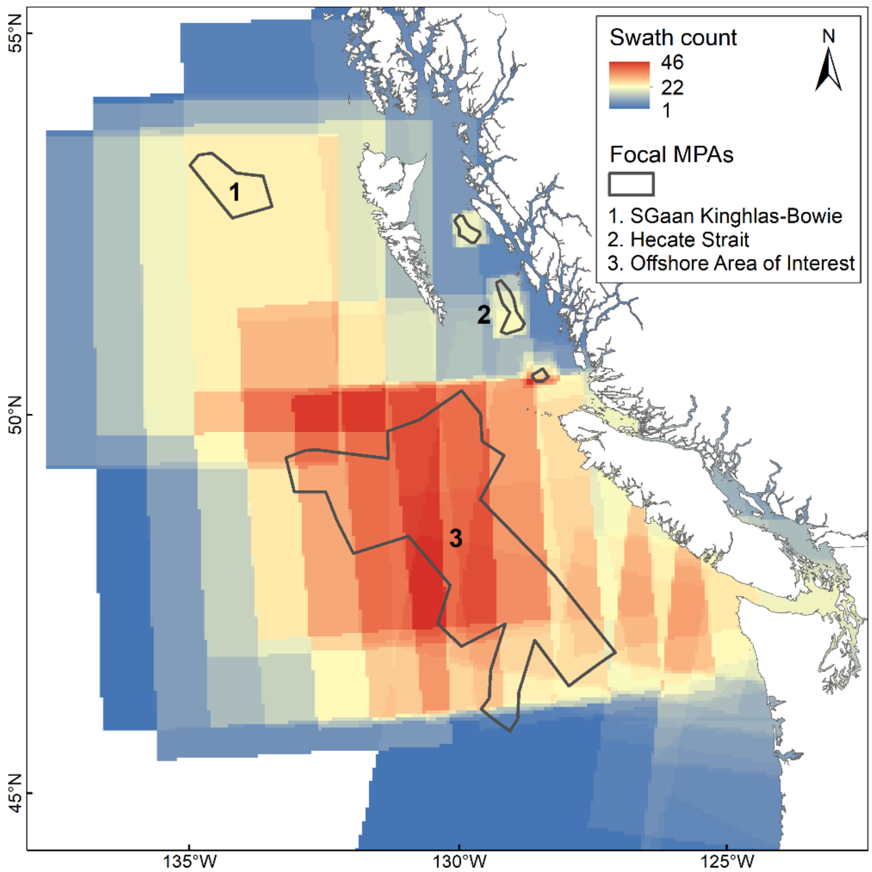

Figure 8. RadarSat II swath counts (i.e. number of times with spatial coverage) in vessel detection beam modes over six months (December 20, 2019 to July 2, 2020) for the Pacific MPAs: (1) SGaan Kinghlas-Bowie Seamount, (2) Hecate Strait & Queen Charlotte Sound Glass Sponge Reefs, and (3) the Large Offshore Area of Interest.

RadarSat II data have been obtained by Conservation & Protection using the Government of Canada's credit (expires July 15, 2020). The Canadian Space Agency provides RadarSat II data to the Government of Canada at a cost of $0.024 / km for ship detection mode. Reports are sent by email and include Google Earth files (.kmz), Over-The-Horizon (OTH) gold text files (.txt), and spreadsheets (.csv) including the time, latitude/longitude, ship length, and percent confidence level of detection (i.e. false detections may occur from waves, rocks, etc.). Emails were not originally archived, though saved emails have been assembled dating back to December 2018. Access to RadarSat II data after July 2020 will be charged per acquisition to the requesting department.

The Government of Canada is transitioning to the RadarSat Constellation Mission consisting of three polar orbiting SAR satellites. These satellites have a slightly lower capacity (number of images per orbit) and resolution (detectable vessel size), but will increase the temporal resolution to cover similar areas once or twice a day (S. Wheeler, C&P, Victoria, BC, personal communication).

Application

Identification of potential IUU fishing activity can be made by comparing the number of ships detected by SAR imaging to the number detected by AIS tracking, assuming voluntary use in Canada or mandated use elsewhere (Vachon et al. 2014). Vessels that are detected by SAR (and aerial surveillance) but not by AIS may be participating in IUU fishing, particularly when this corresponds with the ship going 'dark' (i.e. with a notable gap in AIS data). Comparing detection between SAR and AIS can also provide a measure of underestimation of vessel-related pressures using AIS data. These methods have been applied to detect IUU fishing in the South Atlantic Ocean near West Africa where IUU fishing has been a severe problem (Kurekin et al. 2019). For instance, 75% of ships detected by SAR within Ghana's EEZ were found to not transmit AIS across 17 months (Kurekin et al. 2019). In addition, 40% of ships detected by SAR in and surrounding the Ascension Island EEZ could not be correlated with AIS and overlapped spatially with fishing grounds (Rowlands et al. 2019). Three of the 'dark' vessels detected by SAR were located within the Ascension Island closure and matched the size profile of longline fishing vessels (Rowlands et al. 2019). In Canada, RadarSat II is used in real-time for enforcement (Vachon et al. 2014) and is expected to contribute to situational awareness and maritime security as vessel traffic increases in the Arctic (Horn 2018). However, it has not been used for retrospective analysis of MPA effectiveness and compliance to our knowledge.

VIOLATION RECORDS

Data details

Citations for fishing violations are given by Conservation & Protection using surface patrol vessels that target suspected infringements identified through surface patrols, aerial surveillance, AIS, and RadarSat II (B. Gillard, C&P, Comox, BC, personal communication, 2019). Records of violations are collected on a regional basis by Conservation & Protection. A database is maintained that includes details on the source of information (e.g. fishery officer, public, etc.), fishery and fish species for which the violation occurred, date and time, general location, and the action taken (e.g. ticket or warning issued, etc.). Compiling violation information for specific closures requires considerable time as the database cannot currently be queried by MPA or fishing closure names and the data are not associated with geographic coordinates. However, violation queries are somewhat easier for species-specific closures, such as Rockfish Conservation Areas, which can be searched based on the relevant species.

Application

Law enforcement and violation records are a frequently used metric to quantify non-compliance in MPAs and closures (Bergseth et al. 2015). For example, an increase in illegal lobster fishing in Table Mountain National Park, South Africa was revealed by examining the number of confiscation incidents over nine years (Brill and Raemaekers 2013). In an MPA in Australia, data on fishing fines and fish abundances showed that target fish populations were relatively unchanged in the first three years of enactment, but markedly improved after enforcement was strengthened and more fines were issued (Kelaher et al. 2015). Records of enforcement actions are a direct and substantiated measure of non-compliance, whereas many of the other tools described here (e.g. AIS, VMS, RadarSat II) are best estimates of the activities occurring on the water. Evaluations using violation records have not been reported for Canada’s MPAs or other static fishing closures to our knowledge.

CONCLUSIONS AND RECOMMENDATIONS

The Government of Canada has several ongoing vessel tracking programs that have been traditionally used for maritime awareness, navigational safety, and real-time enforcement efforts. The data from these programs have great potential for monitoring fishing activity and other vessel-related stressors and can make a significant contribution to MPA monitoring programs, especially if programs continue to advance and better data archiving and processing methods are developed. To summarize:

- Automatic Identification System (AIS) data is a powerful tool with high spatial and temporal resolution; algorithms are now available to detect whether a vessel is fishing by analyzing its movement patterns tracked by AIS. The primary challenge is the ability of vessel operators to mask AIS signal transmission. In addition, unlike other countries, Canada presently does not require any fishing vessels to carry AIS. However, many recreational fishing vessels use AIS voluntarily for collision avoidance.

- Vessel Monitoring System (VMS) data is also produced by a satellite-based vessel tracking system, but unlike AIS, it is government-managed, not publicly available, and carried only by commercial fishing vessels. Requirements for commercial fishing vessels to carry VMS vary by DFO region and fishery and are far more extensive on Canada's East coast. Despite significant spatial and temporal differences in VMS data availability, these data are a highly valuable addition to AIS datasets for measuring fishing activity as they capture the commercial fishing vessels that are specifically excluded from AIS-carriage mandates. Canada's VMS program is currently undergoing governance and procedural changes, which has limited data accessibility.
- Aerial surveillance is one of the best methods for determining recreational and commercial fishing activity as small vessels and their activities can often be detected and AIS use for these vessels is voluntary. Flyovers are conducted nationally by Conservation & Protection, Transport Canada, Department of National Defence, and Canadian Coast Guard. The National Aerial Surveillance Program of Conservation & Protection has been recently expanding, however all of the programs are limited by available resources.
- Images from RadarSat II, a Synthetic Aperture Radar (SAR) imaging satellite program, are currently only applied to surveillance of Canada's MPAs in the Pacific region. For this purpose, Conservation & Protection uses RadarSat II to identify potential non-compliance events and may follow up on observed vessels using aerial surveillance. Records may or may not be kept in emails by specific users, but ongoing assembly from weekly email reports has been initiated. The move to the RadarSat Constellation Mission may provide new opportunities for monitoring vessel activity nationally.
- Violation records collected on a regional basis by Conservation & Protection are the only direct and substantiated measure of non-compliance. However, compiling violation information for specific closures requires considerable time as the database cannot currently be queried by MPA or fishing closure names and the data are not spatialized. Compilation is easier for species-specific closures which can be queried by the relevant species.

All of these data sources have challenges in collection, processing, storage, access, and resolutions, but many of the weaknesses of a single dataset can be supplemented by another. For instance, AIS data far exceed all others in resolution and spatial extent, and gaps from vessels not transmitting AIS can be captured with aerial surveillance and RadarSat II. However, challenges remain particularly for small, unregulated fishing vessels. On the East coast, for instance, there are many lobster fishing vessels that are mostly untracked as they are not required to carry AIS or VMS and are too small for the predominant resolution used by RadarSat II (J. Foote, C&P, Halifax, NS, personal communication, 2020). At the MPA level, a targeted focus on select MPAs (i.e. through aerial surveillance, fine resolution RadarSat II images, and AIS geo-fencing; Read et al. 2019) improves the comprehensiveness of surveillance coverage, whereas monitoring across all conservation areas in a region provides information for a greater extent but increases coverage gaps for each area. Data aggregation and processing plans can be created for individual MPAs or Bioregional MPA networks to create the most complete compliance estimates.

In addition to assessing static fishing closures, vessel tracking data can be applied to address questions regarding effectiveness of other conservation measures (e.g. seasonal fishing closures, voluntary avoidance announcements, speed restrictions in whale migration routes) and vessel-related stressors (e.g. marine noise, physical disturbance, discharge, and pollution/spill potential). Collection of these vessel tracking data over the long term will enable the human pressures monitoring that is imperative to evaluate conservation effectiveness (Dunham et al. 2020).

Future data collection by regional programs can reflect a shift from strictly real-time use towards long-term evaluation by compiling and organizing data in a way that makes it more readily accessible and usable for DFO Scientists. Currently, many of these datasets are held by numerous sources within and across regions. Compiling these data is time consuming for both the person requesting the data and the people who then must query databases that were not designed for this purpose. If these data are to be used for ongoing monitoring, as we recommend, consideration should be made on how to better streamline data collection and dissemination, and to ensure data archival within and across regions.

Vessel tracking technology, in particular satellite receivers and imaging, and its application through big-data processing is rapidly advancing. DFO can look towards new developments in Canada's maritime awareness (through the Marine Security Operations Centres and Department of National Defense) that can similarly contribute to conservation management. DFO can also drive developments in using new and existing technologies for surveillance and monitoring of marine conservation areas including increasing VMS requirements for fisheries, working with Transport Canada to expand AIS regulations to include fishing and other high-impact, unregulated vessels, and improving data access and analysis tools.

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