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Impact Analysis of the Marine National Facility

SUMMARY REPORT PREPARED FOR

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1 Introduction

With its state-of-the-art research capabilities and outstanding crew, scientists, and technicians, the Marine National Facility (MNF) plays an important role in Australia's innovation system. It supports research and education about oceanography, seafloor geology, marine life, weather, and climate that further Australian science on a global scale. These capabilities are important because Australia has the world's third largest marine jurisdiction, and the ocean plays an integral role in Australia's climate, culture, and economy. Government agencies, offshore industries, and the public rely on MNF and its Research Vessel (RV) *Investigator* for data and research insights for improving technology, practices, and policies for stewardship of Australia's blue-water resources. CSIRO owns and operates the MNF on behalf of the Australian people.

This report summarises a 2020 impact analysis report series that explored the MNF's impacts along three dimensions: research, training, and economic impact (Wade, 2020; Leonchuk et al., 2020a-b). The series documents the role that the MNF and the RV *Investigator* have played in knowledge creation and in training scientists for jobs in research and industry. It also describes how the MNF and the RV *Investigator* reflect at least a 4.7-to-1 return on investment, meaning that for every $1 invested in the MNF we estimate $4.70 in social benefits.

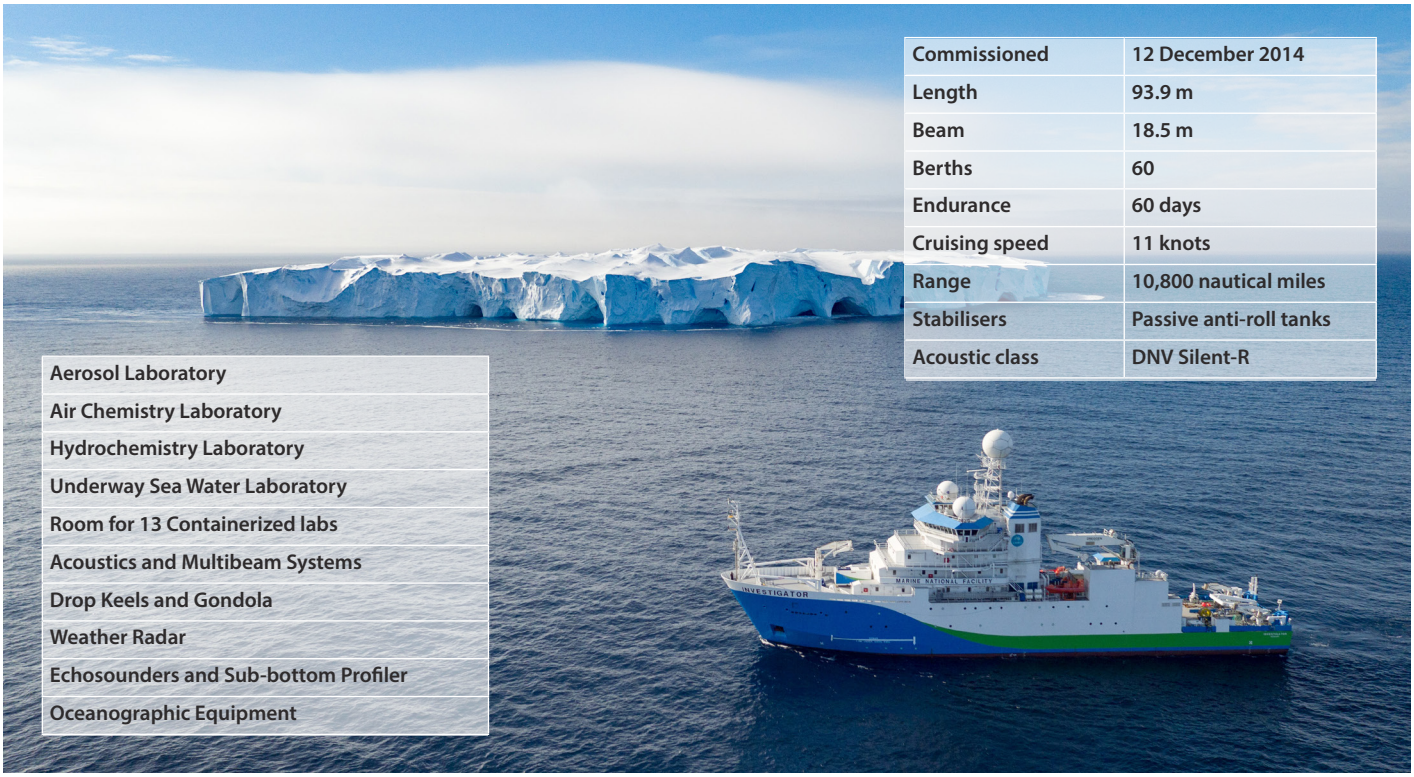
1.1 The Marine National Facility's RV *Investigator*

The RV *Investigator* is a 94-metre research vessel outfitted with world-class instrumentation and gear, and capable of spending up to 300 days per year at sea. The ship can accommodate 40 scientists and a crew of 20 for voyages of up to 60 days and covering 10,000 nautical miles (Figure 1.1). An independent steering committee oversees the MNF and the competitive selection of applications for granted voyages. Scientists apply for sea time, and, if successful, will have their voyage funded by the Australian Government.

There are four major areas of research supported:

1. Geoscience research, including seabed mapping and studying the structure and composition of the seafloor;
2. Oceanographic research, including water and ocean depth surveys;
3. Biological research, including studying fisheries and ocean ecosystems; and
4. Atmospheric research, including studying the interaction between the ocean and the atmosphere and collecting sophisticated weather and climate data.

Figure 1.1. Overview of the RV *Investigator*



1.2 Purpose of the Impact Assessment

Given the RV *Investigator's* status as Australia's premier blue-water research platform, it is important for the MNF to assess and communicate its impact. Yet, at less than 6 years old, it is early in the ship's life cycle. Science is still emerging from its earliest voyages, and there are many voyages still to come over the coming years. However, on-going communication about impact is important even at this early stage to share information about the value Australia accrues from such a significant science investment.

To this end, CSIRO sponsored RTI International, a non-profit research institute, to conduct an independent analysis of the MNF's impact. RTI's scope was to complement the MNF's on-going science communications with an assessment of

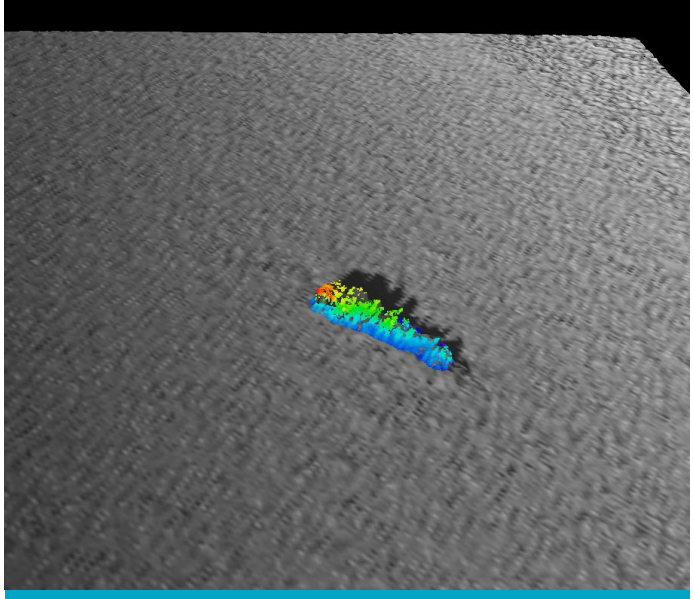
- scientific and research impact,
- the impact of MNF training programs which prepare students for careers in research and industry, and
- the economic value the MNF generates for Australian society.

Beyond the impact assessment's role in describing the value generated to date, this analysis also afforded the opportunity to generate feedback that is important for the MNF's new strategic plan, *MNF 2030*.[1] Studying value generation and acquiring insights from impact analyses are critical to ensuring that CSIRO manages the MNF in such a way as to optimise the value generated for the nation.

1.3 Approach Overview

We focused on the period beginning in 2015, with the RV *Investigator's* entry into service. We considered in-scope research and training activities as well as the use of data and information generated from voyages.

The research impact assessment relied on an analysis of scientific papers, interviews with stakeholders, and surveys of researchers supported by RV *Investigator* and of MNF staff. About 50% of 181 supported researchers and 65% of 75 MNF staff responded. The surveys asked about how their work contributed to impacts in the areas of policy, practice, and technology, among other topics.



Uncovering the SS *Iron Crown*

The SS *Iron Crown* was a 100-metre ore freighter that was sunk on 4 June 1942. The heavily-loaded freighter was hit by a torpedo from a Japanese submarine and sank within 60 seconds. Of the 43 crew on board, 38 lives were lost, and their resting place had been unknown for 77 years until discovered by a team of maritime archaeologists onboard RV *Investigator*. The discovery received global media attention and highlighted the important role that the MNF plays conserving Australia's rich maritime history.

The training impact assessment was informed by interviews and a survey to which 46% of students responded.

The economic analysis was a cost-benefit analysis. We accounted for all actual and projected MNF costs for vessel procurement and operations from 2015 through 2030. Although the research and training impact components were retrospective, use and application of data will grow and therefore our economic analysis also included projections. The cost-benefit analysis was completed in accordance with standards established by CSIRO's *Impact Evaluation Guide* (CSIRO, 2020).

1.4 Report Organisation

Section 2 reviews research impact, Section 3 reports on the value students derive from their training experiences, and Section 4 is the economic impact analysis. Section 5 concludes the report, including overall observations about the impact generated by the MNF since the RV *Investigator's* entry into service.

[1] More information about the MNF's strategy is available online at https://mnf.csiro.au/en/About/MNF-2030-Strategy.

2 Research Impact

The RV *Investigator* is a major research platform that enables the generation of knowledge and insights about oceans, weather and climate, marine geology, and marine ecosystems. Such insights are critical because in its absence, many areas, particularly the Southern Ocean, would remain understudied. This would have consequent impacts not only on science but also on the nation's situational awareness, which in turn affects resource and ecosystem management, industry, and climate policy and planning.

At this early stage in the RV *Investigator's* mission, among the vessel's most notable contributions are the publications that supported researchers prepare to disseminate findings. Because publishing is how information disseminates to those who need it, publications are an important leading indicator of the ultimate contribution of MNF-supported science to impacts on policy, practice, and economic activity.

2.1 Knowledge and Scientific Publications

At present, publication output includes an estimated 150 peer-reviewed papers. These papers have been cited 1,280 times as of July 2020, with an average of 8.5 citations per work (Figures 2.1 and 2.2). Considering that these are largely recent publications, representing the period between January 2016 and June 2020, the impact on knowledge creation is substantial.

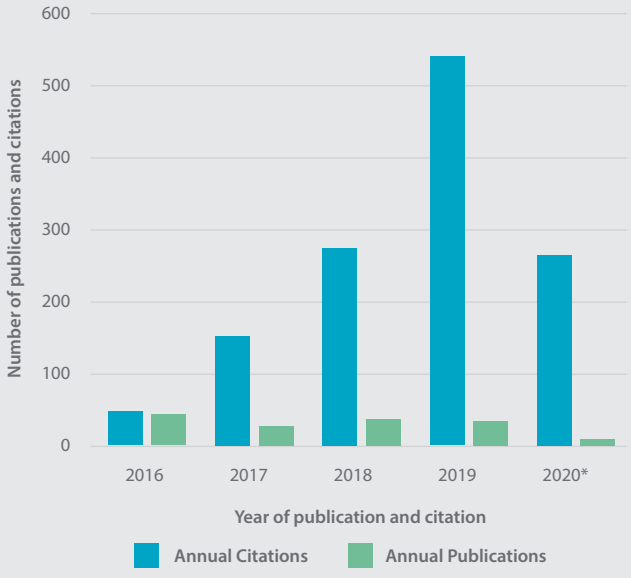
Figure 2.1. Citation Summary of Papers Produced by MNF-Supported Researchers, 2016 to Mid-2020

More than half of these papers were published in top-tier journals. Research supported by the RV *Investigator* has been published in *Nature, Nature Communications, Nature Ecology and Evolution, Nature Geoscience, Frontiers in Marine Science, Scientific Data,* and *Geophysical Research Letters*.

Topics include oceanography, environmental sciences, geosciences, and fisheries (Figure 2.3). Many papers also reflect multidisciplinarity, which reflects scientific collaboration spanning multiple fields of study and reflects broader trends of scientists from different disciplines collaborating to answer questions and address formidable scientific dilemmas.

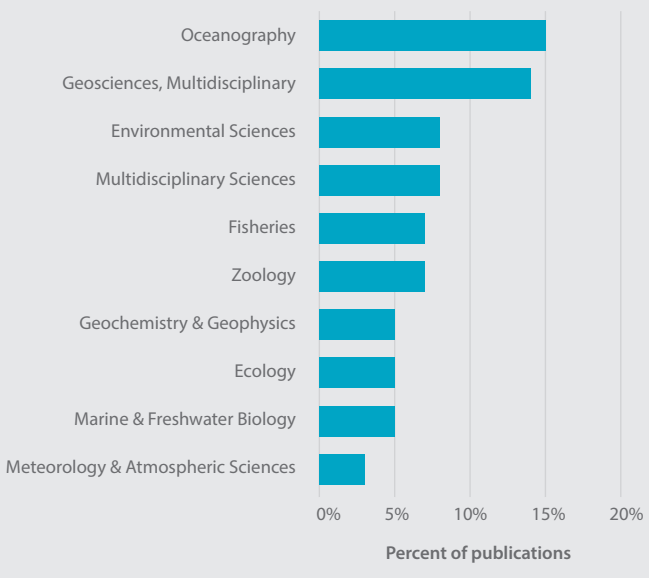
This work also demonstrates greater engagement between Australian scientists and the global scientific community. Scientists' international co-authors represent

Figure 2.2. Scholarly Output Leveraging the RV *Investigator*



*Note: 2020 data are incomplete and only reflect through June 2020.

Figure 2.3. Scientific Fields of Supported Scholarly Output



Note: Fields reflect Web of Science categories.

the United States, New Zealand, France, and Germany, who were in turn supported by research funders such as the U.S. National Science Foundation and the European Union. The diversity in co-authorship and funding patterns combined with the strong scientific indicators signals that the research conducted is of global importance.

2.2 Underway Data Collection

The RV *Investigator* has robust underway data collection capabilities. These include atmospheric sampling, geophysical survey and mapping, and seawater analysis. These data are available for use by government, industry, the scientific community, and the public. Examples include AusSeabed, Australian Ocean Data Network, the Department of Defence, Australian universities, GEOTRACES, and Global Ocean Surface Underway Data.

Broad uses for data include

- informing baseline measurements and constraints for different scientific models in climate, weather, oceans, seabeds, and fisheries, among others;
- informing model predictions, while increasing the reliability and accuracy across a variety of fields;
- planning and managing offshore operations and risk;
- improving understanding about the Southern Ocean; and
- furthering research that strengthens Australia's overall scientific capacity.

The economic value of the information being used is further explored in our cost-benefit analysis, including detailed description of specific use cases.

2.3 Resource Management and Practice, Public Policy Solutions, and Teaching

Research supported by the MNF is having an impact across Australia and beyond. Researchers noted important impacts on research and teaching, but they also emphasised contributions to public policy and practice (Figure 2.4). MNF staff note how the RV *Investigator* is a testbed for new technologies and new ways of working.

Resource Management and Practice

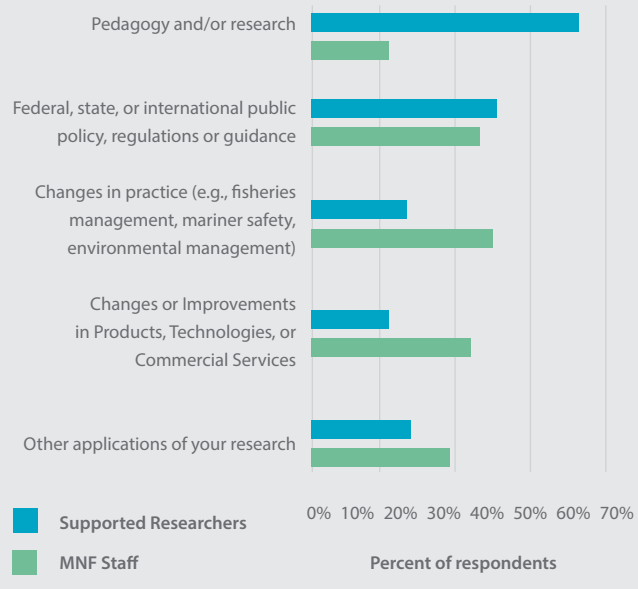
Respondents noted how research leveraging the RV *Investigator* led to changes in practices pertaining to fisheries management, mariner safety, and environmental management. For example, one researcher explained that the data streams coming off the RV *Investigator* are used to inform national fishery stock assessments. Another pointed out that the research pertaining to the relationship between krill and whales provides valuable information to the Commission for the Conservation of Antarctic Marine Living Resources regarding krill fishery management.

Researchers' remarks on how data are used

Based on this cruise a proposal for drilling in the area of research will be submitted and for sure those results will be key in providing constrains to ice sheet models that are used for future predictions of ice sheet/sea level change under ongoing climate warming.

The continuous measurements of atmospheric composition and chemistry will contribute to data collected by EPA Tasmania on air quality in Hobart.

Figure 2.4. Summary of Contributions Reported by Researchers and Staff



Note: Fields reflect Web of Science categories.

Public Policy

Work from the RV *Investigator* has influenced or contributed to federal, state, international public policy, regulations, and guidance.

The data collected on the vessel have been incorporated into the Intergovernmental Panel on Climate Change reports, which directly influence national and international public policies. Several respondents also mentioned how the knowledge gained on these voyages has expanded and enhanced the management plans for national marine parks.

Another survey respondent noted that their work led to the development of standard operating procedures for reporting and recording shipwrecks when they are uncovered. This is an important step in preserving the historical and cultural relevance of these events for future generations.

Teaching and Research Methods

One way that the experiences on the RV *Investigator* have impacted education is through the incorporation of new methodologies and knowledge into curricula. For example, one PI noted that the professional videos taken are used in university classrooms to bring the work performed on the vessel straight to the classroom. Similarly, a staff member explained that their research about marine science has been turned into a presentation to educate schools about the importance of collecting knowledge regarding seabeds. Several respondents noted the significance of incorporating improved understanding of the Southern Ocean into curricula.

New Technology and Innovation

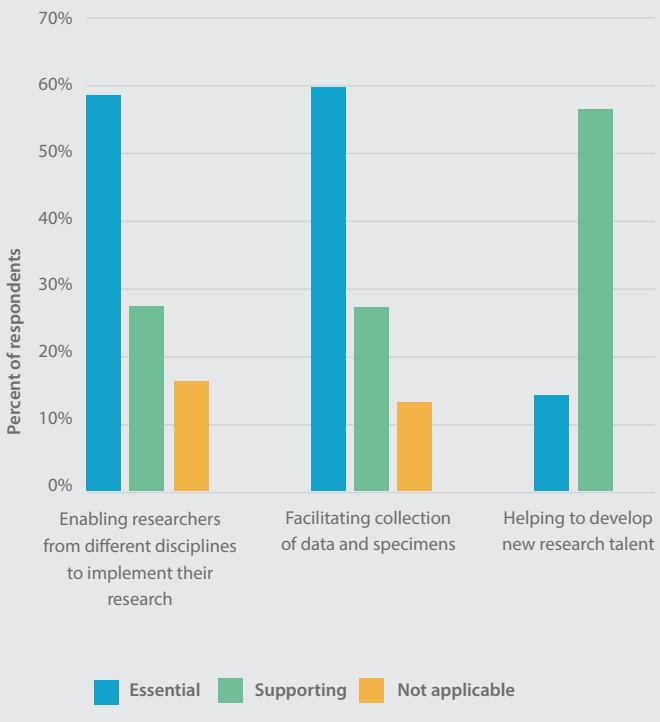
MNF staff play a role in technology development, particularly around development, testing, and refinement of gear and methods that support technology used in harsh ocean environments. When faced with challenges, staff have used their ingenuity to find long-lasting and working solutions. Nearly 72% stated that they have developed new (and 59% said they improved upon) strategies, methods, technologies or best practices to deal with challenges that have arisen. Examples include helping manufacturers improve their products and developing new software tools for data collection, storage, and visualisation.

The MNF staff comprise a diverse group of professionals including technicians, program coordinators and IT professionals. While their jobs are unique and require different skill sets, we wanted to understand how they view their roles in the MNF mission to promote research and science. Figure 2.5 summarises how the staff see their roles in enabling researchers.

Fundamental advances in understanding ocean circulation and the ocean's role in climate variability and change (1) have been incorporated into [Intergovernmental Panel on Climate Change] reports that influence public policy and (2) have contributed to outcomes in the Earth Systems Climate Change Hub.

—One scientist's perspective on the significance of research supported by the MNF

Figure 2.5. MNF Staff Perception of Their Roles in RV *Investigator*'s Research Mission



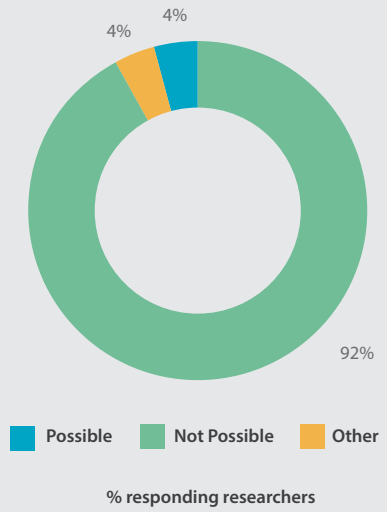
Note: 2020 data are incomplete and only reflect through June 2020.

Image credit: Brett Wilks (Australian Antarctic Division)

Managing the Antarctic Krill Fishery and Conserving Endangered Species

A 49-day, 200,000 square kilometre investigation studied how krill swarms affect the distribution, abundance, and behaviour of whales in the Southern Ocean. The RV Investigator generated three-dimensional pictures of giant krill swarms. The insights contribute to responsible krill fishery management and conservation of endangered species in the Antarctic, such as blue whales.

Figure 2.6. Possibility of Implementing Projects in the Absence of the RV *Investigator*



2.4 Alternatives to MNF Support

Nearly all researchers (92%) think they could not have conducted their research in the absence of the RV *Investigator* (Figure 2.6). They emphasised the importance of the availability of a vessel equipped with high-calibre gear and instrumentation as well as the MNF's staff and crew.

Strengths of the RV *Investigator*

The RV *Investigator* is a unique and complex research vessel. Given its robust scientific profile and expertise of its staff, the platform offers benefits that are hard to find elsewhere.

The survey asked respondents how difficult it would have been to gain access to specific resources provided by the vessel if they could not use the RV *Investigator*. Generally, most of the resources would have been difficult or impossible to access, according to the respondents (See Figure 2.7).

The resources that would be the most difficult to obtain on another vessel were not the gear, but rather ship-time, crew, and research support teams.. For example, 93% of respondents stated that availability of sufficient ship-time was a resource which would have posed a significant challenge to obtain. As many of the respondents explained in the alternate pathways, ship time is costly and potentially difficult to obtain if one is partnering internationally. Likewise, finding a vessel with relevant parameters would have difficult or impossible according to 90% of respondents.

Another important resource that the ship offers is the skilled crew and technical staff to assist with the projects performed on the vessel. Nearly three-quarters of respondents said that their expertise and assistance would have been difficult or even impossible to acquire under different circumstances. This underscores the critical importance of the MNF team and RV *Investigator* crew to enabling the science and impacts described in this report.

Other resources that would be difficult to obtain on other vessels include the unique suite of gear and labs provided on the RV *Investigator*. The specialised and standard laboratories are the most notable. For example, 59% stated that the specialised laboratory and sampling equipment like the TRIAXUS or deep tow camera would be difficult or impossible to obtain in an alternate pathway. Similarly, 57% said that the standard laboratories such as the air chemistry lab, underway seawater analysis lab, or walk in freezer were difficult or impossible to have without the RV *Investigator*.

Gaining Access Under Alternate Pathways

In an open-ended question asking what alternate paths they would have taken in the absence of the RV

Investigator, two main themes emerged. Many noted they would attempt to identify another research vessel. This would have meant partnering with researchers in other countries, but those researchers would have had to lead the research.

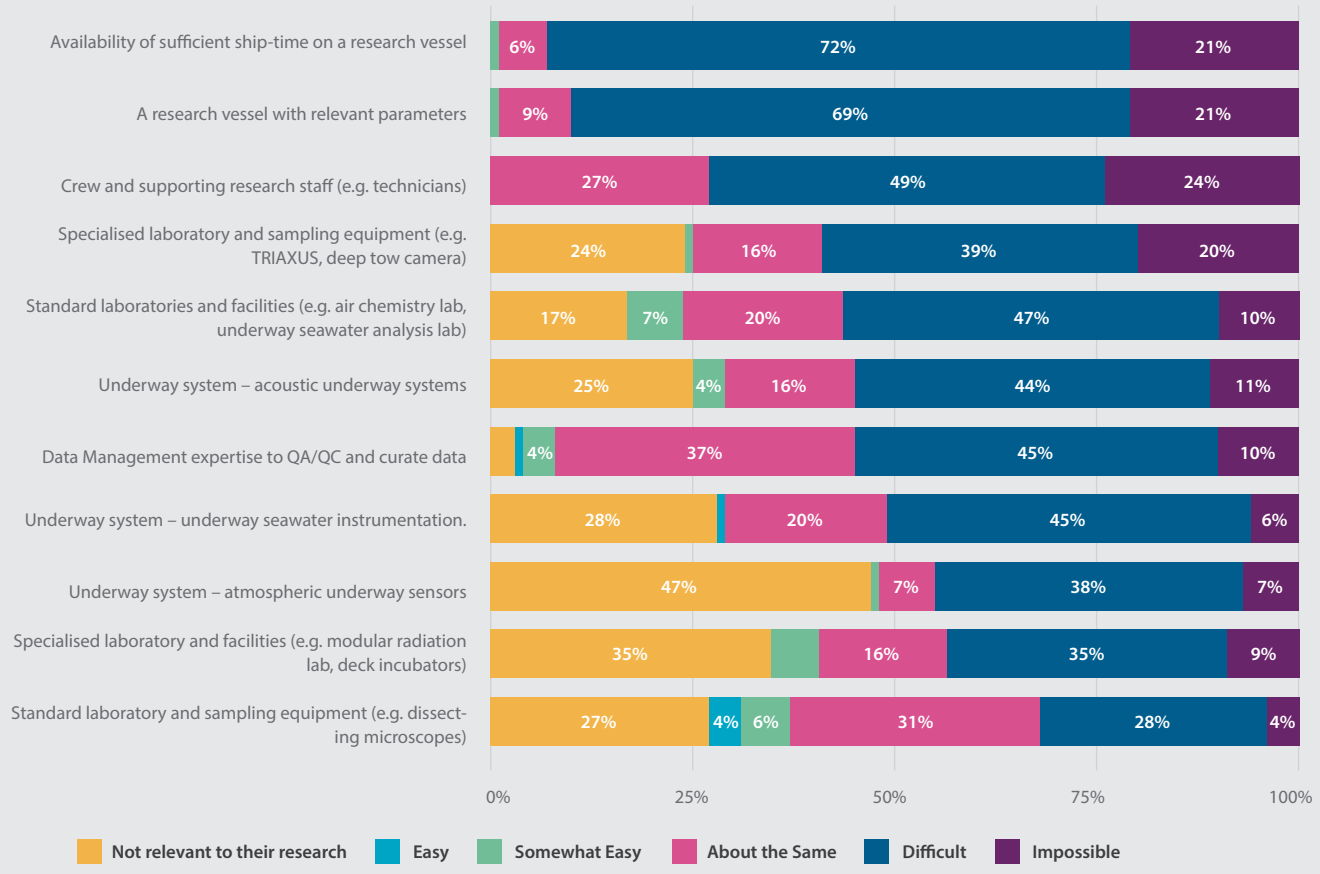
Others noted that there would be cost, safety, and suitability barriers that would have made alternatives to the RV *Investigator* challenging. One scientist noted that their team 'looked at trying to get funding to charter an offshore fishing vessel, but there were significant cost and safety concerns to overcome.'

Image credit: David Dieckfoss

Understanding the Reach of Australia's Marine Jurisdiction

A 2020 voyage explored the ancient rifting, break-up, and separation of tectonic plates in the Indian Ocean. Over 100,000 square kilometres of seabed were mapped as part of an effort to determine whether an area the size of Switzerland should be considered as part of Australia's marine territory. Data were collected for a future submission to the United Nations Commission on the Limits of the Continental Shelf. If judged eligible, it could add 40,000 square kilometres to the continental shelf recognised as Australia's marine territory.

Figure 2.7. Difficulty of Gaining Access to MNF and RV *Investigator* Alternatives



We surveyed researchers to ask them about how difficult it would be to gain access to a vessel, human resources, and research support from a source other than the MNF and the RV *Investigator*.

3 Training Impact

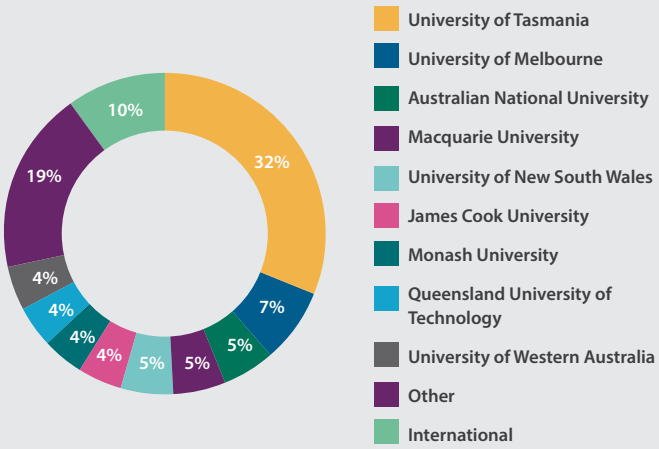
The MNF provides a number of opportunities for students to gain experience performing research at sea. There are three formal mechanisms:

1. involvement in a research project competitively selected for MNF support;
2. the Collaborative Australian Post-Graduate Sea Training Alliance Network (CAPSTAN), a postgraduate training program that is tailored to careers in research, launched in 2017; and
3. the Indigenous Time at Sea Scholarship (ITSS)—an undergraduate and postgraduate scholarship that is targeted at Aboriginal and Torres Strait Islander STEM (science, technology, engineering and mathematics) students, established in late 2019.

3.1 Profile of Students Engaged in MNF Programs

About 70% of students are at the graduate level, 22% are undergraduate, and 8% are postdocs. Applied research experience is very important for all students, but it is especially difficult for undergraduates to access. Thus, the 22% being undergraduates at the time of their voyage is notable.

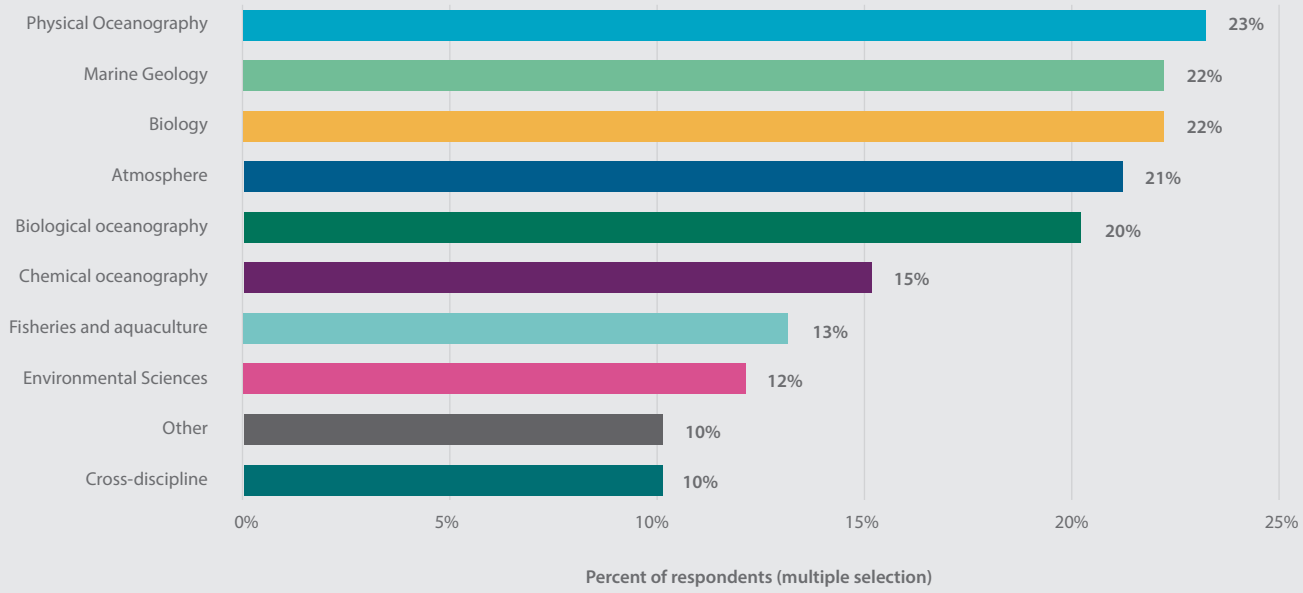
Figure 3.1. MNF Students' Institutional Affiliation



Note: Data are for survey respondents only.

MNF trainees represent more than 10 disciplines and 31 different academic institutions. Almost a third represented the University of Tasmania and its Institute of Marine and Antarctic Studies (Figure 3.1).[1] Figure 3.2 shows students' fields of study; note that students were permitted to make multiple selections when responding to our survey.[2]

Figure 3.2. MNF Students' Fields of Study



Note: Data are for survey respondents only.

[1] 'Other' represents a combined percentage of participants who were affiliated with an Australian university that accounts for 3% or less of the total survey sample. International university affiliations represent Germany, China, New Zealand (n=2), Poland, Switzerland, Taiwan (n=2) and the United States (n=2).

[2] Note, category 'Other' includes disciplines not listed in the current list. Examples include governance and policy, optics, and bioacoustics.

3.2 Impact of MNF on Skill and Knowledge Acquisition

Students responding to our survey noted that the MNF represents a unique platform where trainees are exposed to a high level of multi-disciplinary collaboration with other researchers and students. Such collaboration is particularly important for solving complex scientific problems, especially those related to oceans, climate change, and weather.

They report development of the following top five skills and knowledge acquired from their experience (Figure 3.3):

- technical skills (94% of students);
- collaboration skills (93%);
- applied research knowledge (93%);
- acquired or further developed professional networks (86%); and
- fundamental science knowledge (80%).

Given the hands-on nature of the onboard training experience, it is not surprising that MNF students report the MNF's second highest positive effect to be on applied research skills, after the highest-ranked technical skills. It is also telling to see collaboration skills and professional network development in the top four categories. This suggests that most students gain valuable experience in working with others and building their long-term networks which are known to be critical to success in the working world.

Pertaining to personal qualities encouraged and developed, many students report learning more about 'perseverance', the 'ability to ask for help', 'being prepared', and being more 'flexible' and adaptable to the different people and technical challenges as a result of their experience. The development of these personal attributes has been identified as one of the key characteristics that private-sector employers seek in marine science students according to a report by the National Marine Science Committee on the postgraduate training in the context of meeting the needs of Australia's Blue Economy.[3] Another skill or experience worth noting is that the multi-disciplinary approach and process of working were reported by many students as very valuable. Finally, students show respect for the difficulties associated with living on the vessel and indicate in their answers that 'surviving the ocean' is a skill on its own.

Student Perspectives on Skills Acquisition

Working with a lean of international collaborators, practical technical skills, thinking holistically about a complex project while working under strenuous conditions.

—Undergraduate Student in Marine Geology

Project management, technical skills (oceanic technology and water sampling) teamwork, leadership, project collaboration, and building an extended network of colleagues.

—Graduate student in oceanography

The results demonstrate that the MNF experience has not only a positive effect for a large majority of students, but also the diversity of skills which they acquire during their voyages (which may be of up to 60 days in duration).

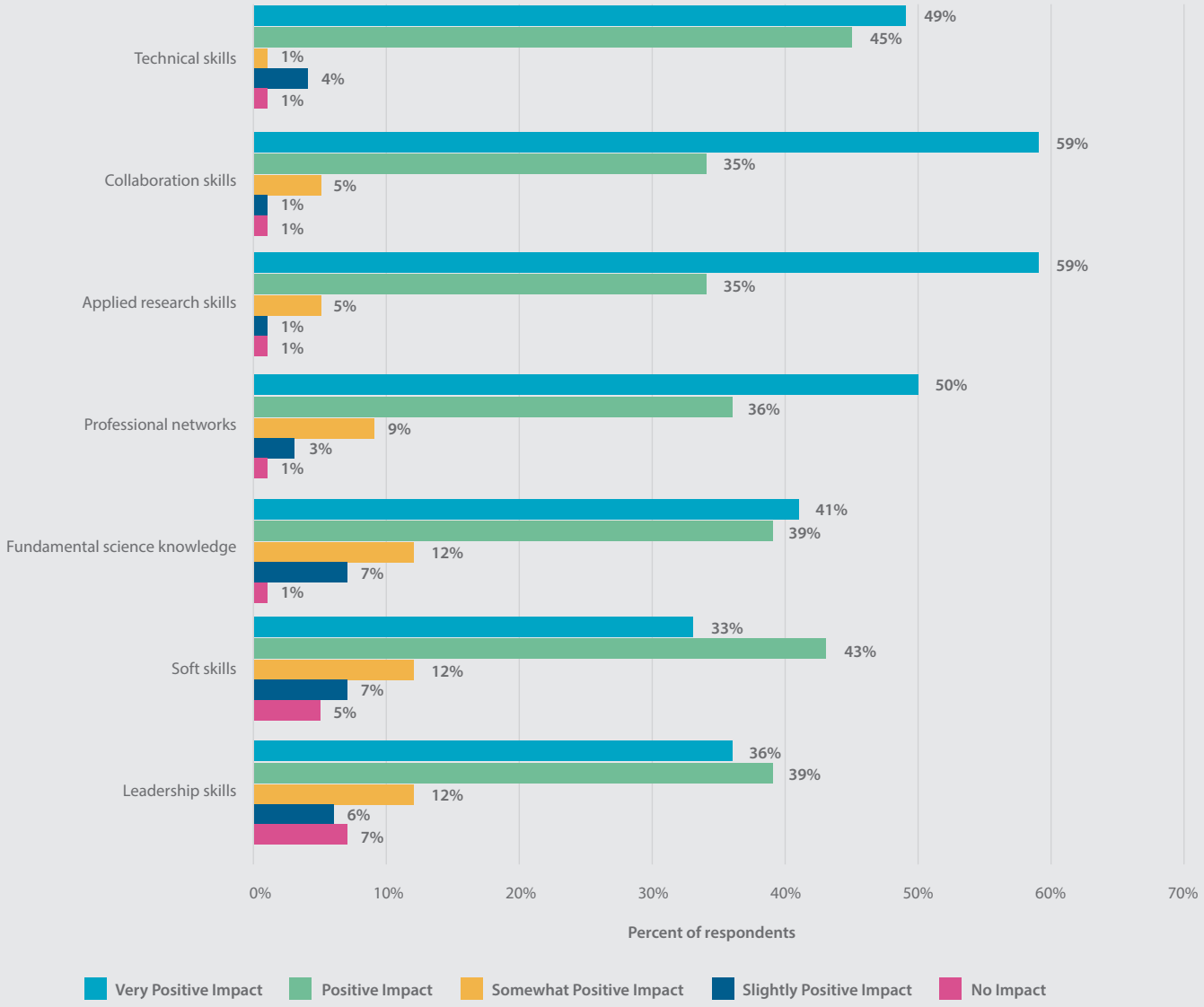
In the absence of the RV *Investigator*, 86% of students say that it would be impossible to gain the same quality of research experience and training elsewhere in Australia. As one student put it, MNF training represents 'unparalleled' experience.

3.3 Career Outcomes

One of the ways to characterise the value of training is to assess its impact on students' professional development and careers. It is, however, important to stress that the timing of the training for more than half of MNF students has been relatively recent, occurring between 2019 and 2020. This indicates that most students were in university at the time of this study. Thus, considering the small amount of time since the MNF training, the results of this section should be taken as conservative estimates of the ultimate MNF impact on the students' careers.

[3] MacKeracher, T. and Marsh. H. 2019. Improving Australia's Marine Science Postgraduate Training System to Meet the Needs of the 'Blue Economy'. National Marine Science Committee.

Figure 3.3. MNF Students' Perception of RV *Investigator* Experience's Impact on Skills Development and Knowledge Acquisition



Note: Data are for responding students only.

Image credit: Owen Foley

"The knowledge and experience gained [on the RV Investigator] cannot be overestimated and provided a level of understanding way beyond what I could have acquired through lectures, textbooks, and research papers."

—Graduate student in biology

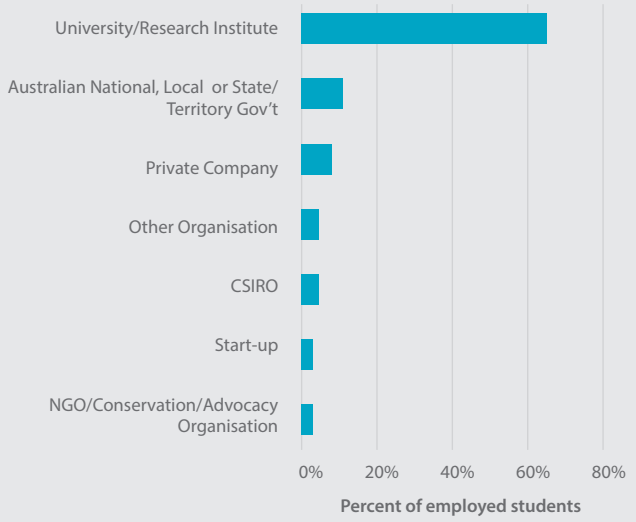
According to the results of the survey, 60% of students are currently employed (see Table 3.1). Among the most recent employment reported by MNF alumni, the majority (64%) are employed in higher education (see Figure 3.4).

Table 3.1. Students Who are Currently Employed

Response	N	%
Employed	59	60%
Still in school/Started new degree	40	40%
Total	99	

Note: Data are for survey respondents only.

Figure 3.4. Organisations that Employ MNF Student Alumni, as of June 2020



Note: Data are for survey respondents only

Many received very competitive fellowships, including the Fulbright Fellowship and the Marie Curie Fellowship; took on leadership roles (e.g., Senior Policy Officer); and hold key science communication roles such as Science Communication and Outreach Officer. Most positions are full-time paid jobs in universities or research institutes. Of those students who are employed, half thought their MNF experience helped them to obtain their current job or position.

Most open-ended comments had more than one type of impact highlighted, suggesting that MNF experience has a multi-dimensional impact. It is therefore an excellent preparation for the future employment, especially, in industries that highly value inter-personal and business skills in addition to technical and research skills. Overall, 71% of students agree or strongly agree that the MNF experience and training helped them achieve their professional goals (Figure 3.5).

My activities with MNF have provided valuable experience, expertise, and connections with other researchers, improving my exposure to other research groups and greatly enhancing my desirability for future collaborative projects. My research conducted ... has also generated extensive datasets that have been vital for the completion of my degree and have been the basis for publishing a scientific paper, raising my profile within the scientific community.

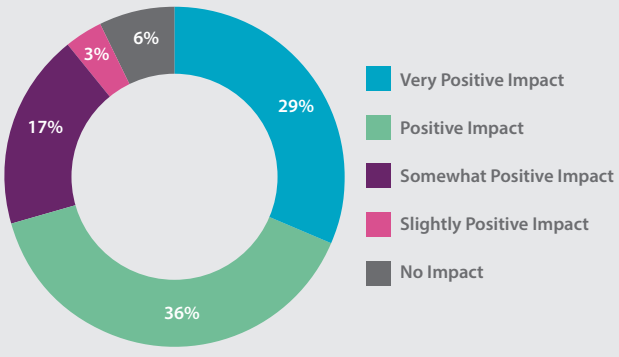
—Graduate student in atmospheric science

Without the experience on the RV Investigator, particularly the CAPSTAN Program, I would not have had the experience of discovering my interest in GIS Analysis as a profession. This has led me to now being a professional GIS Analyst doing work that I absolutely love. In working with experts outside of my discipline, I became a much more well-rounded scientist and expanded my skillsets.

—Undergraduate student in marine geology

For other students who have further progressed in their graduate studies or postdocs, the experience made them more competitive on the job market. It also provided management, research, and teamwork skills that they see as very valuable for their careers. Likewise, the research experience and the data and samples collected during their voyage made their research more relevant, valuable, and publishable.

Figure 3.5. MNF Experience Helped to Achieve Professional Goals



Note: Data are for survey respondents only

4 Cost-Benefit Analysis

One of the strengths of the RV *Investigator* is the ship's ability to collect accurate and precise bathymetric, biological, atmospheric and geophysical data at a fine resolution using a suite of powerful instruments and gear. As described in Section 2, these data are made publicly available and accessible for use by others.

Users in the public and private sectors leverage these data to deepen and expand our collective understanding of the ocean's ecosystems, climate and weather changes in the Southern Ocean, fisheries, and other important topics. Ultimately, underway data play a critical role in evidence-based decision making, resource and risk management strategies, and offshore activities.[4]

We conducted a cost-benefit analysis to quantify the value users derive from underway data collection and the Investigator's on-going research mission. We performed four case studies:

- seabed mapping, including the value generated for improved commercial outcomes for offshore industries, environmental risk reduction, improved reef health, and ecosystem services;
- ecosystem health, particularly the value that people place on protecting marine species;
- weather and climate forecasting, which covers the improvements in forecast models that benefit Australian households and the agriculture industry; and
- shipwreck discovery, which covers the discovery and protection value of two shipwrecks, SS *Iron Crown* and SS *Macumba*, important to 20th century Australian history.

The time frame covered by the economic analysis is FY2010/11 through FY2029/30. We account for the RV *Investigator's* costs and actual and projected operating budgets. Our economic analysis was informed by the scientific and economics literature, interviews with experts and industry, and CSIRO's *Impact Evaluation Guide*. Not all benefits could be monetised (Table 4.1). As such, we consider the results presented in this analysis to be conservative, lower-bound estimates.

Table 4.1. Benefits Included in the Cost-Benefit Analysis

	Benefits	
Case Study	**Monetised**	**Non-Monetised**
Seabed Mapping	• Value of improved ecosystem services • Protection of fishery resources • Value to improved sector growth in aquaculture • Value to offshore development • Value of improved Great Southern Reef health • Avoided oil spill: value to fisheries • Avoided oil spill: value of tourism	• Expansion of the broader base of scientific knowledge • National security and maritime sovereignty
Ecosystem Health	• Marine protection	• Value consumers derive from personal enjoyment of nature
Weather Forecasting	• Benefits to households of improved weather forecasting • Improved weather forecasting for agricultural production	• National defence
Shipwrecks	• Discovery and protection value of SS Macumba and SS Iron Crown • Virtual Tourism	• Cultural value

[4] Note that our analysis focused solely on the application and end use of underway data collection. As noted above, we did not value the impacts of major scientific breakthroughs that may result from supported scientists' research. Those impacts would be in addition to what is presented herein.

4.1 Seabed Mapping

RV *Investigator* is outfitted with specialised instrumentation that allows bathymetric, biological, and geophysical data to be collected in three dimensions. These data have been used to

- improve the management of vital ecosystems in southern Australia (Althaus et al., 2017; Melvin et al., 2016; Williams et al., 2018; Post et al., 2020);
- improve ecosystem services;
- improve economic outcomes from offshore industries such as energy exploration and fishing (van de Kamp et al., 2019; Williams et al., 2018; MNF Annual Report, 2017); and
- enable the reduction of the risk of environmental degradation (Williams et al., 2018; Tooze et al., 2019; Post et al., 2020).

4.1.1 Improved Health of the Great Southern Reef

MNF has supported a range of research centred around the marine ecosystems of Southern Australia, including the Great Australian Bight and the Great Southern Reef. Extensive seabed mapping, research into biodiversity, identifying 277 species new to science and 887 species new to the Great Australian Bight, and other research is vitally important for resource management.

It has been shown that management outcomes of policies and actions taken around ecosystem and natural resource management can improve with greater information about the resource (Williams & Johnson 2013, Runge et al., 2011, Johnson et al., 2014, and Williams et al., 2011). As MNF provides more information on the natural resources that are encompassed in the Great Australian Bight, better management decisions can be made to reduce the negative impact that humans may have on this ecosystem.

The Great Southern Reef contributes nearly $10 billion a year to the Australian economy and covers around 71,000 square kilometres near some of Australia's most populated areas (Australian Academy of Science, 2018).

Australians place substantial value on sensitive ecosystems and are willing to pay to protect them (Rolfe & Windle, 2012). That willingness to pay (WTP) represents the resource's social value.

We estimate that the value of research, information, and improvements in practice related to improvement in the health of the Great Southern Reef is between $481.3 and $1,008.6 million over a 12 year period, with a median cumulative WTP of $536.9 million.

4.1.2 Improved Ecosystem Services

As management and protection of natural resources improves, the services provided by ecosystems also should improve. Temperate reefs, such as the Great Southern Reef, provide a range of benefits to Australia by regulating weather and climate, sequestering carbon and cycling of other nutrients, providing food and natural materials, and protecting shorelines from wave and tidal action (Blamey & Bolton, 2018).

We estimate the cumulative improved ecosystem services to be $49.1 million to $54.2 million, with a median of $51.7 million.

4.1.3 Improved Commercial Outcomes for Offshore Industries

Seabed mapping provides productivity, efficiency, and quality benefits to commercial activities. Offshore development, fishing, and aquaculture all benefit from increased knowledge of the seabed. Most benefits are indirect, in that they do not directly provide revenue to commercial entities. Rather, they improve processes and support activities that increase efficiency, reduce risk, increase yield, or support site selection.

Offshore Development

Industries engaged in offshore development include oil and gas, renewable energy, and telecommunications (e.g., submarine fibre optic cables). We used offshore oil and gas development to represent all industrial sectors engaged in offshore development. This decision was taken because oil and gas is the largest of these sectors, and industry data about other sectors was not sufficiently granular.

Fishing Industry

Fishing is a significant contributor to the overall Australia economy, with $1.79 billion in gross value added (GVA) in 2018. Seabed mapping supports the industry by providing essential fish habitat maps and informing effective conservation measures. Seabed mapping can help inform the impact of physical processes (e.g., current,

oceanography, hydrography) on habitat location. By reducing uncertainty around where and when fish may be, reduction of time at sea can be accomplished. This has the benefits of reduced risk to commercial fishing operations; less likelihood of damage to onboard equipment; reduced fuel consumption (and emissions); and reduced wear and tear on vessels.

Aquaculture

The aquaculture industry has been growing at significant rates over the past few years, including 5% growth in 2018 alone (AWE, 2020). In 2018, aquaculture accounted for $1.42 billion in GVA from a production volume of over 97,000 tonnes (AWE, 2020). The aquaculture industry receives benefits from seabed mapping through the development of hydrographic models. Related research also increases understanding of harmful algae blooms. Licensing procedures can be made more efficient with improved information on the ecosystems used to support aquaculture activities.

We estimate the cumulative benefits from improved offshore commercial outcomes range between $1,624.4 million and $2,619.5 million, with a median value of $2,131.1 million.

4.1.4 Reduction in Risk of Environmental Damage

Industries that rely on the health and services of marine ecosystems also benefit from seabed mapping through the reduction in the risk of oil spills. There is a 3% annual likelihood od an oil spill off the coast of Australia (AMSA, 2013). Data and research from the MNF inform climate risk planning for offshore oil and gas activities; and potentially reduce the risk of negative consequences of oil extraction through improved siting and documentation of habitats, species, and ecosystem services that must be addressed by industry climate action plans.

The fishing industry is at a high risk of negative impacts if an oil spill were to occur. Smith et al. (2011) found that after the BP Horizon oil spill in the Gulf of Mexico, annual fish catch dropped by 40%.

Similarly, the Australian tourism industry relies heavily on coastal resources, with 70% of international tourists enjoying aquatic and coastal experiences (Tourism Australia, 2015). Smith et al (2011) found that the BP Horizon oil spill caused a reduction of between 9-12% of tourism dollars spent in affected coastal communities in the United States.

The total cumulative benefits from a reduced risk in environmental damage ranged from $5.7 million to $22.2 million, with a median of $17.1 million.

4.1.5 Summary Seabed Mapping Benefits

We estimated median benefits of $2.7 billion through FY2029/30 for seabed mapping, with the greatest benefits coming from improved commercial outcomes.

4.2 Marine Species Health

MNF provides a vital service in helping biologists and resource managers quantify the amount of biomass living within the Southern Ocean, including krill, which are

Table 4.2. Cumulative Summary of Benefits from Seabed Mapping

	Reduction in Environmental Risk	Improved Ecosystem Health	Improved Ecosystem Services	Improved Commercial Outcomes	Total
Minimum	$5.7	$481.3	$49.1	$1,624.4	$2,160.5
Median	$17.1	$536.9	$51.7	$2,131.1	$2,736.6
Maximum	$22.2	$1,008.6	$54.2	$2,619.5	$3,704.5

Note: All dollar values are in millions of 2020 dollars and are presented prior to discounting. Sums may not equal totals due to independent rounding.

vitally important to the ecosystem. Scientists have been utilising the unique platform offered by RV *Investigator* to investigate krill and a wide range of other marine species to increase the health of these sensitive resources. This work allows resource managers to better calibrate catch limits, so as not to adversely impact the larger food web system.

The benefits of these activities include improvement to marine species health, which has been shown to be a priority for many people (Ressurreição et al., 2011; Wakamatsu et al., 2016; Davis et al., 2019). Ressurreição et al. (2011) used contingent valuation methods to estimate the public's willingness to pay to avoid loss in the number of marine species. We considered the large amount of research enabled by MNF related to marine invertebrates, fish, and mammals, which are directly impacted by the management of krill.

The cumulative benefits across the 14-year time frame range between $539.4 million and $2157.6 million, with a median of $1,078.8 million.

4.3 Weather and Climate Forecasting

The RV *Investigator* is equipped with a dual-polarised radar which is capable of collecting data from a 300 km diameter range and reaching vertically up to 20 km into the atmosphere. This is complemented by two dedicated atmospheric and aerosol laboratories, and a suite of atmospheric instruments that continually collect atmospheric data when underway. This technology has allowed the RV *Investigator* to be recognised by the World Meteorological Organisation as the first Regional Mobile Station in the Global Atmospheric Water (GAW) program (CSIRO, 2019).

The data collected by the RV *Investigator* are being used to inform, refine and calibrate weather and climate models at both the regional and global levels. Improvements to weather and climate forecasting have been shown to have positive economic impacts on the domestic sector (Lazo et al., 2009), as well as improve efficiencies and outcomes of agricultural activities through reductions in variable costs and improved application of inputs (Mjelde and Hill, 1999, Parton et al., 2019).

Experts in atmospheric sciences and meteorology at both CSIRO and the Australian Bureau of Meteorology expounded on the capabilities of MNF in reducing uncertainty in weather and climate modelling through its expansive data collection in the Southern Ocean. This is an area lacked reliable atmospheric data prior to RV *Investigator*. This inhibited the ability of scientists to calibrate weather and climate models. These improvements are expected to be available in FY2022/23.

Through underway data collection and primary voyages, scientists can better parameterise satellite observations; distinguish between biogenic aerosols and anthropogenic aerosols; and perform sensitivity analyses around weather and climate data availability. These activities are expected to lead to better prediction of near shore weather patterns, including timing and size of precipitation events; improvements in seasonal climatic predictions including La Niña and El Niño events; and better train satellite observations that can improve weather and climate forecasting in data scarce areas. Overall, significant advancements in weather and climate forecasting are expected from the improved data streams and capabilities of the RV *Investigator*.

Households value improvements in forecasts, especially the timing and size of precipitation events. We estimate that households will receive an additional $22.2 million to $88.9 million in benefits from improved weather and climate forecasting, with a median benefit of $44.5 million from the marginal improvements.

Due to the high correlation between agricultural productivity and variability in climate, the impact of improved seasonal climate forecasts — which results in lowered uncertainty and therefore risk — will have considerable direct economic impact on the Australian agriculture sector (Anderson, 1979; Cashin et al., 2017; Hughes and Lawson, 2017). Under the median scenario, we estimate that improved SCFs can benefit the agriculture sector $93.4 million between FY2022/23 and FY2029/30.

4.4 Shipwreck Discovery and Protection

While the RV *Investigator* has been performing seabed mapping, discoveries took place. Researchers found the wreckage of the SS *Macumba* in 2017, and of the SS *Iron Crown* in 2019. Both discoveries have been identified as 'significant discoveries', due to their unique histories.

The SS *Macumba* was sunk on 6 August 1943 when Japanese planes fired on her and her escort (Keck, 2017). Three crew were killed and the survivors boarded

the escort ship. Nearly 75 years later, the RV *Investigator* found the SS *Macumba* using the RV *Investigator's* sonar systems (Keck, 2017). Forty metres underwater and upright, the SS *Macumba* now serves as an artificial reef hosting a variety of marine species (Keck, 2017).

The SS *Iron Crown* was found in the Bass Strait in 2019. She was sunk by a torpedo from a Japanese submarine on 4 June 1942. All but five crew members went down with the ship (Howarth, 2019). The ship was identified by a combination of sonar and a submersible camera.

The discovery of these shipwrecks provides multiple benefits. There is value received when the wreckage is discovered, and once discovered the site can be protected under the Australian Underwater Cultural Heritage Act 2018 (Underwater Heritage Act). Additionally, these ships can be explored and documented in situ and presented virtually to people within museums.

The total benefits from these two shipwreck discoveries are $261.1 million under the median scenario. The majority of benefits stem from the initial discovery and long-term protection of each vessel. Discovering and protecting the vessels contribute between 73% and 92% of the total benefits in each scenario.

4.5 Summary Benefits

The total benefits (prior to discounting) stemming from underway data collection and on-going data collection on the RV *Investigator* range from $2.9 billion to $6.6 billion from FY2016/17 to FY2029/30, with $4.2 billion under the median scenario.

After discounting, the present value of benefits under the median scenario is $3.1 billion. The majority of benefits stem from the work related to seabed mapping, which contributes between 58% and 75% of the total estimated benefits across the scenarios (Table 4.3).

Table 4.3. Total Benefits from FY2016/17 through FY2029/30

Case Study	Benefit	Value ($)					
		Minimum		Median		Maximum	
		Before Discounting	Discounted	Before Discounting	Discounted	Before Discounting	Discounted
Seabed Mapping	Value to Fisheries	0.7	0.5	1.3	1.1	2.6	2.2
	Value of Tourism	5.1	4.2	15.8	13.0	19.6	16.2
	Value to Improve GSR Health	481.3	337.1	536.9	376.0	1,008.6	706.4
	Value to Improved Ecosystem Services	49.1	34.8	51.7	36.6	54.2	38.4
	Value to Fishing	36.5	27.8	72.9	55.6	91.1	69.5
	Value to Aquaculture	43.4	33.1	72.3	55.2	101.2	77.2
	Value to offshore development	1,544.5	1,178.3	1,985.8	1,514.9	2,427.1	1,851.6
Marine Health	Marine Species Protection	539.4	378.5	1,078.8	757.0	2,157.6	1,514.1
Weather Forecasting	Household Benefits	22.2	14.1	44.5	28.2	88.9	56.4
	Agricultural benefits	0.0	0.0	93.4	59.6	373.7	238.3
Shipwrecks	Protection Value - SS *Iron Crown*	103.9	70.8	105.1	71.6	115.7	78.9
	Protection Value - SS *Macumba*	103.9	73.6	105.1	74.4	115.7	81.9
	Virtual Tourism - SS *Iron Crown*	9.0	5.5	25.4	15.7	42.2	26.0
	Virtual Tourism - SS *Macumba*	9.0	5.5	25.4	15.7	42.2	26.0
TOTAL	**ALL MODELS**	**2,947.9**	**2,163.9**	**4,214.4**	**3,074.6**	**6,640.6**	**4,783.0**

Note: All dollar values are in millions of 2020 dollars. Discounting was performed using a 7% real social discount rate with a base year of FY2019/20. Sums may not equal totals due to independent rounding.

4.6 Costs

The costs included in this analysis cover initial procurement for the RV *Investigator*; expected overhaul costs (FY2024/25); and related annual operating expenditures. The costs from FY2010/11 to FY2019/20 are actual, but the costs for FY2020/21 through FY2029/30 are projections. Annual projected operating costs were calculated by taking the average of labour and operating expenditures from the previous 3 years.

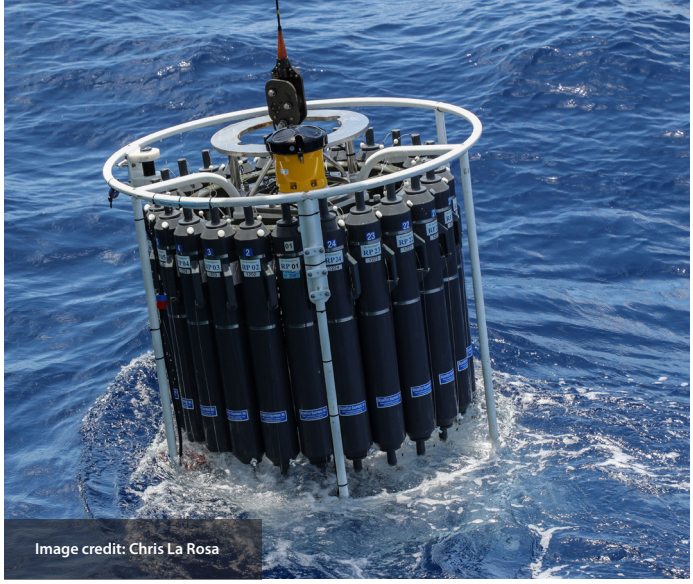


Image credit: Chris La Rosa

Table 4.4. Nominal and Real Costs

	Nominal			Consumer Price Index	Real
	Capital	Staff and Operating Expenditures	Total Costs ($)		Total Costs ($)
2010/11	13.0	0.0	**13.0**	96.9	**15.6**
2011/12	28.0	0.0	**28.0**	99.8	**32.6**
2012/13	54.0	0.0	**54.0**	102.0	**61.5**
2013/14	6.0	0.0	**6.0**	104.8	**6.7**
2014/15	19.0	19.9	**38.9**	106.6	**42.5**
2015/16	0.0	27.6	**27.6**	108.4	**29.6**
2016/17	0.0	30.8	**30.8**	110.0	**32.5**
2017/18	0.0	25.9	**25.9**	112.1	**26.9**
2018/19	0.0	28.0	**28.0**	114.1	**28.5**
2019/20	0.0	32.7	**32.7**	116.2	**32.7**
2020/21	0.0	31.1	**31.1**		**31.1**
2021/22	0.0	30.6	**30.6**		**30.6**
2022/23	0.0	30.6	**30.6**		**30.6**
2023/24	0.0	30.6	**30.6**		**30.6**
2024/25	21.5	30.6	**52.1**		**52.1**
2025/26	0.0	30.6	**30.6**		**30.6**
2026/27	0.0	30.6	**30.6**		**30.6**
2027/28	0.0	30.6	**30.6**		**30.6**
2028/29	0.0	30.6	**30.6**		**30.6**
2029/30	0.0	30.6	**30.6**		**30.6**
TOTAL VALUES	**141.5**	**471.5**	**613.0**		**637.1**

Note: All dollar values are in millions of 2020 dollars. Discounting was performed using a 7% real social discount rate with a base year of FY2019/20. Sums may not equal totals due to independent rounding.

In nominal terms, the initial investment for the vessel was $120 million, which equates to $137.1 million in real 2020 terms after accounting for inflation. Typical annual operating expenditures are expected to be about $30.6 million in most years.

Total costs amount to $637.1 million in real terms by FY2029/30 (Table 4.4).

4.7 Economic Performance Measures

We calculated three economic performance metrics to assess return on investment: net present value (NPV); benefit-cost ratio (BCR); and internal rate of return (IRR). Table 4.5 presents summary measures.

After discounting using a 7% social discount rate, the present value of costs are $656.4 million.

In all cases, the RV *Investigator* represents a sound investment and strong generator of social value for Australia. The NPV is positive, meaning that benefits exceed costs. Looking specifically at the median scenario, which is the number we advise using for a point estimate, the NPV is $2,418.3 million.

The BCR is the ratio of the PV of benefits to the PV of costs. The BCR ranged from 3.3 to 7.3 across our three scenarios. Under the median scenario, the BCR was 4.7. This means that for every $1 in investment and operating expenditure, $4.70 in social value is generated.

The benefit-to-cost ratio for the RV *Investigator* is 4.7 under the median scenario, meaning that for every $1 invested, $4.70 in social value is generated over the time frame from FY2010/11 to FY2029/30.

The internal rate of return demonstrates the overall social rate of return on the RV *Investigator*. We estimate that rate to be between 34% and 49%, with a 41% rate of return under the median scenario. This is far higher than the minimum real social rate of return of 7% that Australia uses as its benchmark.

Table 4.5. Economic Performance Measures for the RV *Investigator*, FY2010/11 through FY2029/30

	Present Value ($)		Net Present Value ($)	Benefit-to-Cost Ratio	Internal Rate of Return (%)
	Benefits	Costs			
Minimum	2,163.9	656.4	1,507.5	**3.3**	**34**
Median	3,074.6	656.4	2,418.3	**4.7**	**41**
Maximum	4,783.0	656.4	4,126.7	**7.3**	**49**

Note: All dollar values are in millions of 2020 dollars. Discounting was performed using a 7% real social discount rate with a base year of FY2019/20.

5 Concluding Remarks

The MNF is a landmark national research platform that enables the generation of knowledge and insights specific to Australia's rich marine environment and adjoining oceans. Science emerging from the RV *Investigator* is of global importance. Although it is early in the vessel's life cycle, insights and research findings are being published in many of the world's leading scientific journals. Such insights are critical because, in the absence of the RV *Investigator*, these areas would remain understudied. Not only would this set back Australian science nationally and on the global stage, but also an island nation's situational awareness, which in turn affects resource and ecosystem management, industry, and climate policy and planning.

Students indicate that the MNF represents a unique platform for experiential learning, tacit knowledge acquisition, and exposure to a high level of multi-disciplinary collaboration. Such collaboration is particularly important for solving complex scientific problems, especially those related to oceans, climate change, and weather.

The MNF's training programs are key to developing the next generation of scientific and industry leaders for Australia's blue-water environment. They provide students rich opportunities to develop students' knowledge and skills while building character and self-confidence. One student called their time at sea `an unparalleled experience.'

We conducted an economic analysis of the value the RV *Investigator* generates by collecting robust data about oceans, marine life, the seafloor and the atmosphere. These data are made available at no cost for use by the public. Users from all segments of Australian society leverage these data to deepen and expand our collective understanding of ocean ecosystems, climate and weather changes (especially in the Southern Ocean), fisheries and other important topics. Ultimately, underway data play a critical role in evidence-based decision making, resource and risk management strategies, and offshore activities.

We found the median net present value generated to Australian society from the RV *Investigator* to be approximately $2.4 billion. We estimated the mean benefit-to-cost ratio to be 4.7. This means that for every $1 invested in the RV *Investigator* and its operations, $4.70 accrued. Such a significant benefit-to-cost ratio, even at this early stage in the RV *Investigator's* life, is not uncommon when public-sector action like procurement of this research vessel fulfils and unmet need (Tassey, 2003). This estimate is likely conservative as the results do not yet reflect any major scientific breakthroughs that scientists may generate.

Overall, the strength of the results leads us to conclude that the RV *Investigator* is a valuable and productive element of research infrastructure for Australia's people and economy.

Image credit: Rob Zugaro (Museums Victoria)

Delivering a World-First Biodiversity Survey of the Abyss

The marine life at abyssal depths (>4000m) along Australia's eastern coastline is little understood. The lack of baseline data about species and their distribution makes it difficult to set policy and measure change. For the first time, the RV *Investigator* provided the opportunity for researchers to sample at these depths.

During the voyage 42,747 specimens were collected, with over one third of the invertebrates thought to be new species. New vertebrate species will require description and be housed at museums and institutions across Australia, providing future material for research and study.

The bathymetry voyage also surveyed marine debris and micro-plastics encountered in surface waters and from abyssal depths. The information gathered from this project will contribute to better understandings of the impact of human activity on natural environments far removed from cities and homes.

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