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Hydrothermal Vents

S. Kim Juniper, Kate Thornborough, Karen Douglas, & Joy Hillier

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Remote monitoring of a deep-sea marine protected area: The Endeavour Hydrothermal Vents

S. Kim Juniper¹ | Kate Thornborough² | Karen Douglas¹ | Joy Hillier³

¹Ocean Networks Canada, University of Victoria, Victoria, BC, Canada

²Independent Researcher, Manly, NSW, Australia

³Fisheries and Oceans Canada, Nanaimo, BC, Canada

Correspondence

S. Kim Juniper, Ocean Networks Canada, University of Victoria, Victoria, BC V8N 1V8, Canada.

Email: kjuniper@uvic.ca

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Abstract

1. Deep-sea marine protected areas (MPAs) present particular challenges for management. Their remote location means there is limited knowledge of species and habitat distribution, and rates and scales of change. Yet, evaluating the attainment of conservation objectives and managing the impact of human activities both require a quantitative understanding of natural variability in species composition/abundance and habitat conditions.
2. Ocean Networks Canada (ONC) and Fisheries and Oceans Canada are collaborating in the development of remote monitoring tools for the Endeavour Hydrothermal Vents MPA in the north-east Pacific. This 98.5 km² MPA, located 250 km offshore Vancouver Island, encompasses five major fields of hydrothermal vents, at depths of 2200–2400 m. A real-time cabled observatory was installed at the Endeavour site in 2010.
3. Scientific research for the conservation, protection and understanding of the area is permitted within the MPA and is the primary activity impacting the area. Research activities require the use of submersibles for sampling, surveying and observatory infrastructure maintenance. Data and imagery from remotely operated vehicle dives and fixed subsea observatory sensors are archived in real time using ONC's Oceans 2.0 software system, enabling evaluation of the spatial footprint of research activity in the MPA and the baseline level of natural ecosystem change.
4. Recent examples of database queries that support MPA management include: (1) using ESRI ArcGIS spatial analysis tools to create kernel density 'heat maps' to quantify the intensity of sampling and survey activity within the MPA; and (2) quantifying high-frequency variability in vent fauna and habitat using sensor and fixed camera data.
5. Collaboration between researchers and MPA managers can help mitigate the logistical challenges of monitoring remote MPAs. Recognition at the policy level of the importance of such partnerships could facilitate the extension of scientific missions to support more formal monitoring programmes.

KEYWORDS

cabled observatory, deep-sea, hydrothermal vents, kernel density, marine protected areas, monitoring

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1 | INTRODUCTION

Marine protected areas (MPAs) have become a central pillar of marine conservation strategies worldwide, within and beyond areas of national jurisdiction. As MPAs increase in number and extent, the ability of responsible agencies to effectively monitor and manage them is being examined by conservation researchers (e.g. Abecasis et al., 2015), and pilot efforts such as the International Union for Conservation of Nature's Green List are setting global standards for MPA management. Research suggests that the development of MPA management tools and the availability of resources for effective MPA management are lagging behind the creation of new protected areas. For example, an examination of 550 coastal and offshore MPAs in the north-east Atlantic found that only 153 had management plans, of which 66 actually had staff and resources dedicated to management of the MPA (Álvarez-Fernández, Fernández, Sánchez-Carnero, & Freire, 2017). In another example, of Canada's 11 currently legislated MPAs (eight more in pipeline), seven have management plans and assigned managers, but none have formal ecological or compliance monitoring programmes to inform management.

Offshore and deep-sea MPAs present particular challenges for effective management and the evaluation of progress towards conservation objectives. Their remoteness and the related cost of sampling and survey expeditions together limit access for the research and monitoring activities (Copley et al., 1999) that are needed to build site-specific knowledge. Effective MPA management requires knowledge of species and habitat distributions, and rates and scales of environmental and biological change (Júnior, Ladle, Correia, & Batista, 2016). This need is particularly accentuated in the case of protected deep-sea hydrothermal vent habitats, often cited as one of most dynamic deep-sea environments known. Hydrothermal vents are found in geological settings that support seafloor volcanism and related hydrothermal circulation, including mid-ocean ridges, volcanic arcs, intra-plate volcanoes and back-arc basins (Van Dover et al., 2018). The chemosynthesis-based ecosystems found at active hydrothermal sites have a high scientific value because of the evolutionary novelty of their specialized faunas and the very high but still unquantified diversity of vent microbial communities. Natural habitat instability and rapid ecosystem change are often cited as general features of deep-sea hydrothermal vents worldwide (Van Dover et al., 2018), although a recent study (Du Preez & Fisher, 2018) suggests that stability may vary with geological setting.

Globally, hydrothermal vent sites are protected under a number of different legal frameworks (Table S1). Two areas of deep-sea vents presently have MPA status. Canada's Endeavour Hydrothermal Vents Marine Protected Area (EHV MPA) encompasses five fields of hydrothermal vents on the Endeavour Segment of the Juan de Fuca Ridge in the north-east Pacific Ocean. Portugal's Marine Park of the Azores protects four hydrothermal vent fields near the Azores archipelago and on the Mid-Atlantic Ridge. Both the Endeavour and Azores MPAs permit research activity, and their remote location means that basic research is the primary source of survey and monitoring information for managers. Only the EHV MPA has a management plan.

The EHV MPA was established in 2003 under Canada's Oceans Act (SOR/2003-87) to protect the spectacular hydrothermal vent fields (Kelley et al., 2012) and their specialized vent fauna, and to encourage scientific research that contributes to the '... conservation, protection and understanding of the natural diversity, productivity and dynamism of the ecosystem' (Fisheries and Oceans Canada [DFO], 2009). The 98.5 km² MPA is located 250 km offshore Vancouver Island and encompasses five major fields of hydrothermal vents, at depths of 2200–2400 m (Figure 1). It has been a focus for research activity since sulphides and tubeworms were found in dredge samples in 1982 (Tivey & Delaney, 1986). Scientific research for the conservation, protection and understanding of the area is permitted within the boundaries of the EHV MPA, which extends from the sea floor to the sea surface. Pelagic fishing and activities for the sovereignty and protection of Canada are also permitted. Research activity is both the only source of disturbance and the only source of monitoring information for the sea bed and deep-water-column portions of the EHV MPA, and this tends to be the case for hydrothermal vents worldwide (Glowka, 2003; Van Dover, 2014). Hydrothermal vent research usually involves the use of scientific submersibles, mostly remotely-operated vehicles (ROVs), for sampling, surveying and observatory infrastructure maintenance. There are often several ROV expeditions per year to some of the intensively studied sites, including the Endeavour vent fields. Incidental observations of faunal community changes at sites frequently visited by researchers (e.g. Tunnicliffe, 1990) led to the adoption of a voluntary code of conduct for research activity at hydrothermal vents by the international organization InterRidge (InterRidge, 2006).

The EHV MPA management plan does not explicitly address the challenge of distinguishing natural change from human-induced change, although it does acknowledge the need to ensure that impacts from research activities 'remain less significant than natural perturbations' (Fisheries and Oceans Canada [DFO], 2009). Within the long-lived vent fields of the EHV MPA, research has shown that there can be significant, annual to intradecadal natural changes in habitat physico-chemical properties and vent faunal composition at spatial scales of individual vents and sulphide edifices (Sarrazin, Robigou, Juniper, & Delaney, 1997). At broader scales, there is accumulating evidence of longer term vent-field-scale shifts in hydrothermal discharge within the EHV MPA that can profoundly influence habitat availability and habitat quality for vent organisms (Kelley et al., 2012; Lilley, Butterfield, Lupton, & Olson, 2003). Effective management of the EHV MPA therefore requires a quantitative understanding of the small-scale dynamics of vent faunal communities, their causes, and an awareness of the larger vent-field-scale processes that determine hydrothermal conditions at the local level. This knowledge of natural variability needs to be related to the distribution of research activity within the MPA and the potential environmental disturbances arising from this work. Potential disturbance from research sampling and experimental deployments tends to concentrate at the scale of individual vents.

The installation of a real-time cabled observatory at Endeavour in 2010 by Ocean Networks Canada (ONC) provided an opportunity for remote monitoring that could serve both basic research and MPA management. Observing technologies are increasing our understanding of the natural variability of deep-sea ecosystems (e.g. Juniper

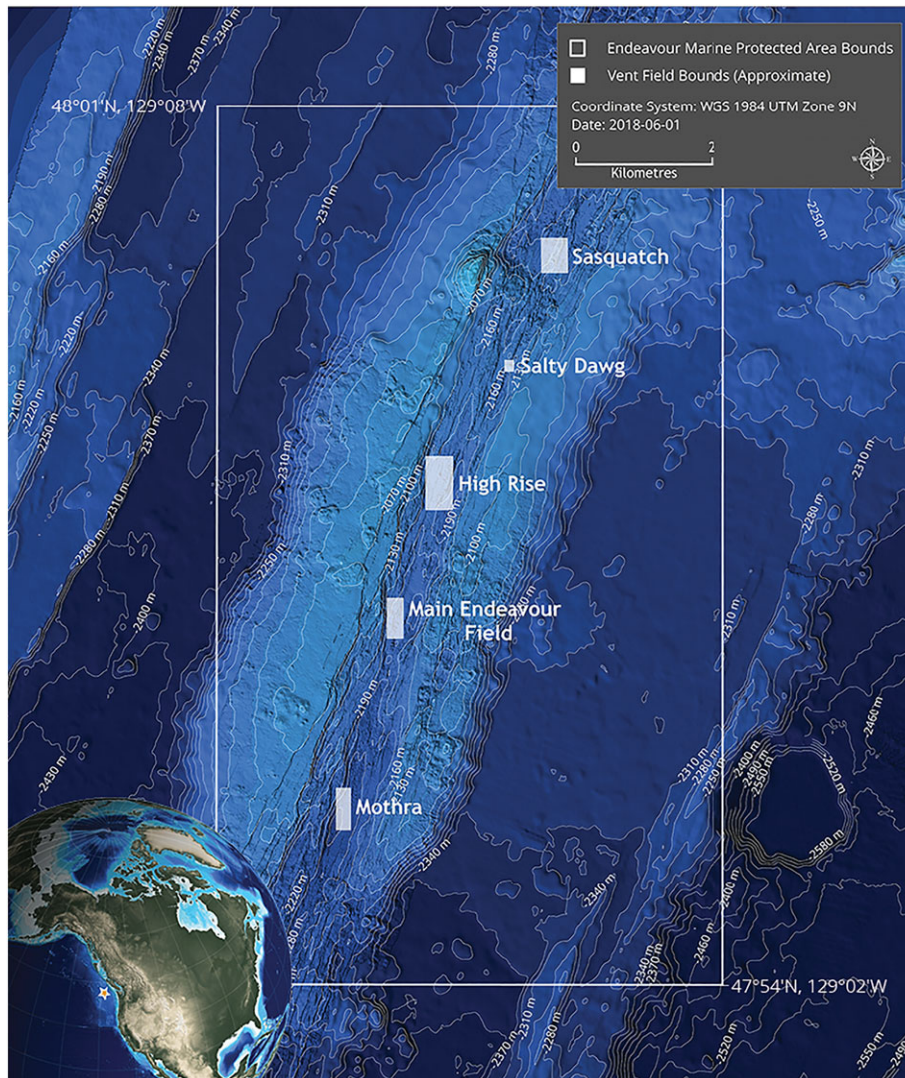


FIGURE 1 Boundaries and individual hydrothermal vent fields for the Endeavour Hydrothermal Vents Marine Protected Area. Inset shows location in north-east Pacific Ocean

et al., 2013; Matabos et al., 2014), which in turn should enable the identification of perturbations resulting from human activities (Matabos et al., 2017). Continuous observing systems, especially cameras, are particularly well suited to building baseline knowledge of small-scale variations in key ecosystem components and how these relate to natural habitat change. There are several examples of this type of research from the EHV MPA (Cuvelier, Legendre, Laës-Huon, Sarradin, & Sarrazin, 2017; Cuvelier, Legendre, Laës-Huon, & Sarrazin, 2014; Lelièvre et al., 2017). In addition to data from the fixed observing systems, annual maintenance of observatory technology by ONC brings ROVs to the EHV MPA, providing opportunities to survey larger areas. All observatory sensor data and ROV expedition video and navigation records from the EHV MPA are archived and made publicly available by ONC. The combined data archive therefore has the potential to support adaptation of the EHV MPA management plan and conservation objectives to a growing understanding of natural rates and scales of environmental and ecosystem change, and the spatial distribution of research activity. This paper examines how this potential is being realized, using some of the concepts developed to support adaptive management and monitoring of the Great Barrier

Reef World Heritage Area (Hedge et al., 2013, 2017). In particular, this paper reviews progress in the definition of monitoring goals and operational objectives, the identification of indicators, the management and analysis of monitoring data, and the reporting of findings relevant to management needs.

2 | CURRENT MANAGEMENT AND RESEARCH ACTIVITIES

2.1 | MPA management

The EHV MPA was established under Canada's Oceans Act (SOR/2003-87). There are five management areas, centred on the known vent fields. Extractive activities are limited to two areas, whereas the remaining vent areas are identified for 'observation only', allowing long-term observation studies to continue (Banoub, 2010).

Researchers must submit proposed research plans to the MPA manager, who seeks the advice of the Technical Advisory Committee, comprising members from government agencies, academia and

environmental groups. The committee evaluates proposed research and advises as to the acceptability of potential impacts. The review framework includes a decision tree to identify situations where disturbance, damage, destruction and removal may be approved under the regulations, as well as situations where they would not be acceptable (Davies, O, & Boutillier, 2011).

MPA regulations do not restrict research activities to the management areas, nor do the regulations restrict the type of research activities that can take place within the MPA (Davies et al., 2011). However, researchers must comply with the provisions of the Oceans Act and with other applicable federal legislation such as the Fisheries Act (which licenses species collection of samples). Using these legislative tools, MPA managers may limit the location and species sampling that occurs and ensure reporting that contributes to the understanding of the area is submitted.

Research and monitoring activities within the EHV MPA boundary are only feasible from large oceanographic vessels, most frequently using scientific submersibles or ONC's North-East Pacific Time-Series Undersea Networked Experiments (NEPTUNE) cabled observatory infrastructure. Research disciplines range from geophysics to the study of vent fluid chemistry and ore-forming processes, and the biology and ecology of hydrothermal vent fauna and microbes. ONC is currently the most active scientific organization working in the EHV MPA, installing and maintaining instruments for in situ experimentation and monitoring, and conducting surveys and mapping the sea floor and venting sites.

Several federal departments conduct additional monitoring of activities in the vicinity of the EHV MPA. Transport Canada monitors ballast water exchange of ocean-going vessels through the Canadian Ballast Water Program, and the National Aerial Surveillance Program monitors pollution from oil spills (Davies et al., 2011). Environment and Climate Change Canada also monitors oil spills and other ocean surface anomalies through the Integrated Satellite Tracking of Pollution programme. The Department of National Defence patrols the

Canadian exclusive economic zone via overflights and its Maritime Pacific fleet operations. Vessel traffic has been assessed as a low risk of harm to the Endeavour ecosystem (Thornborough, Rubidge, & O, 2018). Research vessels comprise the main directed surface traffic in the EHV MPA. Incidental vessel traffic in the area can occur as the result of commercial fishing and naval and commercial shipping activities. Although commercial fishing for albacore tuna and neon flying squid is known to occur occasionally in the area, pelagic fishing is not considered to be in conflict with the MPA conservation objectives as it takes place very near the ocean surface.

2.2 | Real-time observing system (2011–2017)

ONC has been operating real-time observing systems in the EHV MPA since 2011. Individual instruments (sensors, cameras, etc.) and instrument platforms are connected by extension cables to the Endeavour node of ONC's NEPTUNE cabled observing system (Figure 2). The node provides power and two-way data communications to all instruments. The longest standing operational site is in the Main Endeavour vent field, mostly on a sulphide edifice named Grotto. A short-period seismometer installation south of Grotto monitors local seismic activity, which can be one of the underlying causes of changes in hydrothermal discharge at vents on Grotto and elsewhere. North of the edifice, sonar systems monitor the rising warm water plume originating from multiple discharge points. On Grotto itself, several different temperature sensor technologies are monitoring hydrothermal vents that vary from an inhospitable $>335^{\circ}\text{C}$ black smoker vent, to diffuse warm flows that directly support vent organisms. The Tempo-mini video camera system (Figure 3), built and operated by Ifremer (France), monitors hydrothermal activity within its field of view using real-time and autonomous temperature sensors. Two recent publications describe how imagery and temperature data can be combined to study vent faunal responses to temporal variability



FIGURE 2 Endeavour node and typical instrument platform (inset) of the North-East Pacific Time-Series Undersea Networked Experiments cabled observatory network operated by Ocean Networks Canada

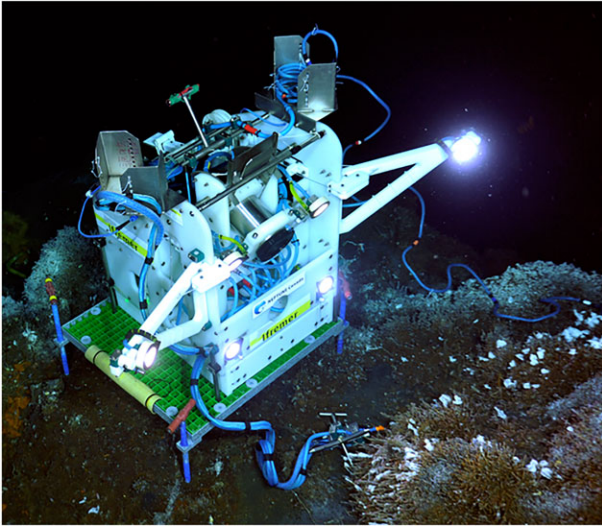


FIGURE 3 Temporo-mini camera and sensor system on Grotto edifice in the Main Endeavour vent field

in hydrothermal habitat conditions (Cuvelier et al., 2014; Lee, Robert, Matabos, Bates, & Juniper, 2015). Three monitoring systems on Grotto provide data on chemical properties of the vent environment.

2.3 | Expanded real-time observing system (2017–2019)

A near-tripling of ONC's observing system at the EHV is currently underway and will be completed by 2019. This expansion will permit the simultaneous monitoring of three separate hydrothermal vent fields (Mothra, Main Endeavour, High Rise; Figure 1). Notable new sensors will include additional cameras and instruments to analyse hydrothermal fluid chemistry in situ and the completion of a short-period seismometer network that will precisely locate seismic events in the hydrothermal upflow zone below the sea floor and support study of their links to vent fluid discharge. Extending the observing system to the Mothra and High Rise vent fields will provide biologists with new settings to test ideas about the coupling of vent communities to habitat dynamics. These ideas, some formalized as conceptual models, were developed from observations at a single location in the Main Endeavour field.

2.4 | ROV activities and sampling

ONC stages annual ROV and research vessel operations at the EHV to maintain the observatory infrastructure and to collect samples for calibration and site characterization. ROV dive records from these operations represent an important but underutilized resource for monitoring the areas adjacent to the instrument installations, and beyond. All operations and visual observations from ROV cameras are logged in real time as the vehicles transit between locations, service instruments and collect samples for sensor calibration and laboratory analysis. Video records are available online through ONC's SeaTube application, and keyword searches of annotations permit rapid access to corresponding video records.

3 | EHV MPA RISK-BASED APPROACH

A systematic, science-based ecological risk assessment framework (ERAF; O et al., 2015) was developed to support DFO's implementation of adaptive ecosystem-based management in Canada's Pacific Region MPAs. The ERAF provides a structured approach to assess the potential risk of harm to significant ecosystem components (SECs) from anthropogenic activities and their associated stressors. This 'top-down' risk-based approach to ecosystem assessment and management was particularly relevant to the EHV MPA, where SECs had yet to be identified, baselines did not exist and the impact from human activities was relatively unknown. The output of an ERAF application is a key information tool for focusing management priorities, selecting and prioritizing indicators for monitoring, and refining conservation objectives.

The ERAF was applied to the EHV MPA in 2015 (Thornborough et al., 2018), in two phases: scoping and risk assessment. The scoping phase identified SECs and anthropogenic stressors with the potential to impact the EHV MPA ecosystem. The semi-quantitative risk assessment calculated the likelihood that a SEC will experience adverse consequences due to exposure to one or more identified stressors. In this context, a SEC is defined as an environmental element that has ecological importance to the ecosystem (O et al., 2015). SECs include components that are unique, sensitive, ecologically significant, play specialized or keystone roles in the food web, support critical life stages, and so on. Six species SECs (primarily sessile/low mobility and vent dependent), four abiotic habitat SECs and one community SEC (found only in one area of the EHV MPA) were identified (Table 1).

Activities identified as having a potential negative impact on the EHV MPA include those associated with transiting and visiting vessels, overboard sampling from research vessels, research submersibles, equipment installation and seismic surveys). The associated stressors identified as posing the highest risk to the EHV MPA SECs include debris and spilled oil from vessels, crushing during sampling and by submersibles, and the potential for the introduction of invasive species from submersibles.

The risk assessment prioritized SECs and the stressors impacting them by both relative and cumulative (additive) risk. The high- and low-flux morphotypes of the tubeworm *Ridgeia piscesae*, the sulphide worms (*Paralvinella sulfincola*) and the benthic clam bed community had the highest cumulative risk scores in the EHV MPA. These can be attributed to high numbers of impacting stressors and slow recovery

TABLE 1 Significant ecosystem components (SECs) identified for the Endeavour Marine Protected Area

SEC type	SEC
Species SECs	<i>Ridgeia piscesae</i> (high-flux morphotype; tubeworm) <i>Ridgeia piscesae</i> (low-flux morphotype; tubeworm) <i>Lepetodrilus fucensis</i> (limpet) <i>Macroregonia macrochira</i> (spider crab) <i>Paralvinella palmiformis</i> (palm worm) <i>Paralvinella sulfincola</i> (sulphide worm)
Habitat SECs	Active venting hydrothermal mineral chimneys Inactive hydrothermal chimneys Hydrothermal plume Diffuse venting basalt flows
Community SECs	Benthic clam bed community

scores (Thornborough et al., 2018). The abiotic habitats had the lowest cumulative risk scores, as a result of their being impacted by less than half the number of stressors as the species and community SECs. The stressors with the highest cumulative scores were debris from vessel discharge, substrate disturbance (crushing) from sampling and submersibles, and aquatic invasive species from submersibles (Thornborough et al., 2018). The highest risk scores were found to be associated with the highest uncertainty, identifying key knowledge gaps.

The outputs of the risk assessment were used to select scientifically defensible indicators to monitor the achievement of MPA conservation objectives. A risk-based indicator selection framework was developed and subsequently applied to the EHV MPA (Thornborough, Dunham, & O, 2016). Using this framework, all SECs, stressors and SEC–stressor interactions were prioritized based on their risk and uncertainty scores. Uncertainty was included in the prioritization process to highlight key knowledge gaps. Indicators were identified from the primary literature and filtered based on selection criteria. Indicators were selected for all SECs and stressors, and for high- and moderate-risk SEC–stressor interactions.

Several recommendations emerged from the risk-based indicator selection process:

1. Establish baselines using low impact methods.
2. Develop a suite of indicators for SECs, stressors and SEC–stressor interactions for a complete monitoring programme.
3. Use nondestructive methods for measuring indicators, where possible, using cameras (baselines and impacts), video mapping (baselines and impacts) and so on.
4. Map potential for impacts/exposure.
5. Use visual (video) surveys for simultaneous measurement of multiple indicators.

The risk-based approach to monitoring the EHV MPA is underpinned by an adaptive management framework. As data are collected through the monitoring of indicators, information may be fed back into the adaptive management framework for future iterations of risk assessments, evaluation of indicators, selection of new/additional indicators and the refinement of monitoring and management plans. A formal monitoring programme for the EHV MPA has yet to be implemented.

4 | POTENTIAL DISTURBANCE RESULTING FROM RESEARCH ACTIVITIES

Van Dover (2014) provides a general overview of the range and impacts of natural and anthropogenic disturbances at deep-sea hydrothermal vents. This paper considers aspects that are particular to the management of research activity in the EHV MPA, and provides examples of monitoring measurements that can inform adaptive management.

All bottom sampling operations (biological, geological, hydrothermal vent fluids), together with seafloor visual surveys and observatory maintenance activities, are carried out by research submersibles, either ROVs or human-occupied vehicles (HOVs). Scientific sampling

from surface vessels by means of dredging, coring and bottom-contact fishing is not permitted in the MPA. Most scientific diving at Endeavour in the past decade has used ROVs. As they transit and work in the area, submersibles produce noise from hydraulic and electric motors and acoustic transponders, noise that could potentially alter behaviours of vent organisms, as could noise from shipboard echo sounders. Van Dover (2014) noted a general absence of studies or evidence of impact of introduced sound on vent ecosystems. The high-intensity lights used for piloting submersibles, and for visual observations and video/photo documentation, have been implicated in photoreceptor damage in vent shrimp, and there is potential for damage in other taxa with photosensitive organs. However, Van Dover (2014) concludes that there is no evidence to date of behavioural responses or population declines in vent organisms as a result of exposure to submersible illumination.

So-called 'scientific trash' (Van Dover, 2014), intentionally and unintentionally abandoned material such as iron ballast from HOVs (up to 375 kg per dive released near bottom to adjust buoyancy) and the markers, anchors, containers, fasteners, and so on that are associated with sample collections and the deployment of seafloor experiments, represents another potential source of disturbance, particularly around sites of long-term research activity. Van Dover (2014) concluded that such material has so far had negligible or minor impacts on vent ecosystems. However, it could be argued that the sight of accumulated waste detracts from the aesthetic and cultural value of any MPA. The EHV MPA 2010–2015 management plan requires researchers to remove waste from the sea floor and funding agencies have supported use of submersible time for voluntary clean-ups.

Submersible movements, and use of their robotic manipulators, are potentially the most significant sources of disturbance in high-use areas of the EHV MPA (Dando & Juniper, 2001). Accidental bumps and collisions during manoeuvres in confined areas around the area's many hydrothermally active sulphide edifices can crush organisms and break portions of the mineral structures that they colonize. Thruster wash from submersibles can resuspend sediment and even dislodge organisms. Fauna can be crushed when vehicles are immobilized (landed) for close-up observations or to perform precise robotic manipulations (sampling, instrument deployments). Dancette (2008) examined damage to sulphide edifices and vent fauna that occurred during submersible operations in the EHV MPA. Video records from four dives by the HOV *Alvin* and the ROV *ROPOS* in the Main Endeavour and Mothra vent fields (one dive/vehicle/vent field) were reviewed to quantify disturbances resulting from activities such as vehicle manoeuvring and station keeping, different sampling operations and sensor deployments. Documented disturbances included breaking or bumping sulphide structures, dislodging or removing organisms and resuspending sediments. Between 33% and 55% of the 160 reviewed activities resulted in detectable disturbances. Disturbance rates were higher for sampling operations, where >75% left visible traces of >100 cm² on edifice surfaces. By comparison, a 4-year time-series mapping study by Sarrazin et al. (1997) of faunal assemblage distribution on S&M edifice in the Main Endeavour field documented extensive turnover in the mosaic of faunal assemblages that were attributed to natural structural collapses and shifts in intensity and location of hydrothermal fluid discharge. Other studies

have identified field-scale changes in hydrothermal discharge within the EHV MPA, presumably related to the waxing and waning of heat sources and cracking fronts that drive hydrothermal circulation in the crustal rock beneath the vent fields (Kelley et al., 2012). Evidence of such field-scale changes includes: (a) the near shutting down of high-temperature discharge within the southern portion of the Main Endeavour vent field, beginning in the early 2000s (Kelley et al., 2012); (b) the growing number of extinct sulphide edifices and individual chimneys that are being discovered outside of the current active vent fields; and (c) the mostly inactive condition of the sulphide edifices in the Salty Dawg and Sasquatch vent fields in the northern portion of the MPA. There are no records or maps of faunal distribution at these same scales that would permit evaluation of related impacts on the distribution of vent faunal assemblages.

Dancette (2008) also mapped the surface areas occupied by previously identified faunal assemblages (Sarrazin et al., 1997) on the sulphide structures visited during the aforementioned dives, and documented the distribution of sampling operations among the various faunal assemblages. This revealed a disproportionate concentration of sampling and resulting disturbance in the relatively rare high-flow tubeworm habitat. Later research revealed that the scarce high-flow tubeworm colonies are the most important reproductive populations within the EHV MPA, providing a source of propagules for the tubeworm aggregations that cover large areas of active sulphide edifices and volcanic rock around seafloor vents (Tunnicliffe, St. Germain, & Hilario, 2014). The high-flow tubeworm assemblage is one of the 'species SECs' that are a focus of management for the EHV MPA.

5 | QUANTIFYING RESEARCH ACTIVITY WITH THE ENDEAVOUR MPA

The upcoming first revision of the EHV MPA management plan will need to consider how use of the MPA by the research community has contributed to 'conservation, protection and understanding' since the management plan was introduced in 2010. The review will require information on how research is increasing knowledge of the area, and information on the accumulation of research pressure (and related potential disturbance). ONC has developed a methodology for quantifying the spatial distribution of research activity using a geographical information system (GIS) database assembled from available submersible navigation and dive logs. Research submersibles are navigated on the sea floor using combinations of acoustic and other navigation tools (inertial guidance, Doppler velocity logs, shipboard global positioning system). Data are recorded for multiple sensors such as depth, latitude, longitude, heading, pitch, roll, and altitude. ONC archives these data, provides quality control flags and resamples the data to a common interval prior to ingestion into the GIS database. In addition, observations and sample collections are matched to vehicle position by timestamp. Available video records from archived ROV dives, together with real-time annotation logs (position, depth, noted features), are also ingested into the database to permit future use for spatial surveys of seafloor biological and geological features. The GIS database contains navigation tracks for all ROV dives in the EHV MPA since 2000 by ONC and by third parties, and video annotation

and sample collection logs from the 120 ONC and DFO dives undertaken since observatory operations began in 2007.

5.1 | Heat mapping of research activity

Since scientific dives within the EHV MPA now number in the hundreds, simply plotting dive tracks would underutilize the available data and yield little insight into the questions mentioned. Instead, spatial analysis tools were used to create kernel density 'heat maps' of submersible movements and sampling activity at the scale of the entire MPA (Figure 4), and for each of the major hydrothermal vent fields (Mothra, Main Endeavour Field, High Rise, Salty Dawg and Sasquatch—not shown). Heat maps were also constructed for sample collections noted in dive logs, according to sample type (geological, biological, and hydrothermal fluid samples; Figure 5). In addition, the database was queried to determine the percentage of submersible time and sample collections occurring within and outside MPA management areas.

The broad-scale heat map for submersible dives shows that the majority of research is focused in the central third of the EHV MPA. Highest values (symbolized in red) are found primarily in the vent fields and the areas of ONC cabled instrumentation; the lowest values (symbolized in blue) are found mostly in between and along exploratory survey paths. Figure 6 illustrates how research pressure and exploration coverage have evolved over the last 18 years. The first 9 years (2000–2008) saw more time spent on the ridge axis (Figure 6a). As the ridge axis is host to the major vent fields, this is an area of active interest. During the subsequent 9 years (2009–2017; Figure 6b), ONC was the primary visitor, undertaking cabled observatory installation and maintenance activities and occasional sampling.

As seen in Figure 7, sampling pressure within the MPA has been concentrated in the management areas, where there is active hydrothermal venting, mostly in the Mothra, Main Endeavour Field and High Rise vent fields. A few samples were collected between management areas, as well as at the Sasquatch vent field, and outside of the ridge axis. Available records show no sampling of any type at the Salty Dawg vent field between 1984 and 2017. The highest sampling pressure is seen at Main Endeavour Field, where ONC has maintained sampling instrumentation since 2010. There, most sampling has been related to validation of data collected by cameras, CTDs, and individual temperature and chemical sensors, so that sampling pressure tends to be collocated with infrastructure.

The submersible track point data illustrated in Figure 4 were analysed to determine the percentage of submersible time spent within management areas versus outside management areas. Since the submersible position data rate is constant at 1 min intervals, these points represent a relative distribution of ROV time within and outside of the management areas. Based on the available data, 28% of submersible time was spent within the management areas as opposed to the remainder of the MPA. Of the total time spent within the MPA, 10% was spent within the Mothra DFO management area, 14% within the Main Endeavour Field DFO management area, 3% within the High Rise DFO management area, and less than 1% was spent in the Salty Dawg DFO management area.

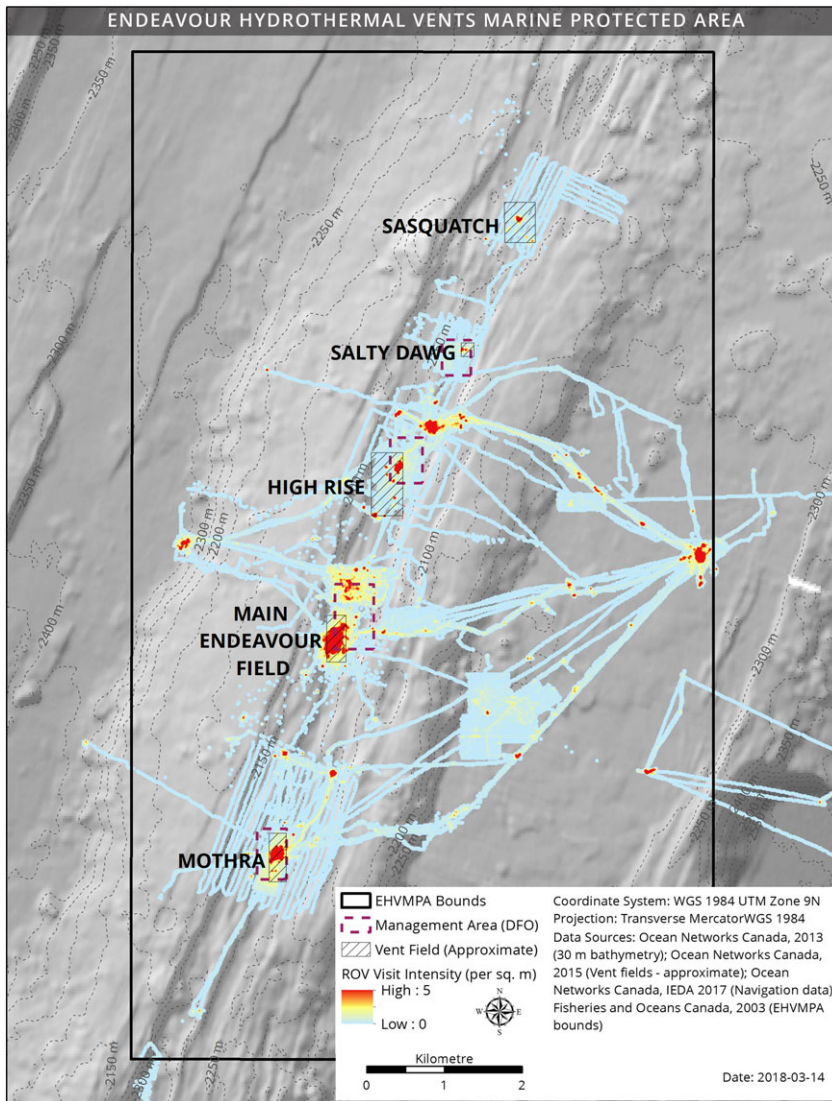


FIGURE 4 Kernel density 'heat map' of cumulative submersible visits per square metre within the Endeavour Hydrothermal Vents Marine Protected Area for all Ocean Networks Canada dives and available third-party dives between 2000 and 2017

The same query was applied to the layer corresponding to the mapped boundaries of the named vent fields. These boundaries only partially overlap with the DFO vent field management areas that were defined in 2003, when data and positioning accuracy were limited compared with later available information. Track points within these vent field boundaries accounted for 75,668 points, for a total of 46% of submersible time in the MPA. This compares with 46,380 points within the DFO-defined management areas (or 28% of points within the MPA). This result indicates that the current management area boundaries only partially encompass the named hydrothermal vent fields and the areas of concentration of research activity, suggesting a need to revise management area boundaries to more completely encompass areas of hydrothermal activity in a future update of the EHV MPA management plan.

The submersible tracks represent both the presence of potential stressors and the distribution of video and CTD records that provide a knowledge base of the area. Two of the largest clusters with high pressure exist at Main Endeavour Field and Mothra. As these management areas are designated for research, the resulting high research pressure is expected (Fisheries and Oceans Canada [DFO], 2009). A detailed report on the heat mapping study is available online (<https://doi.org/10.5281/zenodo.1251261>).

5.2 | Other mapping

In order to determine compliance with the 2010–2015 management plan for the EHV MPA (Fisheries and Oceans Canada [DFO], 2009) and the fulfillment of related information needs, DFO also requires an assessment of introduced anthropogenic materials (Fisheries and Oceans Canada [DFO], 2009) and knowledge of the relative density of target species and available habitats (Fisheries and Oceans Canada [DFO], 2009). Observations recorded in dive logs were used to produce point maps illustrating:

1. Anthropogenic debris classified by type (experiment materials such as plastic cable ties, ballast weights, and other materials, such as aluminium cans).
2. Target species (e.g. corals, sponges, and annelids).
3. Distribution of habitat for target species (e.g. vent species).

Since observations such as the above can be redundant in continuous video records and were made secondarily to other dive objectives, they cannot be considered to provide a quantitative representation of the distribution of these three categories. Density mapping was therefore

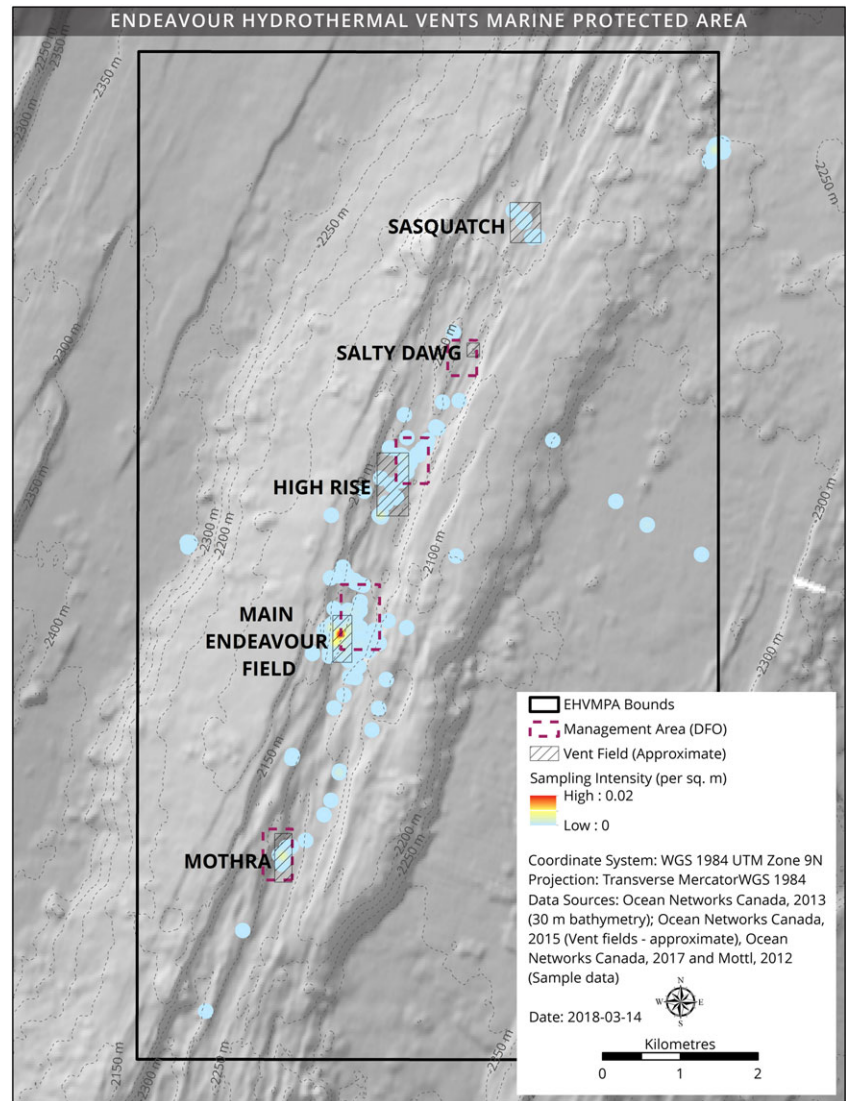


FIGURE 5 Kernel density 'heat map' illustrating accumulated sampling activity in the Endeavour Hydrothermal Vents Marine Protected Area for geological, biological and hydrothermal fluid samples collected by Ocean Networks Canada

not possible, but the points arguably still provide a semi-quantitative assessment of the distribution of species and habitats and anthropogenic materials on the sea floor.

Times and positions of coral/sponge observations, tubeworm observations, vents and debris observations that occurred during submersible dives were extracted from dive logger comments in the Ocean Networks Canada Oceans 2.0 database. Most biological observations are not identified beyond the phylum level in the dive logs because of a lack of available taxonomic information and the difficulty for nonspecialist loggers to make more precise identifications from video. This layer, therefore, does not fully represent species distribution within the MPA, nor can it be seen as a result of systematic benthic community surveys. It simply provides a record of biological, habitat and debris observations made and logged in Oceans 2.0 during ROV dives.

The relative distribution of corals, sponges and tubeworms can be seen in Figure 8a–c. Observed corals were primarily gorgonians (i.e. sea whips and sea fans), whereas sponge records included demosponges and glass sponges. Corals and sponges were widespread and abundant. Any apparent linear distribution patterns

are more likely the effect of the submersible following existing cable routes or shortest distances between observatory installations than any biological distribution. As expected, observations of the vent-specialist tubeworm *R. piscesae* (and SEC) were almost all confirmed to the spreading ridge axis. The two observations recorded off-axis were not the symbiont-bearing tubeworms commonly associated with vent habitats.

To better understand the sources and distribution of anthropogenic debris, observations were mapped by debris type (Figure 9). Categories used were debris from experiments (plastic cable-ties, vent markers, hockey pucks used on grips for ROV manipulators, etc.), lost or discarded fishing gear (nets, rope, etc.), ballast weights left behind by HOV (*Alvin*), and other anthropogenic debris (aluminium cans, plastic bags, boxes, etc.). Most debris was observed on the ridge axis, but that could be a result of observational bias since the submersibles spend most of their time there. However, since the ridge axis is where much of the experimentation has occurred over the years, this is where research-related debris is most likely to be found. Discarded fishing gear was unexpected, and since this is an MPA where bottom-contact fishing has not been permitted since 2003, this debris

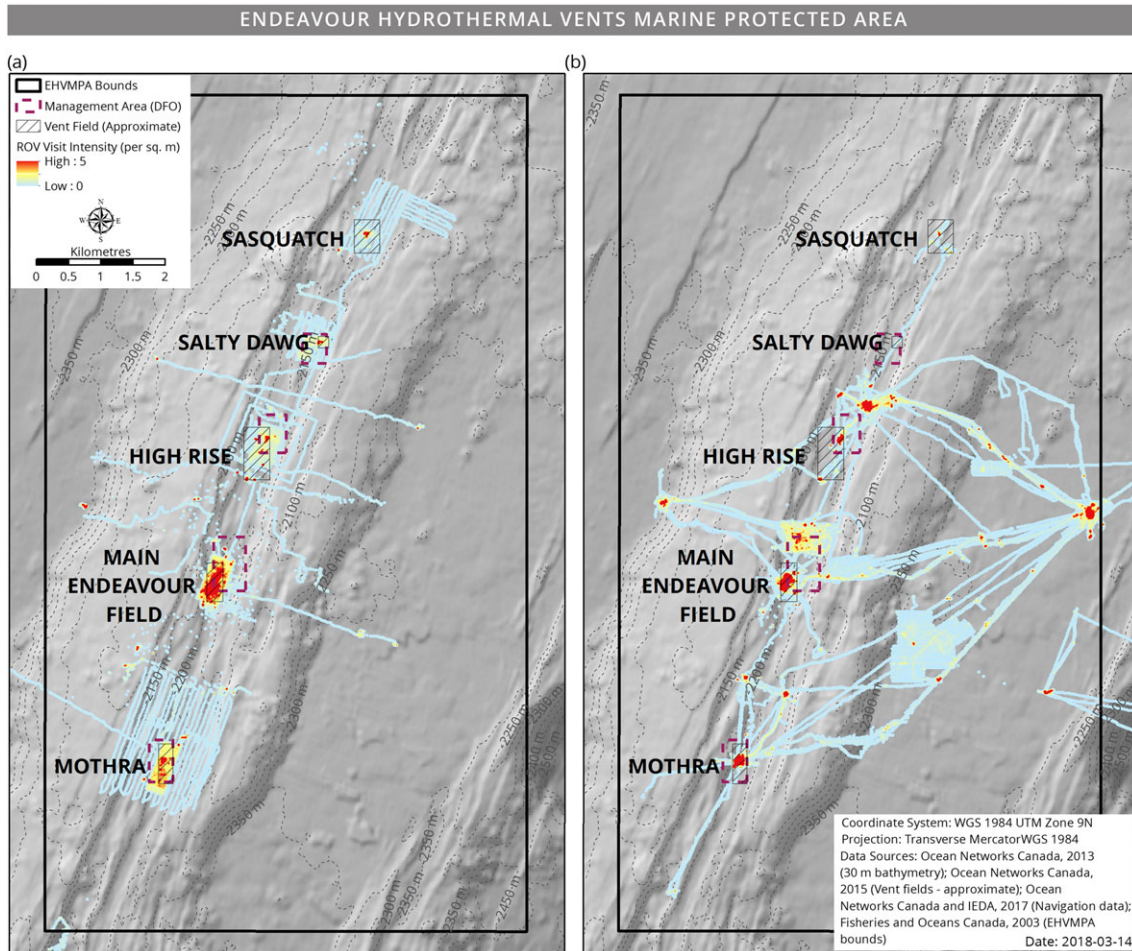


FIGURE 6 Kernel density ‘heat map’ of cumulative submersible visits per square metre within the Endeavour Hydrothermal Vents Marine Protected Area for time periods (a) 2000–2008 and (b) 2009–2017

category may warrant monitoring to improve knowledge of spatial distribution and detect future accumulations.

This exercise has demonstrated the value of a geospatial database of submersible dive tracks, video records and sampling activity with spatial analysis for ensuring compliance with the MPA management plan, for documenting accumulated scientific observations, and for informing revisions to the management plan. A future addition of third-party data from 1982 to 2000, largely comprising *Alvin* dive tracks, would complete an assessment of scientific activity in the MPA since its discovery and establish a more robust basis for managing future use.

6 | FUTURE MONITORING ACTIVITIES

There is currently no formal monitoring programme for the EHV MPA to inform adaptive management. DFO monitoring requirements, from the management plan, include ecological and compliance monitoring. Ecological monitoring is needed to:

1. Establish baselines and thresholds for taking management actions.
2. Determine features and processes of the natural environment.

3. Build foundations for marine environmental quality indicators.
4. Provide data for modelling and other research designs.
5. Ensure necessary information is obtained to measure natural variability.
6. Understand if conservation objectives are being met, based on indicators.

Compliance monitoring includes:

1. Tracking effectiveness of management measures.
2. Determining what is occurring in the MPA with respect to human activity/stressor levels.
3. Enabling the distinction of human impacts from natural variation.
4. Determining general trends in human activities/impacts.
5. Coordination of research activities, equipment and data.

The geospatial database analyses and research results discussed here contribute to understanding research activity and pressures, natural variability of the SECs, and related environmental instabilities and long-term change. Given the remote location of the EHV MPA, a

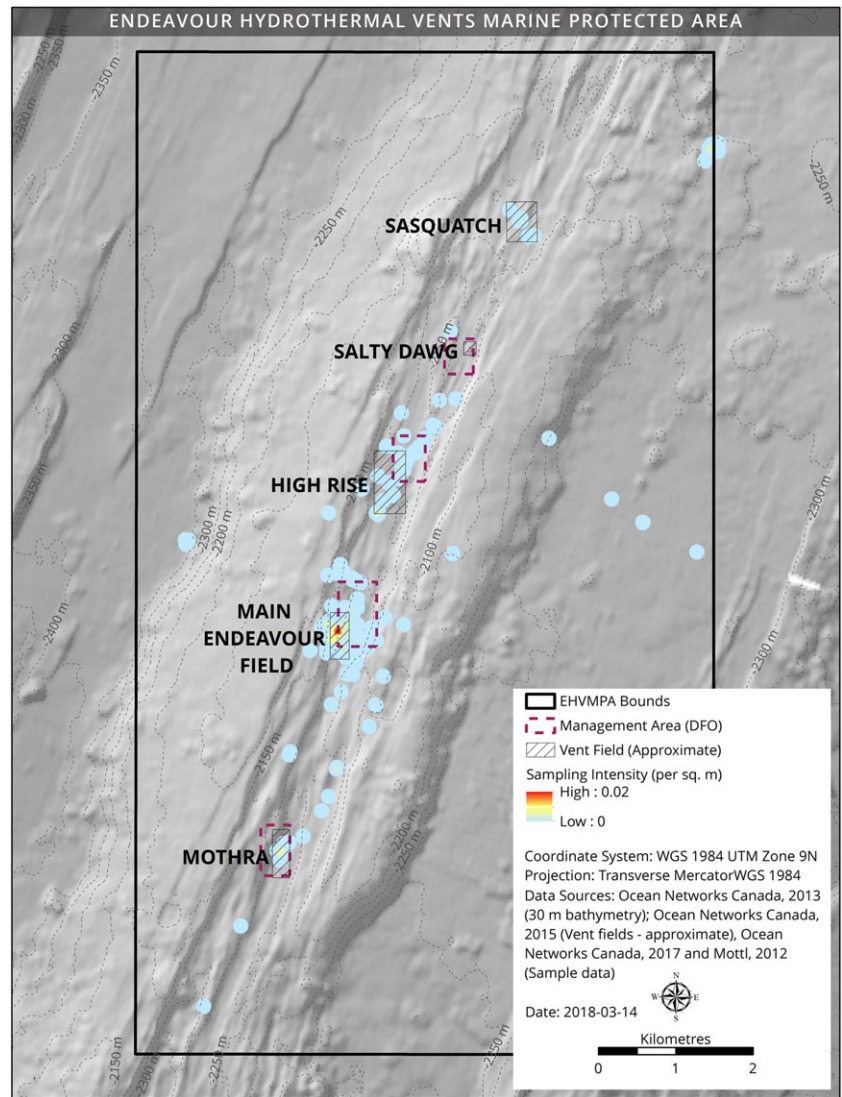


FIGURE 7 Kernel density 'heat map' illustrating accumulated sampling activity in the Endeavour Hydrothermal Vents Marine Protected Area for all types of samples. Data include all sample types in Figure 5 plus vent fluid sample locations from 1984 to 2017 listed in the VentDB Geochemical Database for Seafloor Hot Springs (<http://www.earthchem.org/ventdb>)

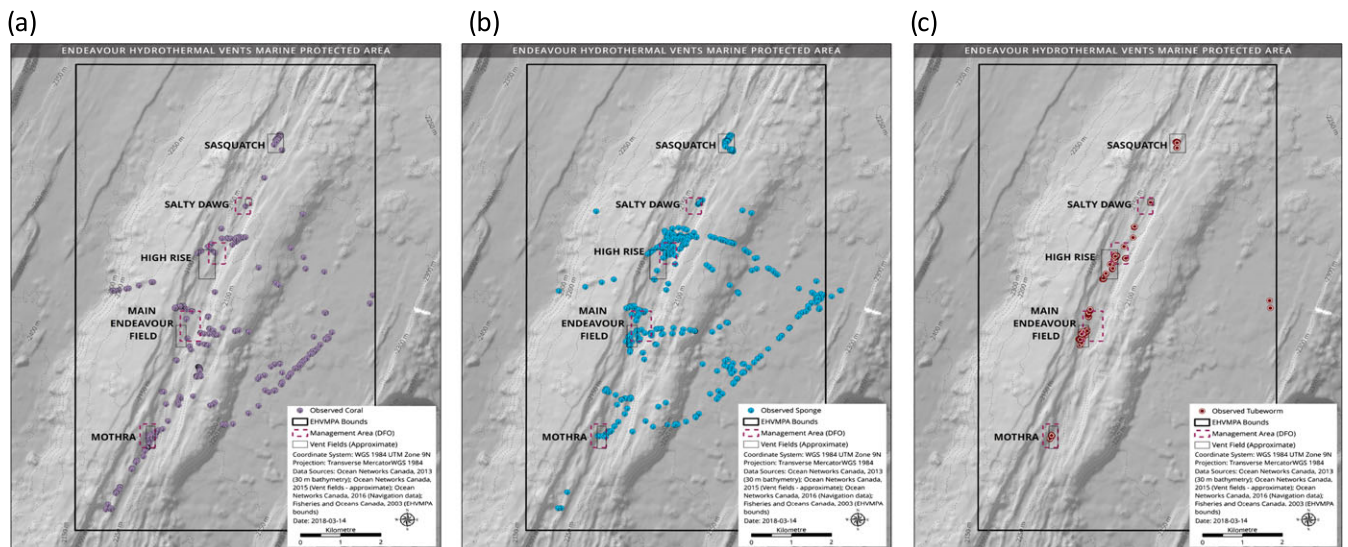


FIGURE 8 Point maps of observations of (a) corals, (b) sponges and (c) tubeworms within the Endeavour Hydrothermal Vents Marine Protected Area

ENDEAVOUR HYDROTHERMAL VENTS MARINE PROTECTED AREA

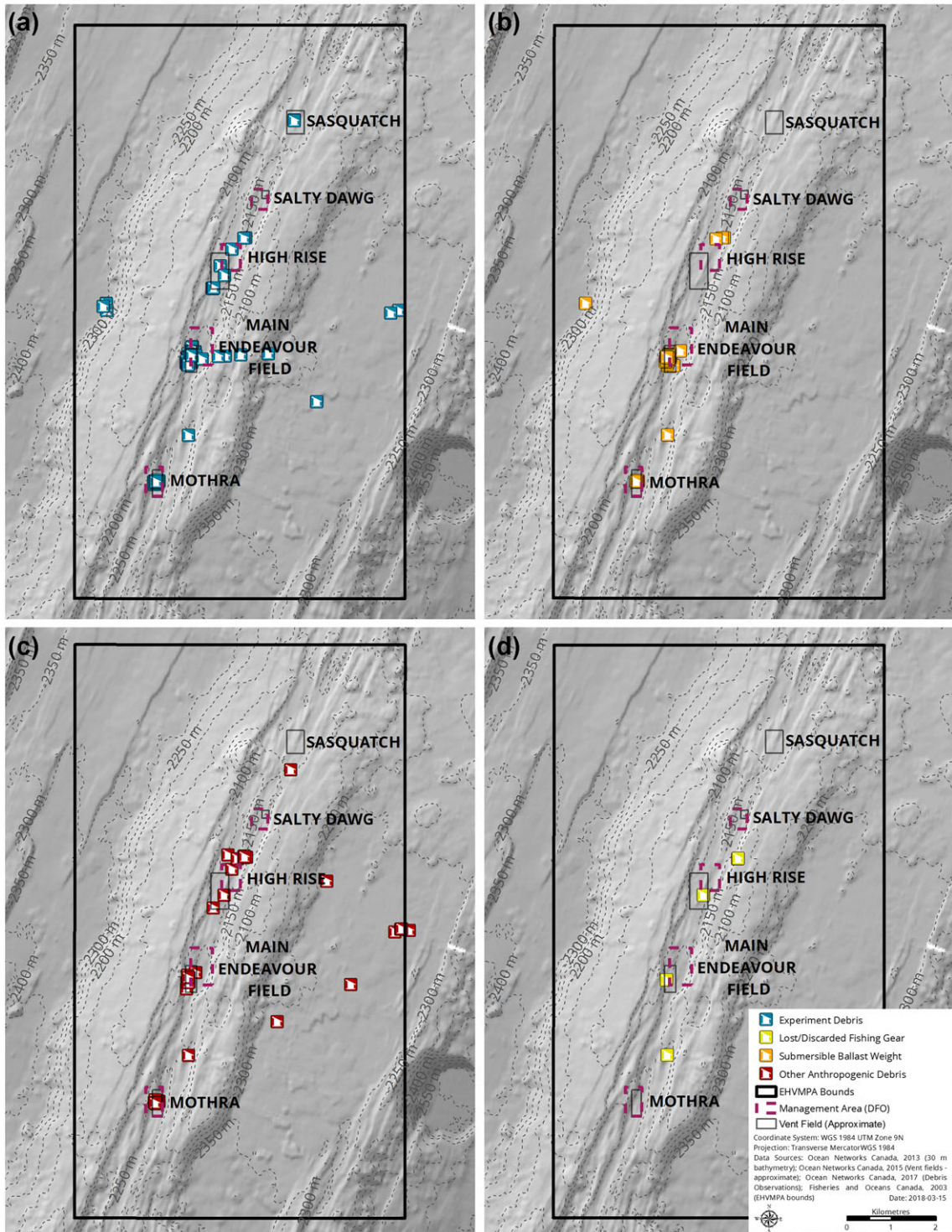


FIGURE 9 Point maps of observations of anthropogenic debris within the Endeavour Hydrothermal Vents Marine Protected Area, classified by type: (a) experiment debris; (b) submersible ballast weights; (c) other anthropogenic debris; (d) lost or discarded fishing gear

realistic monitoring strategy is one that will take maximum advantage of existing observational capacity; that is to say, data collection by visiting scientific ROVs and ONC's cabled sensor network. These sources provide annual survey-scale observations (ROV dives) and high-frequency time-series data from fixed observatory sensors and cameras. Sections 6.1 and 6.2 consider how these data sources can

support MPA management goals and offer recommendations for their incorporation into a formal monitoring programme. In addition to monitoring for conservation and protection of the EHV MPA, there is also a stated goal of 'understanding ... the natural diversity, productivity and dynamism of the ecosystem' (Fisheries and Oceans Canada [DFO], 2009). Section 6.3 provides an example of how management can use

bibliometric tools to monitor the scientific impact of the knowledge of environmental and ecological processes that results from research activity in the EHV MPA.

6.1 | Sampling and video surveys

ROV dives represent a cost-effective solution for extending the observational footprint of the observing systems and developing a larger scale view of natural and human-induced changes to valued ecosystem components within the Endeavour MPA. An initial pilot programme of surveys mapped two neighbouring sulphide edifices within the Main Endeavour Field that have been subjected to contrasting levels of human activity over the past 5 years. These two structures, Grotto and Dudley edifices (Figure 10), are within a 100 m radius, are of similar size and share similar major habitat features, such as black smoker vents, diffuse flows colonized by tubeworms, and an apron of waning hydrothermal habitats at their bases. ONC observing systems and annual maintenance activities are particularly concentrated on Grotto, whereas the Dudley edifice has seen little observatory activity. Both sites were extensively video surveyed in 2015 using the ROV *Hercules*, to permit three-dimensional photogrammetric reconstruction of geological and biological features. A comparative analysis of vertical video transects

of these two structures is reported here. The records of four SECs were quantified: high- and low-flux tubeworm assemblages, sulphide worm communities, and active black smoker chimneys. The goal of this exercise was to evaluate the suitability of the ROV-video transect approach for comparative, long-term monitoring of SEC dynamics that could inform MPA management. Future survey transects could be performed by visiting ROVs during scheduled research or observatory maintenance expeditions, at the request of MPA managers. The evaluation of the feasibility of this approach considered the time required to run individual video transects, the time required to extract SEC data from the video records in the ONC archive and the potential diagnostic value of the resulting data.

Analysis revealed greater than anticipated contrast between the two edifices (Table 2), with respect to intensity of high-temperature hydrothermal discharge through black smoker chimneys. Twenty black smoker chimneys were counted on Dudley and only a single black smoker was observed on Grotto, and there was notably less uncolonized substratum on Dudley. The more intense discharge regime on Dudley is reflected in a greater coverage by colonies of high-flow tubeworms and sulphide worms, both of which are typical of high-discharge habitats. High-flow tubeworms were completely absent from the transect analysed on Grotto. The three faunal SECs are the most common visible faunal assemblages on sulphide edifices

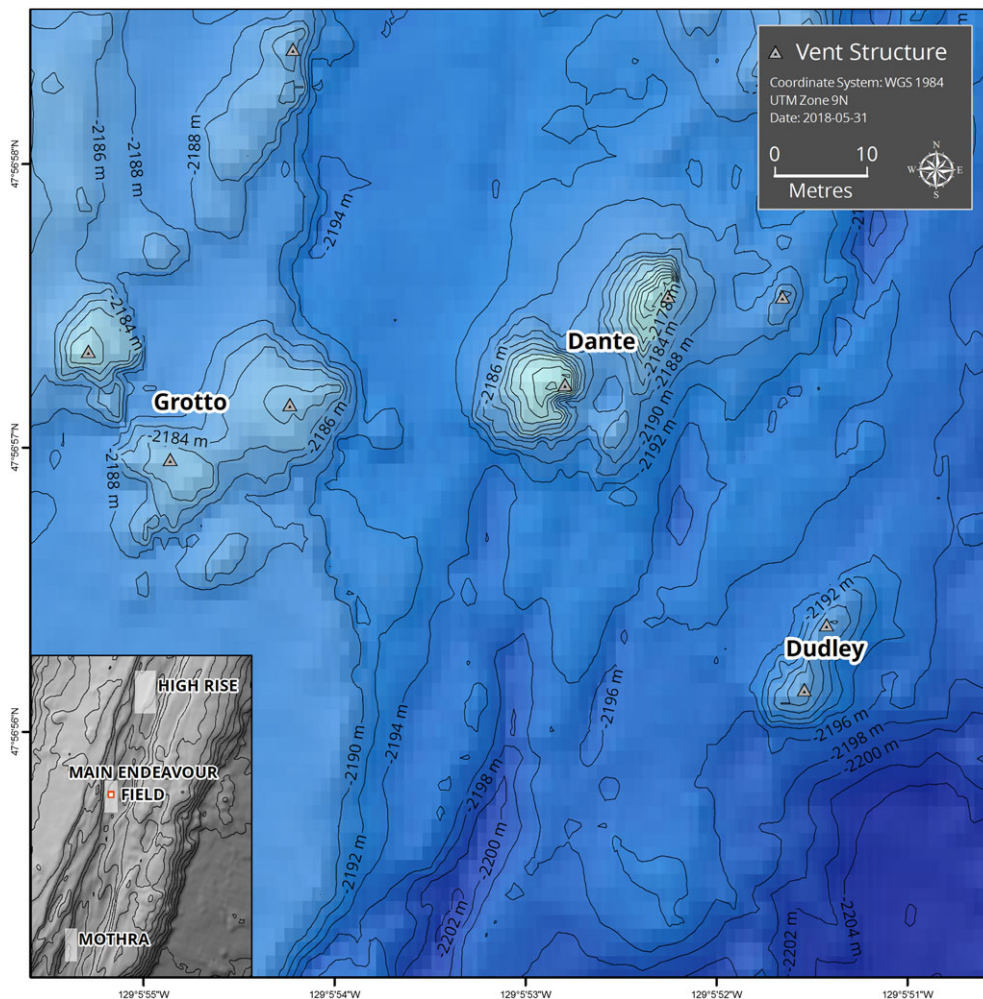


FIGURE 10 Map of Main Endeavour vent field showing locations of Grotto, Dante and Dudley edifices

TABLE 2 Results from analysis of sample video transects from on Grotto and Dudley hydrothermal edifices in Main Endeavour vent field^a

Survey ID	Edifice	Depth interval (m)	Low-flow tubeworms	High-flow tubeworms	Sulphide worms	Uncolonized	Total black smokers on structure
T201 02:05:09	Grotto	2196–2191	*	None	*	***	1
		2191–2188	*	None	**	**	
T284 12:01:01	Dudley	2194–2189	**	*	**	**	20
		2189–2184	**	*	***	*	
		2184–2182	**	*	***	None	

^aData aggregated from 5 m depth intervals during ascent of edifice by remotely operated vehicle (ROV). Asterisks indicate estimates of percentage coverage (* = <25%; ** = 25–50%; *** = 50–75%) of substratum in field of view, by tubeworm and sulphide worm colonies, as well as uncolonized surfaces. Total black smoker counts for each edifice derived from review of additional video transects and ROV fly-arounds. Video records for transects T201 and T284 can be accessed in Ocean Networks Canada's (ONC's) video SeaTube database (<http://www.oceannetworks.ca/sights-sounds/video-archives>; free registration required). To view, select Aug. 2015 ONC Maintenance cruise on E/V *Nautilus*, dive H1480 (3 Sep 2015), and then scroll through annotations to start times or enter transect numbers in the <Search Comments> window.

in the EHV MPA. Other vent faunal species occur within the two tubeworm assemblages, whereas the sulphide worms tend to be monospecific colonizers of high-temperature surfaces. These preliminary data suggest that rapid vertical video surveys can provide results that inform about the intensity of hydrothermal activity on individual edifices and related distributions of SECs. Total ROV time required to conduct individual transects was less than 5 min each, once the vehicle was in place at the base of the structure. Time required for video review and data extraction was less than 30 min per transect. The ROV fly-arounds for counting black smoker vents required 10–15 min of dive time and a similar length of time for analysis. Further analysis will be required to validate this methodology.

6.2 | High-frequency and real-time monitoring

ONC's real-time systems in the Endeavour vent fields continuously monitor geological, hydrothermal and biological features that are relevant to understanding the natural dynamism of this environment. All sensor data and imagery collected by observatory instruments and maintenance ROVs are freely available and searchable through Oceans 2.0, ONC's online system (<http://www.oceannetworks.ca/sights-sounds/video-archives>) that acquires, archives and distributes observatory data. Recent publications (Cuvelier et al., 2014, 2017; Lelièvre et al., 2017) have shown how imagery time series can be combined with sensor data to discover habitat preferences of vent organisms, behavioural responses to habitat fluctuations, and species interactions such as predation, territorial behaviour and facilitation. This research is enriching the fundamental understanding of vent ecosystems and ultimately informing management of the MPA. ONC will therefore continue to encourage observational research. It is also recommended that ONC and DFO collaborate to encourage the use of the observatory infrastructure for experimental field research. Experimental manipulations can permit more definitive and rapid testing of specific ideas and hypotheses than can be possible with passive observations. Because most field experiments involve artificially disturbing organisms and habitats, it is recommended that experimental manipulations be limited to those that directly address questions that are relevant to the management of the MPA, and that such experiments be conducted at more than one location, preferably in two or more vent fields, to validate the application of results to the entire MPA. The

current scientific advisory structure for the MPA could contribute to evaluating proposed experiments and identifying questions that could be addressed by field experiments. These types of experiments would make optimal use of the capability of the observatory infrastructure at Endeavour to continuously monitor experimental conditions. Many could be deployed within the field of view of observatory cameras, and tracked visually as well as with sensors. Manipulative experiments would need to be managed to avoid interference with other observations.

6.3 | Research output

Highlighting the results of individual studies in the EHV MPA provides a qualitative appreciation of the trade-offs between potential disturbance by research activity and the management goal of building knowledge to increase its scientific and social value and to inform future adjustment of conservation goals and protection measures. However, research highlights cannot be used for year-to-year quantitative monitoring and comparison of management outcomes. To this end, a preliminary analysis of the scientific impact of research use of the MPA was undertaken. Citations of peer-reviewed publications from the EHV MPA were quantified using the Web of Science. The search was limited to citation records for 2003–2017 publications that identified the Endeavour segment of the Juan de Fuca Ridge in their title. In addition, institutional affiliations of the first four authors of identified publications were used to gauge the importance of the MPA as a field site for the international mid-ocean ridge research community. For comparison, the same analyses for a similar-scale, well-studied mid-ocean ridge hydrothermal area, Lucky Strike on the Mid-Atlantic Ridge, located in the Marine Park of the Azores, was undertaken.

Publications from the EHV MPA in 2003–2017 were cited 728 times (self-citations excluded) during the same period with an increasing trend since the beginning of ONC observatory activity in 2009 (Figure 11). These publications were authored by researchers from 84 institutions (Figure 12a) in 11 countries (Figure 12b), and most involved inter-institutional and international collaborations. For the same period, publications based on research at the Lucky Strike site, which became an MPA in 2005, were cited 785 times (self-citations excluded) (Figure 11). As for the EHV MPA, most Lucky Strike publications involved international and inter-institutional collaborations, with authors affiliated with 84 institutions in 19 countries (data not shown).

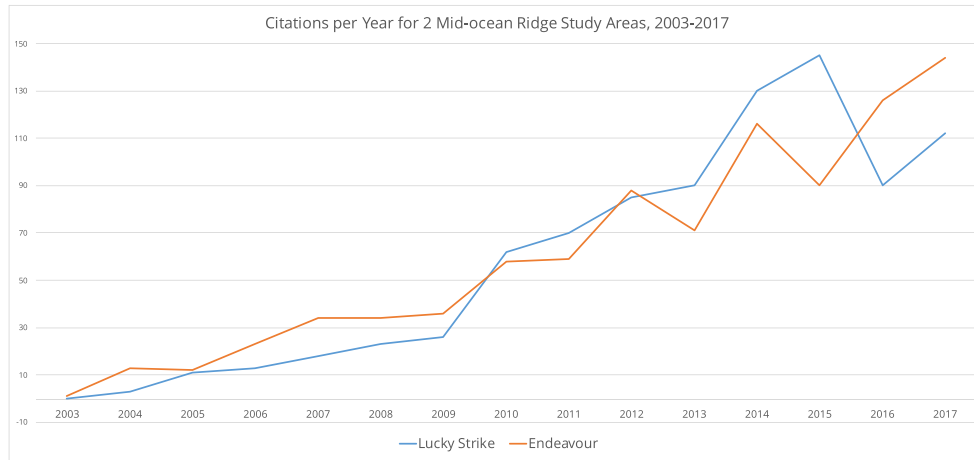


FIGURE 11 Bibliometric data for peer-reviewed publications related to the Endeavour Hydrothermal Vents and Lucky Strike marine protected areas. Impact as measured by annual citations of publications from 2003 to 2017

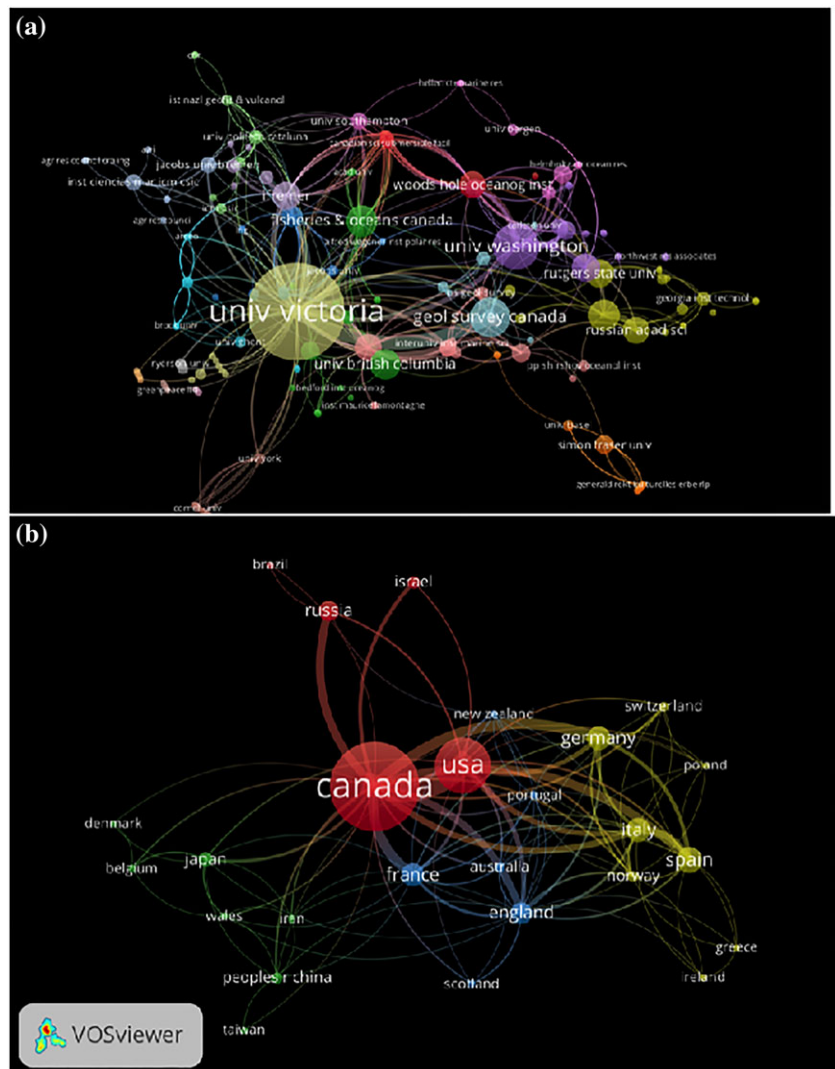


FIGURE 12 Bibliometric data for peer-reviewed publications related to the Endeavour Hydrothermal Vents Marine Protected Area. Collaboration networks as determined by institutional (a) and national (b) affiliations of co-authors on individual publications. Larger circles indicate most frequent affiliations

7 | DISCUSSION

Development of the ONC geospatial database beyond the operational requirements of the cabled observatory has provided EHV MPA

managers with a foundation for a future monitoring programme and a tool for adaptive management. The collaborative, geospatial database can support planning, decision-making and management at scales from the entire EHV MPA to individual management areas and

sulphide edifices. A spatial management approach is especially appropriate for the EHV MPA because of the primarily sessile nature of the SECs and the availability of georeferenced data on organism and habitat distribution (ROV video, cabled observatory imagery) and anthropogenic stressors (e.g. submersible tracks, sampling locations). The database enables managers to visualize the distribution of research activity spatially and over time, and thereby identify areas of high research pressure, poorly explored areas, and areas under the most and least pressure from sampling. It also enables tracking of time spent inside and outside of management areas. This type of database is well suited to an adaptive management framework; as more data are collected and incorporated into the database, trends can be tracked and the uncertainty associated with future risk assessment iterations and decision-making can be reduced.

The mapping of vessel and research debris provides an example of how a geospatial database can inform an adaptive management framework. The original risk assessment for the EHV MPA found debris from vessels to be relatively high risk, driven by a precautionary scoring approach (debris could impact anywhere in the MPA and could be any object), which resulted in a high uncertainty score. However, the geospatial database showed mapped incidences of debris to be low and mostly originating from research activities (e.g. iron ballast from HOVs), rather than surface vessels. This information will be used in future iterations of risk assessments at the EHV MPA, and it is expected to reduce uncertainty and risk scores and create a new stressor for assessment: debris associated with research activities. In turn, monitoring priorities and indicators will likely change. The methods used to build the geospatial database are scalable and applicable to other areas and can handle integration of third-party data.

Hedge et al. (2013, 2017) provide practical guidance for the development of a monitoring framework to support adaptive MPA management of the Great Barrier Reef World Heritage Area. This guidance is not ecosystem specific, and is applicable to a wide range of protected areas. They describe prerequisites for developing a monitoring framework, including the need to identify and/or create governance arrangements and structures, and create principles to guide decision-making and for refining high-level management goals. By comparison, the governance arrangements for the EHV MPA have been established under Canada's Oceans Act (SOR/2003-87) and outlined in the management plan (Fisheries and Oceans Canada [DFO], 2009). The management plan lists key participants in governance related to the EHV MPA, and recognizes the role of partnering arrangements between government and nongovernment organizations in ensuring protection of this deep-sea MPA. The open sharing of data between scientists and MPA management has developed beyond what was anticipated in the management plan, providing a basis for managers to assess progress in ecological and compliance monitoring.

Principles of monitoring exist in the management plan, but they have yet to be linked to specific objectives. A current management plan review will require information on the current state of knowledge of SECs and the activities and stressors impacting them.

The refinement of high-level management goals has not been completed for the EHV MPA, creating challenges at several stages in the development of a monitoring programme. The decision to take a risk-based approach to adaptive management of the EHV MPA has

paved the way for standardized, transparent and repeatable evaluations of biodiversity outcomes, and has removed the subjectivity of relying solely on expert judgement. The ecological risk assessment identified and ranked SECs and the activities and associated stressors impacting them by relative risk. These results were used to develop suites of risk-based indicators, prioritized by risk and uncertainty, and monitoring has commenced. This type of semi-quantitative assessment of ecosystem condition is rarely used in MPA management effectiveness, despite the documented benefits (Addison, Flander, & Cook, 2017). However, the current management plan (Fisheries and Oceans Canada [DFO], 2009) is now out of date, and recent progress (2015–present) has yet to be captured in an updated plan. A management plan review will require information on the current state of knowledge of SECs and the activities and stressors impacting them.

The geospatial database will be an invaluable tool for DFO MPA managers when updating the EHV MPA management plan. For example, kernel density maps and queries of the database showed that the current management area boundaries only partially encompass the named hydrothermal vent fields and the areas of concentration of research activity, suggesting a need to revise the management area boundaries in future management plans. The management-area breakdown of submersible movements highlighted the vent fields under the most pressure. The query also showed that only 28% of total submersible time was spent within the management areas, indicating to managers that activity hotspots outside of the management areas may need to be addressed in the updated management plan. In addition to querying the geospatial database, more directed monitoring efforts will be required to understand the natural variability of the SECs and identify any impacts of research activity. Maps and summaries of submersible movements and sample collections within the EHV MPA only inform managers about potential anthropogenic stressors, and not about impacts of research activity.

The EHV MPA conservation and management objectives are broad. Work has begun on using a stressor-based approach to define specific operational objectives (Thornborough et al., 2016, 2018). Specific, measurable, achievable, realistic, and time-sensitive conservation objectives are essential to the development of a monitoring programme to manage anthropogenic stressors in the MPA. The current lack of clear objectives and useful and relevant indicators inhibits DFO's ability to identify and defend specific monitoring requirements without the latter appearing to be arbitrary (Davies et al., 2011). Specific, measurable, achievable, realistic, and time-sensitive objectives should be developed in conjunction with the elaboration of monitoring strategies, the next step in the implementation of adaptive management. It follows then that the translation of operational objectives for the EHV MPA into monitoring strategies would be based on outputs from risk assessment and the prioritization of SEC–stressor interactions.

In addition to the stated prerequisites for developing a monitoring framework, Hedge et al. (2013, 2017) outline the essential functions of protected area monitoring programmes. Progress towards each of these functions, for the EHV MPA, is outlined in Table 3, together with opportunities and gaps that should be considered. Further development of the monitoring programme for the EHV MPA is ongoing. The immediate focus is on the refinement of high-level objectives,

TABLE 3 Progress achieved towards the essential functions of a monitoring programme for the Endeavour Hydrothermal Vent Marine Protected Area (EHV MPA) outlined by Hedge et al. (2013, 2017)

Essential function	Status
Clearly define the purpose of the monitoring programme and monitoring objectives	High-level conservation and management objectives exist for the EHV MPA. See Discussion.
Compile and analyse relevant information on existing monitoring programmes	A review of current and past monitoring activities within the EHV MPA is complete (e.g. Davies et al., 2011; Fisheries and Oceans Canada [DFO], 2009). The risk assessment also assessed monitoring activities and incorporated the relevant information into the scoring process. Available data were documented in a literature review and bibliography to accompany the geospatial database, and historical data are being incorporated into the database.
Develop conceptual models	The risk-based approach is the equivalent of developing conceptual models in Hedge et al. (2013, 2017). The risk-based approach identified the SECs, the activities and associated stressors impacting them, and the linkages between them. Pathways of effects models were developed to map the effect of anthropogenic activities on the ecosystem. The temporal and spatial scale of SECs and stressors have been defined, and potential consequences and impacts on SEC recovery assessed. Key knowledge gaps have been identified.
Develop overall sampling design for monitoring	Suites of risk-based indicators were developed from the outputs of the risk assessment, and prioritized based on risk and uncertainty scores. Indicators relevant to the geospatial database (e.g. those requiring visual surveys) have been incorporated into monitoring activities, and include sampling design for monitoring. Not all indicators identified in the risk-based indicator selection process are currently being monitored. The development of refined operational conservation objectives will help to further prioritize these indicators suites for monitoring.
Develop monitoring protocols	Monitoring protocols have been developed for a number of indicators currently being monitored, particularly those related to the geospatial database.
Manage data	A formal data management plan has not been developed. However, the collaborative relationship between DFO and Ocean Networks Canada (ONC) will be key to the success of this programme. ONC has comprehensive data management and storage frameworks that will support the development of a data management plan for DFO's EHV MPA monitoring programme.
Analyse data	Some analysis has begun based on ONC's geospatial database. However, a data analysis plan has not been developed.
Report and communicate	A formal framework for reporting and communicating the outcomes of the monitoring programme has not been developed.
Review and audit	A 5-year review cycle for the EHV MPA management plan has been recommended. Although regular auditing of the MPA exists to ensure that activities comply with management and regulatory frameworks, a framework outlining the reviewing and auditing process for the EHV MPA environmental monitoring programme, and how this feeds into an adaptive management framework, remains a work in progress.

the continued development of sampling design and protocols, and building a framework for data management and analysis.

The geospatial database can incorporate multiple datasets over different temporal and spatial scales, making it an ideal foundation for a monitoring programme at the EHV MPA. The majority of data included in the current database were extracted from video and navigation surveys, with multiple datasets (e.g. submersible tracks and tubeworm occurrences) often extracted from a single submersible dive. This ability to concurrently collect data on several SEC indicators and stressors is critical for monitoring remote deep-sea MPAs, where access is limited. The risk-based indicator suites identified for the EHV MPA (Thornborough et al., 2016) were dominated by those that could be measured from visual surveys. Data on additional stressors and SECs could be incorporated into the database for future monitoring by adding them to the current video logging protocols. Examples include sediment resuspension or crushing of the substrate from submersibles, sightings of specific SECs (e.g. spider crab), and so on. The addition of these data combined with the expansion of the ONC observatory (to be completed by 2019) could form the basis of a formal monitoring programme at the EHV MPA.

There are many challenges associated with monitoring and management of remote MPAs, including lack of resources, scientific uncertainty and less than unanimous political support for protected areas

globally (Addison et al., 2017; Hedge et al., 2017). Looking forward, collaborative relationships between policy-makers, managers, scientists and data archives will be crucial. Abecasis et al. (2015) concluded an evaluation of the Azores MPA with calls for the development (and implementation) of a management plan, and partnering with the research community to enable MPA monitoring to provide a sound scientific basis for adaptive management. The example from the EHV MPA illustrates how such collaborations can inform ecosystem-based spatial management (Douglas et al., 2017; Katsanevakis et al., 2011), provided that management can adapt to data provided as a secondary product of research activities. In the case of the EHV MPA, information currently in the geospatial database is better suited to quantifying potential stressors than for tracking the dynamics of SECs. High-frequency observations from fixed observatory cameras and sensors do provide information on small-scale ecosystem dynamics, but these need to be validated at broader scales to be of use to management. The 'price of entry' video surveys proposed here represent one example of how currently informal science user-MPA manager collaborations could be extended to progress towards this goal. In the case of research-only MPAs, ecosystem component and stressor monitoring are not the only sources of information required by managers. This paper provides an example of how bibliometric tools can be used for monitoring the scientific impact of MPA usage. At some point,

management requirements for monitoring will likely exceed what can be provided by 'best effort' contributions from MPA research users or bibliometrics. Recognition at the policy level of the importance of such partnerships could facilitate the extension of scientific missions to support more formal monitoring programmes.

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ORCID

S. Kim Juniper  <https://orcid.org/0000-0002-7608-260X>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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