Marine Seismic Survey Impacts on Fish and Invertebrates

Final Report for the Gippsland Marine Environmental Monitoring Project

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Final Report for the Gippsland Marine Environmental Monitoring Project

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Executive Summary

An important part of managing Australia's marine resources is mapping the geology beneath the seafloor using seismic surveys. Marine seismic surveys involve the use of airgun arrays that are towed behind vessels and produce high-intensity, low-frequency impulsive sounds at regular intervals. These sounds are directed down towards the seafloor and are used to generate detailed images of its underlying geological formations. As part of this work, associated environmental impacts must be understood and mitigated. The Gippsland Marine Environmental Monitoring (GMEM) project was developed in response to concerns from fisheries groups that seismic operations negatively affect catch rates. Specifically, claims that a 2010 seismic survey in the Bass Strait caused mass mortalities of scallops and other invertebrates highlighted the need for field-based research on the potential environmental impacts of marine seismic surveys.

The GMEM is an integrated multi-component project which monitored scallop populations and fish behaviour before, during, and/or after an April 2015 seismic survey in the Gippsland Basin, Bass Strait, across multiple sites in an experimental (0-1 km from seismic survey lines) and control (≥ 10 km from seismic lines) zone. Commercial (Pecten fumatus) and doughboy (Mimachlamys asperrima) scallops were assessed using dredged samples and underwater imagery from an Autonomous Underwater Vehicle (AUV) before and two and ten months after completion of the seismic survey. Sound pressure was monitored at various sites in the survey area with acoustic recording units (ARUs) before and during the seismic survey, and particle motion was modelled. To provide environmental context to the 2010 scallop mortality event, sea surface temperatures (SSTs) were also modelled from 2006-2010. Fish behaviour was monitored using tagged tiger flathead (Neoplatycephalus richardsoni), gummy shark (Mustelus antarcticus), and swellshark (Cephaloscyllium laticeps) released within acoustic arrays in the experimental and control zones; and commercial catch data from 15 species in the region were used to quantify any differences that may have been attributed to the 2015 seismic survey.

For each project component, key results included the following:

- **Sound Monitoring.** Airgun sound signals were detected up to 60 km away, with the highest sound exposure level (SEL) of 146 dB re 1 μPa²s recorded at 51 m depth when the airguns were operating 1.4 km away.
- **Sound Modelling.** Maximum SEL received one metre above the seafloor with airguns directly overhead was estimated to be 170 dB re 1 μPa²s, extending 200 – 250 m away from the receiver depending on water depth and directionality. The highest modelled peak particle velocity was 167 and 171 dB re 1 nm/s at 40 Hz and 80 Hz, respectively.
- **Environmental Modelling.** A large positive temperature anomaly occurred between Feb 2010 and May 2010 in conjunction with the seismic survey (up to 1°C higher than 5-year monthly average), especially for areas in which scallop mortality was subsequently detected.
- **Scallop Assessment (Dredging).** There was no indication of adverse effects of the seismic survey on commercial or doughboy scallop abundance, shell assemblages, or gonad condition. In samples collected two months after the seismic survey from the experimental zone there were larger doughboy scallops with different fatty acid profiles, although reasons for this remain unknown. Importantly, significant differences between sites highlight the importance of sampling from various regions in monitoring studies in order to reduce the risk of spatial variation mistakenly being identified as impact.
Scallop Assessment (AUV). There was no significant interaction between time and seismic survey exposure on commercial scallop types (live, clapper, dead shell, unknown), although short-term or moderate effects could not be determined because the AUV deployed before the seismic survey acquired low-quality images unsuitable for analysis.

Fish Behaviour. Only 35% of the gummy sharks (N=33) and 30% of the swell sharks (N = 43) were subsequently detected two days after release, although various individuals returned sporadically over the period of monitoring including during the seismic survey operations. Behaviour consistent with a possible response to the seismic survey operations was restricted to flathead which increased their swimming speed during the seismic survey period and changed diel movement patterns after the survey. The increased swimming speed may indicate a startle response, but the range of movement did not cause significant difference in displacement (travel) across the monitored array.

Catch Rate. Catch rates in the six months following the seismic survey were different than predicted in nine out of the 15 species examined across both Danish Seine and Demersal Gillnet sectors. Across both fishing gear types, six species (tiger flathead, goatfish, elephantfish, boarfish, broadnose shark and school shark) indicated increases in catch subsequent to the seismic survey, and three species (gummy shark, red gumard, sawshark) indicated decreases in catch. These results support previous work in which the effects of seismic surveys on catch seem transitory and vary among studies, species, and gear types.

The GMEM project provided no clear evidence of adverse effects on scallops, fish, or commercial catch rates due to the 2015 seismic survey undertaken in the Gippsland Basin. Although there are limitations with some of the analyses (e.g. large variance in scallop catch; no imagery data from before the seismic survey; limited shark data for behavioural analysis), the multiple components of the project provide a robust and evidence-based assessment of the potential effects of a seismic survey on some fish and scallops. However, results must be interpreted in the context of other concurrent research in the region (e.g. Day et al. 2016), as well as a larger body of international research. Importantly, generalisations should not include other animals due to the vast range of physiology and sensory systems among animal groups. The current study and Day et al. (2016) substantially advance our understanding of impacts by showing that seismic airguns can negatively affect scallops at close range (Day et al. 2016), but this does not necessarily translate to commercially relevant effects (current study).

The main recommendations from the GMEM project are to focus future research efforts on understanding the mechanisms underpinning impacts due to marine seismic surveys, as well as to explore reasons (e.g. multiple stressors) for differences among studies. In addition, we highlight the need for interdisciplinary collaboration to appropriately design, conduct, and interpret experiments on seismic impacts. Finally, we recommend more widespread adoption of established protocols (e.g. National Investigation and Reporting Protocol for Fish Kills) during mortality events, such as that which occurred in Bass Strait 2010, to provide appropriate data so that the magnitude and cause of such future events can be determined.
1 Introduction

1.1 Justification for Study

Fisheries groups worldwide are concerned that seismic operations negatively affect local catch rates (Christian et al. 2004, Parry and Gason 2006, Harrington et al. 2010). Despite a lack of field-based studies addressing this (Carroll et al. 2016), several countries have adopted precautionary principles in their seismic survey approvals process based on potential impacts to commercially important species (Bréthes et al. 2004, DFOC 2004, Dalen et al. 2007). Australia has not yet done this, although any industry-proposed seismic survey must minimise potential impacts as part of offshore petroleum and gas regulation.

In southeast Australia, marine seismic surveys were blamed for a mortality event towards the latter half of 2010 involving scallops and other benthic invertebrates (Hall 2010). In particular, fishermen pointed to the fact that western and eastern scallop beds within the seismic survey area were devastated, while a southern scallop bed ~50 km from the seismic survey was healthy (J. Semmens, personal communication). Several studies aimed to address this issue using field experiments with lobsters (Parry et al. 2002, Harrington et al. 2010, Day et al. 2016b) or historical catch data (Parry and Gason 2006), with most of them finding no short-term effects (< 2 months) on scallops. Day et al. (2016a), however, found evidence of seismic impacts in lobsters (statocyst damage, reflex changes) and scallops (increased mortality, inability to maintain homeostasis, reflex changes) after they had been exposed at near range to airguns. The authors pointed out that the ecological relevance of their results require further investigation, particularly as they relate to fisheries and associated catch.

For fish, several previous studies have examined the impact of seismic airgun discharge on the behaviour and sensory capabilities of caged individuals in the field or laboratory. These experiments have produced mixed results ranging from significant epithelial damage within the otic capsule (responsible for hearing) and startle responses to the airgun pulses, to no observed damage or behavioural modification (McCauley et al. 2003, Popper et al. 2005, McCauley and Fewtrell 2008). However, field studies examining the propensity for similar effects on unrestrained fish, particularly elasmobranchs, have not been trialled, and overall observations on fish behaviour in response to a seismic survey are few (Wardle et al. 2001, Slotte et al. 2004).

Catch and abundance effects are the response type most directly of interest to the fisheries industry, but to date there are no clear effects of seismic surveys on catch rates of marine invertebrates or fish. The potential effects of seismic operations on fish distribution, local abundance or catch have been examined for some teleost species (reviewed by Hirst and Rodhouse 2000, McCauley et al. 2000, Popper and Hastings 2009), with varying results, possibly due to gear- and species-specific effects (Løkkeborg et al. 2012). For marine invertebrates, the potential effects of seismic signals on catch rates or abundances have been tested on cephalopods, bivalves, gastropods, decapods, stomatopods, and ophiuroids with no significant differences detected in any of these studies between sites exposed to seismic operations and those not exposed (Wardle et al. 2001, Parry et al. 2002, Christian et al. 2003, Parry and Gason 2006, Courtenay et al. 2009).

Although an increasing number of laboratory experiments have been conducted to investigate the effects of seismic airguns on marine organisms (Carroll et al. 2016), many of these have incorporated intensities or durations of sound exposures that are unlikely to be encountered in the field, particularly for simulated seismic signals in tanks (Gray et al. 2016). These studies may simplify their
interpretation to only show an effect or no effect (e.g. Aguilar de Soto et al. 2013), where instead results should be interpreted in the context of realistic exposure scenarios and field conditions. Of the few field studies investigating the potential impacts of seismic operations, many use inappropriate experimental designs resulting from a lack of observations from control sites prior to the seismic operations (Parry et al. 2002, DFOC 2004, Andriguetto-Filho et al. 2005), or they have limitations related to the compilation of catch rate or seismic data (i Jákupsstovu et al. 2001, Thomson et al. 2014). In addition, very few studies concurrently monitor and model sound exposure, thus restricting the ability to predict impacts in other regions with different seismic array configurations. Finally, researchers use different measures of sound and associated units, and this hinders comparisons among studies and may not even be applicable to the target organism. For example, while marine mammals and bony fish are sensitive to sound pressure and particle motion, elasmobranchs (i.e. sharks and rays) and invertebrates are sensitive only to particle motion, thus indicating that the particle motion aspect of sound is most applicable to impact assessments on invertebrates and elasmobranchs (Hawkins et al. 2015). The extent to which underwater noise impacts marine fisheries remains unclear. This underscores an urgent need to conduct well-designed observational studies and sound monitoring and modelling before, during, and after seismic surveys.

The Gippsland Marine Environmental Monitoring project was developed in response to stakeholder concerns from the fisheries industry about a Geoscience Australia (GA) seismic survey in the Gippsland Basin, in addition to a broader need to acquire baseline data that may be used to quantify potential impacts of seismic operations on marine organisms and habitats. As part of GA’s stakeholder engagement, individual fishermen and industry groups mentioned the lack of appropriate scientific studies associated with their observations of catch reductions. GA then commissioned a collaborative desktop study with CSIRO to examine the relationship between fisheries catch and seismic surveys by compiling all available data for the region. Although no definitive relationships were found, the report presented new statistical methodologies and recommendations for future work, including a focus on individual seismic surveys with measured sound exposure (Thomson et al. 2014).

The current study addressed this recommendation by acquiring baseline observational data on benthic and demersal communities in the field before, during, and after a seismic survey. Stakeholders can use this information to develop, or further refine, precautionary policies according to the best information on species-specific responses to known exposure levels of low-frequency sound (Parsons et al. 2009). Results from this study will be of direct use to a range of stakeholders in the fisheries industry to better understand the potential impacts of competing industries on future stocks. These findings will also assist the oil and gas industry to develop best practice techniques with regard to the timing, location, and operational characteristics of proposed seismic surveys to mitigate potential environmental impacts.

1.2 Study Area

The Gippsland Basin forms much of eastern Victoria’s offshore region. It is a hub of marine resource activity, including petroleum exploration and production, as well as both Commonwealth and state fisheries (Figure 1.1). The entire region includes the Eastern Scalefish and Shark Fishery, Eastern Tuna and Billfish Fishery, Small Pelagic Fishery, and Southern Squid Jig Fisheries. The Gippsland Basin also includes two scallop fisheries: The Commonwealth Bass Strait Central Zone Scallop Fishery and the adjacent Victorian Scallop Fishery.
At a regional scale, the principal geomorphic features of the offshore Gippsland basin include an inner to mid shelf, a shallow valley, a terrace and several large canyons (Heap and Harris 2008). Where canyons incise the continental shelf offshore along the eastern edge of the basin, cold nutrient-rich water is periodically drawn up the canyons where it mixes with the warmer surface waters of the shelf and increases productivity, making these areas important feeding grounds for migrating cetaceans and large fish. Overall, seabed sediments are sandy in composition, though silt and clays are present in the central part of the shelf (Lavering 1994). Bathymetry acquired during seismic survey GA-352 (Section 1.3 below) revealed a relatively flat seabed with depth gradually increasing with distance offshore (Figure 1.2). The seafloor is not homogenous, however, and is interspersed with tracts of sand waves (Figure 1.2), indicating strong currents and unconsolidated sediments.
Figure 1.2 Bathymetry acquired from seismic survey GA-352 in the Gippsland Basin. Bathymetric lines match with seismic lines in Figure 1.1. Dots indicate sites with available bathymetry over which the AUV was deployed, with insets showing the 1m-scale bathymetry including sand waves (all sites) and a pronounced channel (Site 41).
1.3 Seismic survey

In April 2015, a 2-D marine seismic survey (GA-352) was undertaken over part of the western Gippsland Basin (Figure 1.1) as part of the Australian Government’s National CO₂ Infrastructure Program investigating targeted offshore basins as potential CO₂ geosequestration sites. The M.V. Duke was used to tow a single 2530 cubic inch airgun array (BOLT Long Life Array), comprised of 16 airguns towed at 6 ± 1 m depth. Airguns had varying chamber sizes to optimise the array for power, primary-to-bubble ratio and frequency content (2 x 40 LLX, X 70 LLX, 1 X 80 LLX, 2X 100 LLX, 4 X 150 LLX, 2 X 200 LLX, 2 X 250 LLX and 2 x 300 LLX units). The array was operated at a working pressure of 2000 psi, with a lower acceptable limit of 1800 psi. The locations of seismic lines are shown in Figure 1.1, and the seismic acquisition times can be found in Table 1 of Przeslawski et al. (2016).

The current study area included two zones based on their spatial proximity to this seismic survey area: an experimental zone located 0-1 km from airgun operations and a control zone located more than 10 km from seismic airgun operations.

1.4 Components of Study

The GMEM project consisted of a series of integrated desktop and field study components:

1. Sound monitoring using moored hydrophones,
2. Sound modelling using theoretical and field data,
3. Environmental modelling using satellite data,
4. Scallop impact assessment using samples obtained by dredging,
5. Scallop impact assessment using Autonomous Underwater Vehicle (AUV) imagery,
6. Fish behaviour assessment using acoustic tags, and
7. Catch analysis using historical fisheries data.

The components related to scallops and fish behaviour (points listed 4-6 above) were undertaken on environmental field surveys conducted in both control and experimental areas three weeks before (survey GA350), two months after (survey GA353) and ten months after (survey GA355, scallops only) a GA seismic survey (GA-352) (Figure 1.3). There were no other seismic surveys undertaken in the region during this time period. Due to resource limitations (e.g. equipment issues, insufficient time), not all biological analyses were included in the before, short-term, and long-term assessment periods (Table 1.1).

The results of some components of this study (short-term impacts on scallops, sound modelling, sound monitoring) were submitted as a report in December 2015 (Przeslawski et al. 2016). Due to an unexpectedly long review process, this report was not released until October 2016. The current report includes and expands upon those results and therefore supersedes Przeslawski et al. (2016).
Figure 1.3: Components of the Gippsland Marine Environmental Monitoring project, with field surveys (blue) connected to their respective experimental components (yellow).

Table 1.1: Summary of scallop data used in analyses that was acquired from before (GA-350), short-term after (GA-353), and long-term after (GA-355) surveys. C = commercial scallop (Pecten fumatus). D = doughboy scallop (Mimachlamys asperrima).

<table>
<thead>
<tr>
<th>Data type</th>
<th>Collection method</th>
<th>Species</th>
<th>Before</th>
<th>Short-Term after</th>
<th>Long-Term after</th>
<th>Reason for exclusion</th>
<th>Statistical analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scallop assemblages (live, dead, unknown)</td>
<td>AUV imagery</td>
<td>C, D</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>AUV on before survey collected low quality images</td>
<td>PERMANOVA</td>
</tr>
<tr>
<td>Number of live scallops</td>
<td>Dredged samples</td>
<td>C, D</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>n/a</td>
<td>PERMANOVA (univariate)</td>
</tr>
<tr>
<td>Shell assemblages</td>
<td>Dredged samples</td>
<td>C</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Shells not recorded consistently from before survey</td>
<td>PERMANOVA</td>
</tr>
<tr>
<td>Morphometrics</td>
<td>Dredged samples</td>
<td>C, D</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>n/a</td>
<td>PERMANOVA (univariate)</td>
</tr>
<tr>
<td>Fatty acid &amp; sterol profiles</td>
<td>Dredged samples</td>
<td>C, D</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Samples not retained from before survey (commercials only)</td>
<td>PERMANOVA</td>
</tr>
</tbody>
</table>

1 Biological data was square-root transformed
2 Only shell height and width were included for doughboys, morphometrics based on internal organs were unavailable as doughboys were not opened.
1.5 Study Species

Due to concerns from stakeholders regarding the potential impacts of seismic surveys on fisheries, this study focused on commercial species: the commercial scallop (*Pecten fumatus*), tiger flathead (*Neoplatycephalus richardsoni*) and gummy shark (*Mustelus antarcticus*), as well as several other species of fish included in the catch analysis. We also use associated surrogates with similar habitats and life histories to species of commercial interest: the doughboy scallop (*Mimachlamys asperrima*) and swellshark (*Cephaloscyllium laticeps*).

The commercial scallop *Pecten fumatus* typically spawns from June to November in Tasmanian and Victorian waters (Dredge et al. 2016), and peak settlement of larvae occurs in mid-late September (Hortle and Cropp 1987). After two years, commercial scallops reach maturity and can grow to about 70 mm and then grow slowly (Young and Martin 1989, Edgar 2000). Healthy scallops recess their convex right valve beneath the sediment such that the flat left valve is level or slightly below the sediment surface. They are strongly associated with finer sediments, as well as with depth, seastar abundance, shell and macroalgae cover (Mendo et al. 2014). Like many other scallop fisheries, spatial and temporal variability of commercial scallops results in a boom-and-bust fishery (Figure 1.4) (Dredge et al. 2016). See Section 1.2 in Appendix D for further information on life history.

![Figure 1.4 Production from Pecten fisheries in Australia from 1922-2015. Values taken from (Dredge et al. 2016), except for Victoria 2000-2015 taken from (Victoria 2016) and Tasmanian and Bass Strait 2014-2015 from Jayson Semmens, personal communication. Whole weight to meat weight conversion is 7:1.](image_url)

The doughboy scallop *Mimachlamys asperrima* has been shown to spawn in late September to mid-October in the D’Entrecasteaux Channel in Tasmania, with scallops growing to 80 mm in 3.4 years (Zacharin 1995). Unlike commercial scallops, they attach to a substrate using their byssal threads throughout their entire lives, although they can break these threads and move if needed, often in response to a predator (Chernoff 1987). Populations of doughboy scallops can reach high densities,
with ‘an immense mobile population of dwarf animals 20-40 mm in length…present in the deeper waters of Bass Strait’ (Edgar 2000). Doughboy scallops often have an association with different species of epizootic sponges which may protect them from predation by seastars (Chernoff 1987, Pitcher and Butler 1987). See Section 1.2 in Appendix D for further information on life history.

The gummy shark *Mustelus antarcticus* is distributed throughout the temperate waters of Australia. Tagging studies have indicated that this species is capable of long-distance migrations throughout this region (Last and Stevens 2009). It is primarily a demersal species found in depths from nearshore to approx. 80 m (Last and Stevens 2009). Gummy shark mature at about 70 cm (males: age ~4 years) and 80 cm (females: age ~5 years); reproduction is ovoviviparous (Gomon et al. 1994, Last and Stevens 2009). Gestation takes approx. 11-12 months, producing a litter of about 14 pups (although up to 57 have been recorded) which are born at 30-35 cm in length (Last and Stevens 2009). The gummy shark diet consists primarily of cephalopods and shellfish (Daley et al. 2002, Last and Stevens 2009). This species forms the major component of the Southern and Eastern Scalefish and Shark Fishery and is currently managed under an individual transferable quota system (Daley et al. 2002).

The swell shark *Cephaloscyllium laticeps* is distributed throughout southern Australian waters between the Recherche Archipelago (Western Australia) and Jervis Bay (New South Wales). Tagging studies have indicated that this species does not move large distances, but instead remains in the area where they were tagged (Last and Stevens 2009). Swell shark can be found in depths from nearshore to approx. 650 m (Gomon et al. 1994). Swell sharks mature at approx. 76 cm (males) and 82 cm (females) (Last and Stevens 2009); reproduction is oviparous (Daley et al. 2002, Last and Stevens 2009). Females lay two eggs per month throughout the year, peaking in January-June, with gestation taking approx. 11-12 months. The swell shark diet consists mainly of cephalopods and crustaceans (Last and Stevens 2009). This species has little commercial value but are a common bycatch species of the SSF and southern rock lobster fishery (Daley et al. 2002, Last and Stevens 2009).

The tiger flathead *Neoplatycephalus richarsoni* is distributed throughout southeastern Australian waters from the head of the Great Australia Bight, South Australia to Coffs Harbour, New South Wales. There are no tagging studies to indicate the degree to which tiger flathead are capable of migrating; however, there is evidence that mature fish migrate to shallower waters prior to spawning (AFMA 2016). Tiger flathead are a demersal species that can be found in depths ranging from 10-400 m (AFMA 2016). Tiger flathead mature at approx. 3-5 years of age and reach a maximum length of approx. 65-70 cm (Gomon et al. 1994, AFMA 2016). Spawning occurs primarily over the spring – summer period; with females producing 1.5-2.5 million eggs per spawning season (AFMA 2016). The tiger flathead is an important commercial species throughout its range.

### 1.6 Aims & Scope

The aim of this project was to investigate and identify impacts of marine seismic operations on scallops and demersal fish, specifically as related to a 2-D seismic survey conducted in the Gippsland Basin by GA in April 2015. As part of this overarching objective, several components were developed (Section 1.4), each of which had its own specific purpose:

- The sound monitoring and modelling components quantify sound exposure at the seabed at varying distances from the airguns, including predictions of both sound pressure and particle motion.
- The environmental modelling uses remote sensing data to identify potential temperature and chlorophyll-a anomalies before and during the mass scallop mortality of 2010.
• The scallop assessment from dredging uses standard sampling techniques to quantify potential impacts from a seismic survey.
• The scallop assessment from seafloor imagery evaluates the use of an AUV to assess scallop communities and quantify potential impacts from a seismic survey.
• The fish behaviour assessment characterises the swimming movement and speed of several species of fish (tiger flathead, gummy shark, swellshark) as they interact with acoustic noise from a marine seismic survey.
• The catch analysis uses fisheries and industry data to investigate relationships between historical catch and marine seismic surveys in the Gippsland Basin.

For scallops, we chose to assess short-term impacts two months after completion of the seismic survey to allow direct comparisons with Harrington et al. (2010) who used the same time period. We assessed long-term impacts ten months after completion of the seismic survey based on the recommendation of scallop fishermen on the GMEM Project Board, as well as previous indications that the 2010 mortality event occurred approximately six months after completion of the 2010 seismic survey.

1.7 Report Structure

The main body of this report includes a brief description of each experimental component (Section 2) and associated results (Section 3), as well as an interpretation of the results in the overarching context of the project aims (Section 4).

Comprehensive methods and results of each experimental component are presented as technical reports in the Appendices. Each appendix represents the independent report as received from the agency responsible for the respective experimental component:

• Appendix A: Theoretical noise modelling (SVT Engineering),
• Appendix B: Sound monitoring and field-based modelling (Gardline Marine Science),
• Appendix C: Environmental modelling (GA),
• Appendix D: Scallop assessment using dredged samples (GA),
• Appendix E: Scallop assessment using AUV imagery (GA), and
• Appendix F: Fish behaviour and catch analysis (CSIRO).
2 Methods

In this section we briefly describe the methods associated with the sound monitoring, sound modelling (theoretical and field-based), invertebrate assessment (imagery and dredging), fish behaviour assessment, and catch analysis. Comprehensive descriptions of methods for each study component are available in the respective Appendices.

2.1 Sound Monitoring

Four acoustic recording units (ARUs) were moored to the seabed (≥35 metres below the surface) before the seismic survey and collected afterwards, thus measuring benthic sound exposure before, during and after airgun operations. The ARUs used were shallow and deep water Song Meter SM2M+ Marine Recorders, submersible 16-bit digital recorders with a dynamic range of 78-165 dB (sound pressure level), and an audio sampling rate of 4-96 kHz (see Przeslawski et al. 2016 for calibration methods and associated corrections). ARUs were deployed at four sites representing various depths in the experimental zone, as well as a control site located over 25 km from seismic airgun shots (Figure 2.1).

Figure 2.1: Map of sound monitoring and modelling sites overlaid on seismic survey lines. Numbers indicate seismic lines in which sound monitoring was analysed (See Section 3.1 below). ARUs were deployed at all four sites and associated data modelled. Theoretical sound modelling was conducted only at the three experimental sites (A, B, and C).
ARU data was analysed by calculating the measured level in terms of the sound exposure level (SEL), expressed in one-third octave band (TOB) units, relative to 1 μPa from 20 Hz to 24 kHz. The SEL is a measure of the pulse energy content. The SEL for a single pulse was calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse. Further details of ARU deployment and SEL calculations can be found in Appendix A.

### 2.2 Sound Modelling

Two independent contractors were engaged to undertake sound modelling according to their respective standard practices at locations shown in Figure 2.1. The first contractor (SVT) developed theoretical models of received sound exposure (sound pressure) using estimated source levels and minimal field-collected data (see Appendix B for full report), and the second contractor (Gardline) developed field-based models to estimate source levels and received particle velocities (particle motion) using the acoustic data acquired, as described in Section 2.1 (see Appendix A for full report). Since elasmobranchs (i.e. sharks and rays) and invertebrates are sensitive only to particle motion, this aspect of sound is most applicable to impact assessments on invertebrates and elasmobranchs (Hawkins et al. 2015). Table 2.1 provides a comparison of methods, input parameters and assumptions for each model.
<table>
<thead>
<tr>
<th></th>
<th>Theoretical Sound Modelling</th>
<th>Field-Based Sound Modelling</th>
</tr>
</thead>
<tbody>
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<td>Contractor</td>
<td>SVT Engineering Consultants</td>
<td>Gardline</td>
</tr>
<tr>
<td>Modelled response</td>
<td>Received level (SEL unweighted)</td>
<td>Source Level, Received level (Particle velocity)</td>
</tr>
<tr>
<td>Number of sites</td>
<td>3 (Sites A, B, C)</td>
<td>4 (Sites A, B, C, D)</td>
</tr>
<tr>
<td>Source</td>
<td>16-gun 2530 cubic inch array, as provided by seismic vessel operator</td>
<td>16-gun 2530 cubic inch array, based on field measurements</td>
</tr>
<tr>
<td>Source Level</td>
<td>215 dB re 1 μPa²s²¹</td>
<td>To be estimated by model</td>
</tr>
<tr>
<td>Source Height</td>
<td>6 m below sea surface</td>
<td>8 m below sea level</td>
</tr>
<tr>
<td>Received Level</td>
<td>To be estimated by model</td>
<td>140 – 146 dB re 1 μPa²s², as measured in current study</td>
</tr>
<tr>
<td>Receiver Height</td>
<td>1 m above seabed</td>
<td>1 m above seabed</td>
</tr>
<tr>
<td>Model category</td>
<td>Parabolic Equation</td>
<td>Parabolic Equation</td>
</tr>
<tr>
<td>Model type</td>
<td>Monterey Miami Parabolic Equation (MMPE)</td>
<td>Range-dependent Acoustic Model (RAMSGeo)</td>
</tr>
<tr>
<td>Model limitations</td>
<td>Rough surface scattering², vertical launch angle³, omnidirectionality⁴</td>
<td>Omnidirectionality⁴</td>
</tr>
<tr>
<td>Environmental inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tides/wave height</td>
<td>3.1 m (tide)</td>
<td>1-2 m (average wave height)</td>
</tr>
<tr>
<td>Substrate type</td>
<td>Medium sand²</td>
<td>Coarse sand²</td>
</tr>
<tr>
<td>Sound speed profile</td>
<td>From CTD data (Appendix B)</td>
<td>From CTD data (Appendix A)</td>
</tr>
</tbody>
</table>

¹ As derived from the time domain signal provided by seismic vessel operator  
² The model is conservative because acoustic wave scattering due to the roughness of the sea surface/seabed is not included.  
³ The launch angle of the model is limited to ±40°. The sound waves predicted at angles close to the noise source outside of this angle are evanescent waves, i.e. strongly decaying.  
⁴ The model conservatively assumes an omni-directional source that does not take directionality into account. Seismic airguns are directional sources, and the measured level is therefore dependent on the relative angle of the seismic survey to the receiver.  
⁵ Highest recorded level recorded at Port Welshpool (Bureau of Meteorology) for worst case scenario  
⁶ Tide information from Global Ocean Tide Model (http://www.space.dtu.dk/english/Research/Scientific_data_and_models/Global_Ocean_Tide_Model)  
⁷ Based on GA’s Marine Sediments (MarS) database and assuming unconsolidated sub-surface geology. Sound speed of 1774 m/s, density of 2.05 g/cm³, sound attenuation of 0.374 dB/m/kHz from Richardson and Briggs 2004.  
⁸ Based on grain size from grab samples collected at sites in June 2015 and assuming unconsolidated sub-surface geology. Sound speed of 1893 m/s, density of 2285 kg/cm³, sound attenuation of 0.87 dB/λ from Ainslie 2010.

### 2.3 Environmental Modelling

Sea surface temperature (SST) and chlorophyll-a (Chla) time-series imageries were derived from MODIS (Moderate Resolution Imaging Spectroradiometer) satellites. Five study areas were generated to provide different spatial scales for the analysis (Figure 2.2). Area 1 represents the southern zone scallop bed with minimal impact in 2010, and areas 2-3 represent eastern and western zones in which scallop mass mortalities were detected (S. Richey, personal communication). Area 4 includes the extent of GA-352 seismic survey in April 2015, and Area 5 covers the entire Bass Strait. The mean SST and Chla values in these five areas were extracted from the monthly data layers between 2006 and 2010. The positive and negative anomalies of SST and Chla were defined as above or below the five-year average for each month, respectively.
Conductivity-temperature-depth (CTD) data collected during the sound monitoring component of the project (see Appendix A) were used to confirm that vertical mixing was strong enough to allow applicability of our SST modelling to the seabed. Further details including temperature and salinity depth profiles can be found in Appendix C.

2.4 Scallop Assessment

Two methods were used to assess scallop condition in response to a seismic survey: dredging was used to collect scallops as per traditional sampling methods (Harrington et al. 2010), while an AUV was used to quantify scallop condition in situ. AUVs allow the non-destructive collection of high quality images of repeat areas of seabed (Barrett et al. 2010), and their inclusion in this study provides an innovative opportunity to evaluate the effectiveness of this technology to monitor infauna.

2.4.1 Dredging

A standard commercial box dredge (4.26 m wide with 46 x 70 mm mesh) was deployed for ~500 m from the Dell Richey II at various locations in control and experimental zones during three surveys (before, short-term, long-term)
Figure 2.3. All tows were on the seabed for ~ 500 m except for dredge numbers 33 and 34 which were retrieved early due to large cobbles and rocky outcrops on the seafloor.

Figure 2.3 Map of dredging operations showing survey GA350 (before) in red, GA353 (short-term after) in green, and GA355 (long-term after) in blue with region (a, b, c, d, e) shown. Insets magnify regions with multiple dredges adjacent to each other.

Upon completion of each dredge tow, all live bivalves were counted, with representative photos and samples taken for subsequent taxonomic identification. All live *Pectens fumatus* were photographed to quantify size, and at least ten animals (if available) from each dredge were opened and photographed to examine various metrics of scallop condition (see Figure 6 in Appendix D). Samples of both species of scallop were also frozen for analysis of fatty acids and sterols to identify potential depletion of energy reserves due to excessive swimming activity in response to seismic airguns. For the short- and long-term surveys (GA-353 and GA-355), *P. fumatus* shell assemblages were counted based on five categories as adapted from (Harrington et al. 2010): clappers, newly dead shell, old dead shell, very old dead shell, and broken shell (see Figure 2 in Appendix D for definitions and images). After each survey, the software package Image J-Fiji (http://imagej.nih.gov/ij/index.html) was used to extract data from *P. fumatus* images, including upper valve (i.e. flat shell) height and length, adductor muscle (AM) diameter, gonad area, and gonad stage (Appendix D).

For both doughboy and commercial scallops, biochemical analyses were undertaken on dissected digestive glands from at least five individuals, from four dredges representing each combination of zone and time, with the exception of commercial scallops before the seismic survey as sufficient numbers of samples had not been retained. The digestive gland is the main repository for lipids, while reserves of protein and glycogen are stored primarily in the adductor muscles (Wilkinson et al. 2008). Fatty acids (FA) were prepared using a rapid and direct transmethylation protocol (Parrish et al. 2015),
followed by treatment with BSTFA to convert free alcohols and sterols (ST) to their OTMSi ethers. FA and ST content (µg/g) and composition (as percent of total) of the two fractions were determined using gas chromatography (GC) analysis, with confirmation of component identification performed by GC-mass spectrometry (GC-MS). Further details on fatty acid and sterol extraction and quantification can be found in Appendix D.

For imagery data, statistical tests were performed according to the metric (i.e. dependent variable) under consideration. The differences between control and experimental sites on live scallop abundances and shell assemblages was investigated using a permutational multivariate analysis of variance (PERMANOVA) in which spatial regions (a, b, c, d, see Figure 2.3) were nested within a control or experimental zone. Differences in shell size, gonads, and adductor muscle among BACI sites were analysed with separate two-factor PERMANOVAs in which individual scallops were nested within a tow. Numbers of scallops varied among metrics and between the surveys because there was limited knowledge of scallop distribution before the first survey, and the scallops collected during this first survey were used to inform dredging operations and increase sample numbers on subsequent surveys. PERMANOVAs were undertaken with permutation of residuals under a reduced model using a fully partial analysis; this conservative approach is recommended for unbalanced designs (i.e. Type II Sum of Squares) (Anderson et al. 2008). All images with no scallops were excluded from the PERMANOVA (Clarke and Warwick 2001) but included in descriptive statistics and figures. For biochemical data, PERMANOVAs were performed separately on compositions of fatty acids and sterols, using both µg/g and percent composition, as well as the ratio of fatty acids to cholesterol. Fatty acids were excluded from composition analyses if they were not consistently at levels >0.5% or 1000 µg/g (Jeffs et al. 2004). Further details on statistical analyses including sample sizes can be found in Appendix D.

2.4.2 Imagery

As a result of low quality AUV images acquired during the ‘before’ survey, a different platform (AUV-Phoenix) was used to acquire images for the ‘after’ surveys (Przeslawski et al. 2016). For this reason, imagery data from before the seismic survey were unavailable and only long-term effects could be assessed for this project component.

As with dredge tows, AUV missions were chosen both in control (> 10 km from seismic lines) and experimental (0-1 km from seismic lines) zones (Figure 2.4). The transect shape was designed as a right-angled figure-eight (Appendix E), rather than the traditional grid formation often used in AUV studies (Foster et al. 2014). This was done to increase the number of habitat types covered, as we had very little prior knowledge about current scallop locations in the Gippsland region and wanted to maximise the chances of imaging scallops. The transect shape was also designed with two cross-over points (loop closures) to assist in refining vehicle position estimates during data post-processing.
Figure 2.4: Location of AUV transects from which seafloor images were analysed. Images were collected from surveys GA-353 (short-term after) and GA-355 (long-term after), with the exception of Station 48 from which images were acquired only on survey GA-355 and therefore not included in statistical analyses. See Figure 1.2 for high-resolution bathymetry available for Sites 45, 08, 40, and 41.

The AUV-Phoenix was deployed on the ‘short-term after’ survey 20-24 June 2015 and on the long-term after survey 20-22 February 2016. The AUV-Sirius was also deployed on the long-term survey in dense grids to provide a comparative platform at sites from which scallops were identified. AUV specifications, including camera descriptions, are detailed in Appendix E. Stereo image pairs were collected at a rate of 2 Hz with a target altitude of 2 m above the seabed and speed of 1 m s\(^{-1}\) (2 knots). Post-processing included image colour-balancing and simultaneous localisation and mapping (SLAM) processing of the stereo imagery to improve georeferencing. Further details on the AUV platforms and online links to imagery data can be found in Appendix E.

Data were extracted from images using the online annotation platform Squidle (https://squidle.acfr.usyd.edu.au) which allowed an analyst to categorise georeferenced images based on *in situ* observations of the seafloor. Approximately every 4-5 images were annotated, depending on the speed of the AUV, such that a continuous but non-overlapping series of images were annotated. Image annotation used the CATAMI classification scheme (Collaborative and Automated Tools for Analysis of Marine Imagery, Althaus et al. 2015) to identify substrate type (e.g. unconsolidated: sand/mud), bedforms (e.g. two-dimensional ripples), and animals of interest including scallops, other bivalves, and fish. This information was used to provide broad habitat characterisations (Przeslawski et al. 2016). Both commercial and doughboy scallops were counted and assigned modifiers based on the position of their valves (open, closed, indeterminate) and their location in the sediment (fully, partially, or un-buried). Dead or disarticulated scallop shells were also scored, except for images which had dense cover of screwshells or shell rubble which obscured scallops; these were found in both experimental and control zones and were not indicative of recent scallop mortality (Figure 2.5) (Appendix E, Przeslawski et al. 2016). Categorisation of scallops based on these classifiers allowed for the determination of scallop condition and overall health within each site.
A total of 9349 images were annotated for bedforms, substrate, scallops and other organisms. The software package PRIMER 6 (v. 6.1.13) with PERMANOVA+ (v. 1.0.3) was used to perform statistical analyses (Anderson et al. 2008). Biological data were square-root transformed to reduce the influence of abundant taxa (e.g. doughboy scallops in Site 06) (Clarke and Warwick 2001). To investigate potential differences in scallops and other bivalves between zones (control, experimental), times (short-term, long-term surveys) and associated interactions, three-factor nested PERMANOVAs were performed separately for commercial and doughboy scallops on square-root abundances of clappers, disarticulated shells, known live scallops, and unknown viability. PERMANOVAs were undertaken with permutation of residuals under a reduced model using a fully partial analysis; this conservative approach is recommended for unbalanced designs (i.e. Type II Sum of Squares) (Anderson et al. 2008). All images with no scallops were excluded from the PERMANOVA because this multivariate procedure cannot incorporate zeroes across all variables (Clarke and Warwick 2001); however, these images were included in descriptive statistics and figures. Further details on statistical analyses including sample sizes can be found in Appendix E.

2.5 Fish Behaviour

The behaviour of three species of fish was monitored before, during and after the seismic survey. Tiger flathead (*Neoplatycephalus richardsoni*) and gummy shark (*Mustelus antarcticus*) were selected based on their importance to fisheries in the region across multiple sectors (gear types); longevity and population stability, and previous research (Thomson et al. 2014). In addition, swellshark (*Cephaloscyllum laticeps*) were tagged due to their abundance and the low number of flathead (Figure 2.6).
Rectangular arrays each comprising 20 acoustic receivers (five rows of four receivers) were deployed in both the experimental and control zones (Figure 2.7). Receivers were spaced at 1000 m intervals with every second row offset by 500 m, providing acoustic receiver coverage of an approximate 20 km² area of sea floor assuming a nominal receiver detection range of 500 m. Two types of acoustic receivers were deployed on three mooring styles (Appendix F).

Bottom-set, baited longlines were used to catch fish in the 400 km² areas centred on each receiver array. Upon landing, all fish were carefully de-hooked, and non-target species of fish deemed unsuitable for tagging were immediately returned to the water. Fish suitable for tagging were transferred to holding tanks (approximately 1000 litres each) with flow-through seawater (Appendix F).

Tagging followed protocols outlined in Bradford et al. (2009), with both an internal acoustic tab (Vemco V13A or V9A, depending on fish size) and a conventional external plastic tag inserted (Appendix F).
Once tagging was complete, fish were generally returned to the holding tanks for observation prior to release. Fish were then released within a central location over the acoustic array in the experimental zone, overlapping AUV Station 08 with the maximum density of seismic survey lines, or the control zone overlapping AUV Station 12 (Figures 2.4 & 2.7). Both zones were in 50 – 60 m water depth. Acoustic tag data for the first two days after release were excluded from both displacement and movement analyses to allow for a recovery period following the release of tagged fish. In total, 88 fish were tagged and released between 30th March and 1st April 2015, comprising 33 gummy sharks (20 in the experimental array; 12 in the control array), 43 swell sharks – (24 experimental; 19 control), 11 tiger flathead (all experimental) and one blue-spot flathead (*Platycephalus caeruleopunctatus*) – (experimental). See Table 2 in Appendix F for further details of tagged fish.

Acoustic telemetry data was used to examine whether tagged fish responded to the seismic survey by estimating: 1) *Displacement*, the distance (metres) travelled ‘between’ receivers within each of the arrays, and 2) *Movement*, as determined by the accelerometer data (essentially, speed of movement in metres/second). Movement differs from displacement as a fish may move in response to a stimulus (e.g. the shot pulses from the seismic survey) but remain wholly within the detection radius of the same acoustic receiver (hence showing zero displacement).

For displacement, a centre of activity (COA) was estimated for each fish (Simpendorfer et al. 2002), and the resulting set of estimated positions was used as input for analysis. Displacement was then measured as the distance between COAs for each fish, over each consecutive time interval that it was detected. This was modelled against: 1) hour of the day, to determine any diel patterns; 2) average daily temperature (recorded by the VR2AR receivers and averaged across each array); 3) zone (experimental, control); 4) period (before, during or after the seismic survey) if sufficient data was available; and 5) a period-hour interaction to test for changes in diel displacement due to the seismic survey. For
movement, accelerometer values transmitted by each tagged fish were modelled using the same structures as displacement against the distance from the seismic shot (based on vessel location), hour of day, and date. Flathead movement combined numerous periods of inactivity (movement = zero) with periods of active swimming. Data were therefore further investigated via a binomial generalised linear mixed model (GLMM) to examine if the number of active ‘swims’ and their magnitude (based on the accelerometer values) differed before, during and after the seismic survey. See Appendix F for model selection methods and further details on displacement and movement calculations.

2.6 Catch Analysis

The catch analysis was restricted to fishing operations within an area of 13,000 km² extending to distances of approximately 50 km from the geographical mid-point of the survey area and encompassing both the experimental and control acoustic receiver arrays (Figure 2.7). We used the conclusion by Kenchington (1999) that effects on commercial catch rates from seismic surveys may extend to distances of up to 50 km as a guide to set this area. We assumed for the purpose of this study that fishing operations within the 50 km range would be most likely to show impacts if they occurred. This area also ensured that a sufficient number of fishing operations were available for analyses both before and after the seismic survey.

Fisheries catch data were extracted from the AFMA Commonwealth logbook database held by CSIRO for each gear-type. Separate analyses were performed for each gear type: 1) catch biomass for each species/species-group (herein referred to as ‘species’) caught in each fishing operation; 2) the amount of effort in each fishing operation (e.g. hours trawled; length of net or, in the case of Danish Seine, number of fishing operations); 3) the date of each fishing operation and 4) what vessel performed the operation. Catch data were analysed over the period January 2012 to October 2015, incorporating data from three years prior to the seismic survey to take into account seasonal and interannual effects as well as recent catch trend history, and six months after the survey to examine potential impacts. See Appendix F for further information on parameters for data inclusion, as well as maps of fishing effort distribution before and after the seismic survey.

Sufficient data were available to examine the catch histories of fifteen species before and after the seismic survey. However, not all 15 species were taken in sufficient quantities by each gear type. Nine species were examined from Danish Seine catches: John dory (Zeus faber), tiger flathead (Neoplatycephalus richardsoni), red gurnard (Chelidonichthys kumu), morwong (Nemadactylus macropterus), goatfish (Upeneichthys spp), sawshark (Pristiophorus spp), elephantfish (Callorhinchus milii), gummy shark (Mustelus antarcticus); Gould’s squid (Nototodarus gouldi). Nine species were examined from Demersal Gillnet catches: Boarfish (Pentacerotidae); sawshark; swell shark (Cephaloscyllium spp); elephantfish; gummy shark; angel shark (Squatina spp); broadnose shark (Notorynchus cepedianus); school shark (Galeorhinus galeus); snapper (Pagrus auratus).

A Generalised Additive Model (GAM) was used to determine if the observed catch rates varied in the region after the seismic survey for each gear type (Appendix F for details including equation). Briefly, date, the day of the year (1 to 365), and period (before or after the seismic survey) were used as the explanatory variables. The model was fitted separately to each of the species and gear types, and the expected catch was predicted from each of the GAM models to determine if the catch rate increased or decreased after the survey. Estimates of model parameters were converted to multiplicative effects on the biomass scale (from additive on the log-scale). This resulted in a multiplicative factor whereby values of less than one infer a lower catch than expected (and hence an inferred reduction in catch) after the seismic survey, whilst those greater than one inferred an increase in catch for a particular species after the survey.
3 Results

3.1 Sound Monitoring

A total of 879 hours of acoustic data were obtained, and background noise was measured from all four ARUs prior to the commencement of the seismic survey (sound spectra shown in Appendix A). The primary contributors to background sound levels in the Gippsland Basin were wind, rain, and current- and wave-associated sound. Biological sounds, including dolphin vocalisations, were also recorded. There was considerable variation in background sound for all four locations, although low frequencies (<2 kHz) dominated. Sites C and D are subject to lower background sound levels at 100 – 500 Hz (maximum background spectral density level of 100 and 89.2 dB re 1 µPa²/Hz, respectively) than the sites A and B (maximum background spectral density level of 109.9 and 104.6 re 1 µPa²/Hz, respectively) likely due to increased distance from shipping activity (Site D) and deeper water associated with fewer acoustic interactions from boundaries (Site C).

The primary frequency of airgun operations was between 20 and 500 Hz. Four seismic lines were selected for sound monitoring analysis based on their distance from the ARUs (lines 1024, 1032, 1027 and 1033 in Figure 2.1). Among these lines, the highest sound exposure level (SEL) recorded was 146 dB re 1 µPa² at Site B (51 m depth) when the airguns were operating 1.4 km away. Maximum received sound levels were lower at greater depths even when horizontal distance was less due to sound attenuation in water (e.g. Site A vs. Site D along Line 1032 in Table 3.1). Airgun sound signals were detected up to 60 km away (e.g. Site A in Table 3.1). Sample spectrograms and amplitudes are shown in Appendix A.

Table 3.1 Received sound levels recorded from the ARUs during seismic survey lines 1024, 1032, 1027, and 1033. See Figure 2.1 for site and line locations. Values from Site C at Line 1027 are not considered accurate (see footnote).

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (m)</th>
<th>Seismic Line</th>
<th>Distance to acoustic source (km)</th>
<th>SEL (dB re 1 µPa²s) a</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>41</td>
<td>1024</td>
<td>38.7</td>
<td>107.1</td>
</tr>
<tr>
<td>B</td>
<td>51</td>
<td>1024</td>
<td>20.1</td>
<td>124.3</td>
</tr>
<tr>
<td>C</td>
<td>68</td>
<td>1024</td>
<td>8.2</td>
<td>135.4</td>
</tr>
<tr>
<td>D</td>
<td>52</td>
<td>1024</td>
<td>51.3</td>
<td>93.7</td>
</tr>
<tr>
<td>A</td>
<td>41</td>
<td>1032</td>
<td>60.0</td>
<td>123.6</td>
</tr>
<tr>
<td>B</td>
<td>51</td>
<td>1032</td>
<td>37.3</td>
<td>121.4</td>
</tr>
<tr>
<td>C</td>
<td>68</td>
<td>1032</td>
<td>19.5</td>
<td>120.9</td>
</tr>
<tr>
<td>D</td>
<td>52</td>
<td>1032</td>
<td>38.1</td>
<td>113.7</td>
</tr>
<tr>
<td>C</td>
<td>68</td>
<td>1027</td>
<td>0.2</td>
<td>140.3 b,c</td>
</tr>
<tr>
<td>B</td>
<td>51</td>
<td>1033</td>
<td>1.4</td>
<td>146.0 d</td>
</tr>
</tbody>
</table>

a Unweighted SEL TOB
b Estimated airgun pulse duration: 0.4068 sec
c These values are lower than those known for a similar size airgun array at that distance (~170 dB re 1 µPa²s) (Day et al. 2016 and references therein), and it is likely that the signals overloaded the recorders at the short range of 200 m. This value is therefore not considered accurate.
d Estimated airgun pulse duration: 0.3925 sec
### 3.2 Sound Modelling

The theoretical model predicted the maximum SEL received one metre above the seafloor with airguns directly overhead to be 170 dB re 1 μPa²/s, extending 200 – 250 m from the receiver depending on water depth and directionality. Predicted SELs greater than 150 dB re 1 μPa²/s extended almost 4 km from the receiver, with predicted SELs of 125-130 dB re 1 μPa²/s extending out to 30 km. For further details and figures on theoretical sound modelling results see Appendix B.

For particle motion, field-based models for lines 1024 and 1032 (Figure 2.1) show highest particle velocity directly below the sound source and at the seabed boundary (Figure 3.1). Particle velocity was also higher at 40-80 Hz than 160-200 Hz. For Line 1024 the highest modelled peak particle velocity is 171 dB re 1 nm/s at 40 Hz, and for Line 1032 the modelled peak particle velocity is 166.7 dB re 1 nm/s at 80 Hz (Appendix A).
Figure 3.1 Modelled particle velocity field (y-axis, mm/s) throughout the water column at various frequencies and distances from sound source for a) seismic line 1024 and b) seismic line 1032. See Figure 2.1 for seismic line locations. Black lines indicate the seabed.
3.3 Environmental Modelling

The chlorophyll-\(a\) anomaly plot did not show a clear temporal pattern (Appendix C). In contrast, a large positive temperature anomaly occurred between Feb 2010 and May 2010 (up to 1°C), especially for areas 2 and 3 (Figure 3.2). Figure 3.3 shows SST images of the study area to provide an indication of inter-annual variability for March (Figure 3.3a-d), as well as variation within a year (Figure 3.3d-f).

These data confirm higher SST values in March 2010 (Figure 3.3d) than previous years (Figure 3.3a-c). Within 2010, February had similar SST values (Figure 3.3e) to March (Figure 3.3d) while April was much cooler (Figure 3.3f).

![Figure 3.2 SST anomaly plot between Jan 2006 and Dec 2010 with periods of seismic operations and scallop mortality indicated. Coloured lines indicate data from study areas defined in Figure 2.2.](image-url)
Figure 3.3 SST images showing inter-annual and intra-annual variability. Rectangles represent study areas labeled in (A).
3.4 Scallop Assessment

In interpreting the statistical results below, it is important to note that PERMANOVA tests yield a Pseudo F value which is used with degrees of freedom to calculate a p-value. The p-value is what determines significance at a predetermined confidence level. For the GMEM study, we set a standard confidence level of 95% which equates to a p-value of 0.05. This means that for any relationship described below, there is a 95% probability of it being significantly different if p ≤ 0.05.

It is also important to understand interactions between treatment factors. When there are two or more fixed and non-nested treatment factors in an experimental design, an interaction term should usually also be analysed. This allows the quantification of impacts of one factor in relation to the other and is often used to determine impacts in BACI designs such as that used here. In the context of the GMEM study, seismic impacts would therefore be associated with a significant interaction (i.e. p ≤ 0.05) between zone and time. This would mean significant differences existed between the experimental and control zone only at a particular time (e.g. after the seismic survey).

3.4.1 Imagery

The AUV returned usable images of commercial and doughboy scallops in the Gippsland Basin, although assessing viability was challenging for many individuals. An evaluation of AUV imagery as a potential monitoring tool for scallops is provided in Appendix E. Notably, there were no dense beds of scallops observed at most sites, with the exception of doughboys at sites 06, 37, and 45 (Figures 3.4 & 3.5) (See Table 2 in Appendix E for total numbers per site).

There was no interaction between zone (experimental, control) and time (short-term, long-term) on commercial scallop types (live, clapper, dead shell, unknown) (Pseudo F = 1.5143, p = 0.3). This indicates that no long-term effects attributable to the seismic survey were detected on commercial scallops, although short-term or moderate effects could not be tested due to lack of AUV data before the seismic survey. There were no differences in scallop types between experimental and control zones (Pseudo F = 2.091, p = 0.193), but there was a significant effect of time (Pseudo F = 8.3949, p = 0.023), with scallops from the short-term survey dominated by a higher proportion of disarticulated shells compared to those from the long-term survey (Figure 3.4).
There was a significant interaction between zone (experimental, control) and time (short-term, long-term) on doughboy scallop types (live, clapper, dead shell, unknown) (Pseudo F = 4.0485, p = 0.02). Pair-wise comparison PERMANOVA tests showed that in the experimental zone, there were differences in scallop types between the short-term and long-term surveys; there were no such differences in the control zone. This was attributed to more doughboy scallops with unknown viability observed the short-term survey (site 45) and more live doughboys observed in the long-term survey (sites 08 and 41) (Figure 3.5). Importantly, there were negligible dead doughboys (clappers and shells) detected in the experimental zone during short- or long-term survey (Figure 3.5) which would have indicated potential adverse impacts of the marine seismic survey.
In addition to assessment of scallops, the AUV provided continuous imagery of the seafloor which facilitated seafloor characterisation of each site. These characterisations are detailed in Appendix C of Przeslawski et al. (2016) for before and short-term after surveys, and notable differences based on the long-term survey are detailed in Appendix E of the current report.

### 3.4.2 Dredging

#### 3.4.2.1 Catch (live and dead scallops)

For both *P. fumatus* and *M. asperrima*, the abundance of live scallops was not significantly different among zone (*P. fumatus*: Pseudo F = 0.53845, p = 0.48, *M. asperrima*: Pseudo F = 0.3738, p = 0.667) or time (*P. fumatus*: Pseudo F = 6.5097, p = 0.197, *M. asperrima*: Pseudo F = 0.4900, p = 0.729). Similarly, there were no significant differences detected among recently dead *P. fumatus* shells among times (Pseudo F = 2.5737, p = 0.273) or zones (Pseudo F = 2.8942, p = 0.188), although data from the control zone from before the seismic survey was limited to a single dredge tow (Figure 3.6a).
There was extremely large variation among some of the control dredge tows (Figure 3.6) which may have increased the probability of Type II error (i.e. false negative). In general, *P. fumatus* catch increased over time (Figure 3.6), but this was almost certainly due to growing awareness of commercial scallop bed locations in the area as the surveys progressed.

![Graph showing catch for commercial scallops and doughboys scallops](image)

Figure 3.6 Catch for a) commercial scallops and b) doughboys scallops for each dredge (numbered) towed in control (blue) and experimental zones (red) before, two months (short-term), and ten months (long-term) after a seismic survey in the Gippsland Basin. 'New dead' is defined in the text. Clappers were only collected in dredge tows 39 and 42, and each clapper was included as two 'new dead' shells here. Dead shells were only recorded from commercial scallops, and asterisks show dredge tows where this information was not recorded.

### 3.4.2.2 Shell assemblages

There was no effect of zone or time on commercial scallop shell assemblages, nor any interactions, although only short- and long-term data was included in this analysis (Appendix D). There was, however, a significant difference between regions (Pseudo F = 7.6337, p = 0.001) which highlights the
importance of sampling from various regions in monitoring studies in order to reduce perceived impact being mistakenly identified due to spatial variation (Appendix D).

3.4.2.3 Morphometrics

For commercial scallops, there was no detectable impact due to seismic activity on commercial scallop shell size (growth), adductor muscle diameter, gonad size, or gonad stage. This was confirmed by PERMANOVA tests in which ‘zone’ (control, experimental) and ‘time’ (before, short-term after, long-term after) did not show a significant interaction for any metric measured (Table 4 in Appendix D). There was a significant effect of zone, with scallops in the control zone showing smaller shells, adductor muscles, and gonads than those in the experimental zone; this relationship existed before and after the seismic survey (Figure 3.7). Time had a significant effect on size of adductor muscles and gonads, with scallops collected in Feb 2016 showing significantly smaller gonads than those from the previous surveys, and scallops collected from April 2015 survey showing significantly larger adductor muscles than those from the subsequent surveys (Figure 3.7). Dredge tow had the most universal effect on scallops, with strong differences among tows for all metrics (p = 0.001).

![Figure 3.7 Commercial scallop metrics averaged from control and experimental zones before, two months after (short-term) and ten months after (long-term) a seismic survey in the Gippsland Basin: a) shell height and length, b) adductor muscle diameter, c) ovary area, d) testis area, e) total gonad area and f) gonad stage. Refer to Table 2 in Appendix D for sample numbers. Error bars are standard error mean.](image-url)
In contrast to commercial scallops, the size of doughboy scallops was affected by a significant interaction between zone and time (Appendix D), but this was not associated with adverse effects from the seismic survey. Both control and experimental zones showed similar patterns, with larger doughboy scallops collected from both the short- and long-term surveys compared to the before survey, although there was a much larger difference in the experimental zone between scallops collected before the seismic survey and those collected two months after (Figure 3.8). As with commercial scallops, dredge tow had a strong effect on doughboy shell size ($p = 0.001$).

![Figure 3.8 Doughboy shell size averaged from control and experimental zones before, two months after (short-term) and ten months after (long-term) a seismic survey in the Gippsland Basin. Refer to Table 2 in Appendix D for sample numbers. Error bars are standard error mean.]

### 3.4.2.4 Biochemical analyses

For biochemical analyses, commercial scallops showed no differences in fatty acids, sterols, or the ratio of fatty acids to sterols among zone or time. This was shown by the lack of a significant interaction between ‘zone’ and ‘time’ (Table 7 in Appendix D), although it should be noted that biochemical data from before the seismic survey were unavailable for commercial scallops (Table 1.1). Doughboy scallops showed no differences in sterols that could be attributed to the seismic survey. However, potential effects on doughboy fatty acids and ratios of fatty acids to sterols cannot be excluded due to marginally significant interactions between ‘zone’ and ‘time’ (Table 8 in Appendix D).

### 3.5 Fish Behaviour

Despite releases over the centre of the acoustic arrays, only 11 (35%) of the gummy sharks and 13 (30%) of the swell sharks were subsequently detected after the first two days (see Figures 9 and 10 in Appendix F). The movement of tagged sharks out of the monitored area provided limited data from which to assess their behavioural characteristics in response to the seismic survey. Various individuals returned sporadically over the period of monitoring including during the seismic survey operations. In contrast, nine out of the eleven tiger flathead tagged and released (81%) were detected in the experimental array for extended periods after release (Figure 3.9). Eight of these were detected during...
the seismic survey of which four were present during the entire seismic survey period. The detections of four individuals ceased during the seismic survey suggesting their departure from the monitored area, but the lack of an available control for flathead means these departures cannot be linked to the seismic survey.

Displacement was not modelled for gummy sharks due to insufficient numbers or for tiger flathead due to low number of displacement events (Appendix F). For swellsharks, no tagged individuals were detected in the experimental array during the seismic survey, and displacement was thus modelled against zone (control, experimental), hour of the day and temperature in lieu of data comparing before, during and after the seismic survey. Swell sharks in the experimental zone travelled smaller distances than those in the control zone (log-scale estimate: Control = 7.45, Experimental = 6.95), and there were also temperature and diel effects on displacement (Appendix F).

Movement was analysed for all three species, although gummy shark and swell shark analyses only included hour and temperature not time and zone (see Appendix F for these results). Therefore, only flathead movement could be assessed for movement effects due to the seismic survey. Flathead moved more frequently after the seismic survey than before or during it (log-scaled estimates: before = -9.78, during = -9.57 and after = -9.36). They also showed a bimodal pattern of diel movement before and during the survey, while movement was more evenly distributed during the 24-hour cycle after the seismic survey (Figure 3.10). When flathead did move, the range of movement speed recorded was significantly greater during the survey than before or after (Figure 3.11) (ANOVA: F = 12.54, p < 0.001).
Figure 3.10 Percentage frequency of movement events for tiger flathead before, during, and after the seismic survey. Temperature range experienced is provided in the bottom right panel.

Figure 3.11 Speed of movement by tiger flathead over the periods before, during and after the seismic survey.
3.6 Catch Analysis

Nine out of 15 species indicated significant deviations ($p \leq 0.05$) from their predicted catch rates after the survey, with deviations being gear-specific in species caught across both gear types. No species indicated significant before and after deviations in catch across more than one gear type. Across all gear types, six species (tiger flathead, goatfish, elephantfish, boarfish, broadnose shark and school shark) indicated increases in catch subsequent to the seismic survey, and three species (gummy shark, red gurnard, sawshark) indicated decreases in catch (Figure 3.12, Figure 3.13). Of these species, most were caught using Danish Seine, which was the more common of the two fishing operation across the area examined. See Appendix F for multiplier and $p$-values from the generalised additive model.

Figure 3.12 Danish seine expected catch for a randomly chosen vessel. The timing of the seismic survey is indicated by the vertical red line. The black line is the observed catch history including that predicted for the seismic survey. Grey shaded areas are confidence intervals (60%, 80%, 90% and 95%). The green dashed line is the predicted catch if the survey had not taken place. Red boxes identify species where the catch was significantly less than expected after the seismic survey; green boxes indicate catch was significantly higher than expected.
Figure 3.13 Demersal gillnet expected catch for a randomly chosen vessel. The timing of the seismic survey is indicated by the vertical red line. The black line is the observed catch history including that predicted for the seismic survey. Grey shaded areas are confidence intervals (60%, 80%, 90% and 95%). Green dashed line is the predicted catch if the survey had not taken place. Green boxes identify species where the catch was significantly higher than expected after the seismic survey.
4 Discussion

The current study monitored scallop populations and fish behaviour before and after a 2-D seismic survey in the Bass Strait across multiple sites in an experimental (0-1 km from seismic survey lines) and control (≥ 10 km from seismic lines) zone. Scallops were assessed using dredged samples and underwater imagery from an Autonomous Underwater Vehicle (AUV). Sound pressure was monitored at various sites in the survey area before and during the seismic survey, and particle motion was estimated. To provide environmental context to a previous scallop mortality event in 2010, sea surface temperatures were also modelled from 2006-2010. Fish behaviour was monitored using tagged fish released within acoustic arrays in the experimental and control zones, and commercial catch data in the region were used to quantify any differences that may be due to the 2015 seismic survey.

Results from this project provide no clear evidence of adverse effects on scallops, fish, or commercial catch rates due to the 2015 seismic survey undertaken in the Gippsland Basin. However, our results must be interpreted in the context of other concurrent research in the region, as well as a larger body of international research (addressed in subsequent sections). Importantly, results from the current studies cannot be generalised to include other animals due to the huge range of physiology and sensory systems among animal groups.

Previous research has found no differences attributed to seismic surveys for scallop condition or catch (Parry et al. 2002, Harrington et al. 2010), fish behaviour (Wardle et al. 2001, Løkkeborg et al. 2012), or catch rate (Hassel et al. 2004, Miller and Cripps 2013). However, other studies have detected such effects, particularly on fish behaviour and catch (Figure 4.1). In Figure 4.1 and Figure 4.2, we summarise available research investigating the effects of seismic surveys on fish and invertebrates, using colours to indicate significant effects and realistic exposure scenarios.

It is difficult to relate the sound exposures in the current study to other field studies due to a lack of published sound exposures, as well as various methods and units among those that do publish such values. Day et al. (2016b) recently compiled cumulative SELs for several seismic airgun configurations which provide some context to the current study (Table 4.1). Among the four seismic lines analysed in the current study, the maximum SEL recorded was 146 dB re 1μPa²·s at 51 m depth when the array was operating 1.4 km away (Appendix A). Although the distance from the sound source is greater than those from other studies, this value seems low compared to those from other commercial sources (Table 4.1). Field measurements may have suffered from error at low frequencies due to the fact that there is currently no standard for the calibration of hydrophones attached to a digital recording unit at low frequencies (Hayman et al. 2016) (See Przeslawski et al 2016 for further details on calibrations). Indeed, our theoretical sound modelling showed that SEL could reach 170 dB re 1μPa²·s directly beneath and extending up to 250 m from the airgun array (Appendix B). These values more closely match those from other commercial arrays (Table 4.1).
Figure 4.1 A summary of the potential impacts of low-frequency sound on marine fish. Identified impacts are classified according to the sound exposure treatments as realistic (i.e. short bursts of low-frequency sound at a distance of greater than 1-2 metres) or unknown/unrealistic (i.e. long duration and/or short distance of <2 metres to sound source).

N.B. there are significant differences between seismic studies including air gun size, the number of air guns, operating pressure to the guns, the sound exposure and recovery time of fishes, and the environment in which studies were conducted. See Carroll et al (2016) for full reference list.
Figure 4.2 A summary of the potential impacts of low-frequency sound on various responses of marine invertebrates. Identified impacts are classified according to the sound exposure treatments as realistic for seismic surveys (i.e. few short bursts of low-frequency sound at a distance of greater than 1-2 metres) or unknown/unrealistic (i.e. continuous sound exposure, > 100 bursts of nearfield sound exposure). N.B. there are significant differences between seismic studies including air gun size, the number of air guns, operating pressure to the guns, the sound exposure and recovery time of fishes, and the environment in which studies were conducted. See Carroll et al (2016) for full reference list.
Table 4.1: Sound exposure levels from various field studies using airguns or arrays. SELs are given in dB re 1μPa²·s. Source depth of commercial arrays is not included, as it was not available for several studies.

<table>
<thead>
<tr>
<th>Sound source</th>
<th>Depth (m)</th>
<th>SEL type</th>
<th>SEL value</th>
<th>Reference</th>
<th>Biological results</th>
</tr>
</thead>
<tbody>
<tr>
<td>2530 in³ array</td>
<td>51 (array 1400 m away)</td>
<td>Maximum</td>
<td>146</td>
<td>Current study</td>
<td>No impacts on scallops</td>
</tr>
<tr>
<td>45 in³ airgun (four passes)</td>
<td>10-12</td>
<td>Median cumulative</td>
<td>194</td>
<td>Day et al. 2016a</td>
<td>Impacts on scallops</td>
</tr>
<tr>
<td>150 in³ airgun (four passes, two experiments)</td>
<td>10-12</td>
<td>Median cumulative</td>
<td>196-198</td>
<td>Day et al. 2016a</td>
<td>Impacts on scallops</td>
</tr>
<tr>
<td>45 in³ airgun</td>
<td>10-12</td>
<td>Median cumulative</td>
<td>190</td>
<td>Day et al. 2016a, b</td>
<td>Impacts on lobster adults, no impacts on larvae</td>
</tr>
<tr>
<td>150 in³ low pressure airgun</td>
<td>10-12</td>
<td>Median cumulative</td>
<td>191</td>
<td>Day et al. 2016a, b</td>
<td>Impacts on lobster adults, no impacts on larvae</td>
</tr>
<tr>
<td>150 in³ high pressure airgun</td>
<td>10-12</td>
<td>Median cumulative</td>
<td>197</td>
<td>Day et al. 2016a, b</td>
<td>Impacts on lobster adults, no impacts on larvae</td>
</tr>
<tr>
<td>3590 in³ array</td>
<td>990 (receiver 250 off seafloor)</td>
<td>Maximum / cumulative</td>
<td>178 / 187</td>
<td>(Tashmukhambetov et al. 2008)</td>
<td>n/a</td>
</tr>
<tr>
<td>2130 in³ array</td>
<td>152</td>
<td>Maximum / cumulative</td>
<td>174 / 188</td>
<td>McCauley and Gavrilov as cited in Day et al. 2016b</td>
<td>n/a</td>
</tr>
<tr>
<td>3040 in³ array</td>
<td>152</td>
<td>Maximum / cumulative</td>
<td>178 / 189</td>
<td>McCauley and Gavrilov as cited in Day et al. 2016b</td>
<td>n/a</td>
</tr>
<tr>
<td>3130 in³ array</td>
<td>36 (500 m range)</td>
<td>Maximum / cumulative</td>
<td>172 / 190</td>
<td>R McCauley unpublished as cited in Day et al. 2016b</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Unfortunately, there is very limited data on particle motion from seismic airgun arrays, making contextual comparisons between studies even more challenging than with sound pressure (e.g. SELs). Day et al. 2016a recorded unexpectedly high values of ground-borne acceleration (up to 68 ms⁻² at 34 m range) but noted that ground roll showed high variability at a given range likely due to fine-scale differences in the substrate. The values of the current study (peak particle velocity of 171 dB re 1 nm/s at 40 Hz 166.7 dB re 1 nm/s at 80 Hz) should therefore be considered in conjunction with the seabed sediment (e.g. grain-size) and lithology (e.g. distance to bedrock) of the Gippsland Basin when extrapolating these results to other scenarios.

4.1 Impacts on Scallops

There were no detectable impacts of the seismic survey on the abundance of live scallops (from images), catch of live or dead scallops, or gonad condition. However, there were possible effects noted on doughboy size and energy reserves, as measured by fatty acid content and composition and ratio of fatty acids to sterols in the digestive glands. Specifically, doughboy scallops exposed to the seismic survey were larger than unexposed scallops two months after completion of the survey (Figure 3.8). The ecological meaning of the differences in doughboy fatty acid assemblages remains unknown and will be explored in future research.
This is the first study to use a standard seismic airgun array to investigate long-term impacts on scallops. Scallops were monitored in situ with no handling or transplanting. This had the benefit of assessing impact in natural habitats, but also meant that sample numbers from dredges were comparatively low during the ‘before’ survey since scallop populations, already known to be highly spatiotemporally variable, were identified concurrently with initial sampling. Due to technical and logistics issues, biochemical data from commercial scallops and image data from both species were not available from ‘before’ surveys, however evidence of mass mortality, such as that seen in 2010, would still have been evident from the data acquired.

To date, there are five scientific studies that have examined the effects of seismic surveys on scallops (Parry et al. 2002, Harrington et al. 2010, Aguilar de Soto et al. 2013, Day et al. 2016a), each of which is summarised in Table 4.2 and reviewed in Appendix D. None of these studies indicate that seismic surveys can cause catastrophic or short-term mortality in scallops with realistic exposure scenarios. However, the two most recent studies (current study and Day et al. 2016a) provide apparently contrasting results. Day et al. (2016a) showed that exposure to noise from an airgun < 10 m away can adversely impact scallops through behavioural or physiological change, as well as an increase in long-term mortality rates, while the current study did not find negative impacts on scallops from a commercial seismic survey with a typical array of airguns. Day et al. (2016a) point out that even the highest scallop mortality rates they found after 4 passes of airgun exposure were modest (17.5% and 20%) compared to naturally occurring annual mortality rates of 11-51%. Therefore, it is possible that naturally high mortality rates in situ in the current study may have masked weaker effects due to seismic surveys. The contrasting results of the two scientific studies may also be attributed to differences in the following:

- **Scientific methods.** Day et al. (2016a) used a manipulative approach in which scallops and lobsters were transplanted to the study area, exposed to an operating airgun, and then held in captivity during subsequent monitoring. The current study used an observational approach in which scallops were opportunistically monitored in the field during a seismic survey. In addition, each study measured different things. The manipulative study measured a large range of biochemical, behavioural and physiological variables, while the current study focussed on coarser metrics such as abundance, mortality, and size.

- **Scallop populations.** Day et al. (2016a) used scallop populations obtained from commercial sources or transplanted from other regions to coastal waters, while the current study targeted in situ populations in the Bass Strait. Stress associated with handling may have contributed to impacts (see Section 4.5.1). Alternatively, scallops from the Bass Strait, where seismic surveys are historically common, may be more resistant to adverse effects. These suggestions are speculations only, and further research is required to validate them.

- **Sound exposures.** Day et al. (2016a) used a single airgun at depths of 10-12 m, while the current study used a commercial array at depths of 36-61 m. Although sound pressures from the single airgun were similar to values recorded from commercial arrays, there are no comparisons of particle velocity (e.g. ground roll) with commercial arrays. In addition, sound exposure levels can vary dramatically among seismic arrays and environments. For example, seafloor substrate likely differed between the studies which can affect the sound pressure and particle velocity to which the organisms are exposed, particularly as distance from the sound source increases. Indeed, measured SELs in the current study were far lower than those detected from Day et al (2016) and other airgun arrays, although distance was generally greater (Table 4).

- **Environmental conditions.** Both studies monitored scallops in open water conditions, but temperature, salinity, food availability, stocking density and other factors almost certainly varied between the studies thereby adding potential concurrent stressors. In addition, Day et al. (2016a) identified long-term impacts after rearing scallops in suspended lantern nets such that the scallops
were not in their natural environment (i.e. buried beneath sediment), thereby adding potential, though undetected, stress.

- **Variability and sample size.** In the current study, environmental differences among sites combined with low scallop abundances meant that there was high variation among sites and times. Such high variation can lead to Type II errors (i.e. false negatives), meaning that milder effects may have been superseded by natural variability in scallop abundances, mortality, or condition. In contrast, all scallops within each experiment of Day et al. (2016a) were reared in similar environmental conditions and associated variability may have been lower to facilitate detection of moderate mortality effects.

The 2010 scallop mortality event and associated stakeholder concern were the drivers for the GMEM project, but it remains difficult to identify causes of the mass mortality. Nonetheless, the environmental modelling component of the GMEM project clearly shows a pronounced thermal spike in the eastern Bass Strait between February and May 2010, coinciding almost exactly with dates of operation for the seismic survey (Figure 3.2). In September 2010, mass mortalities of scallops and other bivalves were observed, indicating a die-off occurred sometime between early June (when Harrington et al. 2010 detected no significant mortality) and September (when fishermen recorded mass mortality in dredges). These events occurred in study areas 2 and 3 where the waters were warmest (Figure 3.3D, E) but also where the 2010 seismic survey operated. High temperatures have been linked to scallop death in Queensland (Courtney et al. 2015) and Western Australia (Caputi et al. 2015). Further research is recommended to investigate the role of temperature in scallop population and catch rate fluctuations in the Bass Strait, particularly in combination with noise and other stressors.
Table 4.2 Summary of studies investigating the effects of marine seismic surveys on scallops

<table>
<thead>
<tr>
<th>Study</th>
<th>Species</th>
<th>Type of Study</th>
<th>Sound Source</th>
<th>Duration of sound exposure</th>
<th>Responses measured</th>
<th>Key Findings</th>
<th>Study Strengths</th>
<th>Study Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Przeslawski et al. 2016 (GA-FRDC study)</td>
<td><em>Pecten fumatus</em> (Commercial scallop), Mimachlamys asperrima (Doughboy scallop)</td>
<td>Field (observational)</td>
<td>Airgun array (2530 cubic inches, 16 airguns)</td>
<td>9-day seismic operations (shots every 18.75m)</td>
<td>Abundance (live, dead), gonad stage, meat condition, size, fatty acid and sterol profiles</td>
<td>No short- or long-term changes in measured responses due to sound exposure</td>
<td>Field conditions, <em>in situ</em> scallops monitored throughout experiment, sound pressure measured and modelled</td>
<td>Low sample sizes or missing data before seismic surveys</td>
</tr>
<tr>
<td>Day et al. 2016 (UTAS-FRDC study)</td>
<td><em>Pecten fumatus</em></td>
<td>Field (manipulative)</td>
<td>Single airgun (45 and 150 cubic inches) *</td>
<td>1, 2 and 4 airgun passes, each pass having between 51–167 shots every 11.6 seconds</td>
<td>Mortality, haemolymph biochemistry, haemocyte counts, righting reflect, recessing rate, condition indices</td>
<td>Long-term mortality effects, short-term haemolymph effects, delay in righting reflex and increase in recessing reflex after sound exposure</td>
<td>Sound pressure and motion accurately measured, field conditions during exposure, multiple metrics measured</td>
<td>Scallops handled and long-term effects measured suspended in captivity (lantern nets), mechanism of effects remains unknown</td>
</tr>
<tr>
<td>Aguilar de Soto 2015</td>
<td><em>Pecten novaazelandiae</em> (New Zealand scallop) (larvae)</td>
<td>Lab</td>
<td>Recording of airgun array</td>
<td>Pulse every 3 seconds for 90 hours</td>
<td>Developmental stage, abnormality rate</td>
<td>Delayed development and higher abnormality rate in larvae exposed to seismic noise</td>
<td>Only study to examine scallop larvae</td>
<td>Acoustic conditions in small tanks make extrapolations to field conditions challenging, sound exposure durations are unrealistic</td>
</tr>
<tr>
<td>Harrington et al. 2010</td>
<td><em>Pecten fumatus</em></td>
<td>Field (observational)</td>
<td>Airgun array (4130 cubic inches)</td>
<td>2-week seismic operations (shots every 5 seconds)</td>
<td>Abundance (live, dead), size, gonad stage, meat condition</td>
<td>No short-term changes in measured responses due to sound exposure</td>
<td>Field conditions, <em>in situ</em> scallop monitored</td>
<td>Long-term effects not included, control 3.5 km from seismic operations</td>
</tr>
<tr>
<td>Parry et al. 2002</td>
<td><em>Pecten fumatus</em></td>
<td>Field (manipulative)</td>
<td>Airgun array (3642 cubic inch, 24 airguns)</td>
<td>4-day seismic operations (shots every 18.75m)</td>
<td>Mortality, adductor muscle strength</td>
<td>No immediate changes in measured responses due to sound exposure</td>
<td>Field conditions</td>
<td>Scallops not in contact with substrate, only immediate effects considered (17 days after seismic survey complete)</td>
</tr>
</tbody>
</table>

* The estimated cumulative sound exposure levels received by test animals in Day et al. (2016a) were considered similar to that of a large commercial seismic array passing at ~ 30 to 524 m for the 45 and 150 in³ sources. The magnitude from the ground borne motion from the 150 in³ air gun emulated that measured for a 3130 in³ array at around 100-200 m.
4.2 Impacts on Fish Behaviour

Although data on fish movements were limited due to most sharks leaving the array within two days of release, we found little evidence consistent with behavioural changes induced by the seismic survey in the species studied. Individuals of both shark species were observed to move in and out of the monitored areas across the study period, and gummy sharks were detected returning to the experimental zone during the period of seismic survey operations. Behaviour consistent with a possible response to the seismic survey operations was restricted to flathead which showed an increase in swimming speed during the seismic survey period and change in diel movement patterns after the survey. The increased swimming speed may indicate a startle response, but if so, the range of movement was not sufficient to generate a significant difference in displacement (travel) across the monitored array. Diel movement patterns showed a largely bimodal pattern both before and during the seismic survey. An increase in movement events has previously been reported for some species prior to seasonal departure (Andrews et al. 2010) and it is possible that the increase in flathead activity after the survey reflected an impending movement away from the area as part of a normal seasonal cycle.

Airgun discharges have been reported to elicit varying degrees of startle and alarm responses in caged teleost fish and changes in schooling patterns, water column positions, and swimming speeds (Pearson et al. 1992, Santulli et al. 1999, Wardle et al. 2001, Hassel et al. 2004, Boeger et al. 2006, Fewtrell and McCauley 2012). There is some indication that a sudden onset of sound can also cause a startle response in sharks (Myrberg Jr et al. 1978). Thresholds at which airgun sounds elicit behavioural responses in captive marine fish have been shown to vary among species (Pearson et al. 1992). Startle and alarm responses have been observed in captive fish several kilometres from the sound source, with European Sea Bass and the Lesser Sandeel responding at distances up to 2.5 and 5 km from a seismic source, respectively (Santulli et al. 1999, Hassel et al. 2004). These caged studies collectively provide an indication of acoustic and environmental conditions in which fish may show behavioural responses to seismic noise, but startle responses of captive fish may have little or no resemblance to responses in open conditions.

Behavioural studies on unrestrained fish exposed to airgun sound are scarce, but while logistically challenging, they provide the most ecologically realistic evidence of seismic survey impacts. Chapman and Hawkins (1969) and Slotte et al. (2004) show that vertical movement rather than horizontal movement could be a short-term reaction to seismic sound. Similarly exposure to airgun emissions did not interrupt the diurnal rhythm of free-ranging saithe and cod, and only slight changes to the long-term diurnal movements of two tagged Pollock were recorded (Wardle et al. 2001).

4.3 Impacts on Catch

Catch rates in the six months following the seismic survey were different than predicted in nine out of the 15 species examined across both Danish Seine and Demersal Gillnet sectors. In the majority of cases (six) this manifested in an increase in reported catch. Notably a key target species for the Danish Seine sector (tiger flathead) recorded an increase in catch after the survey whereas a key target species for the gillnet sector (gummy shark) indicated no significant change in catch rates.

Many factors can account for changes in logbook recorded catch rates including differences in fishing practices, market forces influencing the retention of catch and environmental effects influencing the distribution and catchability of species. A more refined approach to our analyses would be to look concurrently at a control fishing area outside of possible influences of the seismic survey via a Before-After-Control-Impact (BACI) approach. In such an approach, catch rates before and after the seismic
survey would be compared across regions exposed to the seismic survey (experimental) and those that were not (control). The major difficulty with the BACI approach when looking at commercial fisheries data is that it is impractical, if not impossible, to find a control region that is identical to the experimental in all aspects (physical, biological and with identical fishing fleet dynamics). In the current analyses, we considered our ‘control’ to be displaced in time (i.e. examining catch rates across the region over years back to 2012 and seeing if there was a change in the 2015 pattern). This focus on individual surveys at a given location with good resolution of catch data was recommended by the only other attempt to investigate the relationships between seismic surveys and Australian fisheries data (Thomson et al. 2014).

There is evidence, however, in at least one ‘species’ of possible confounding factors that may have influenced the before and after seismic survey catch analysis. Sawshark catch rate in the Danish Seine sector increased sharply prior to the seismic survey, with recorded catches being higher than in previous years. This is likely to have inflated the predicted catch rates for the period after the survey, leading to a greater perceived decrease in catch from ‘expected’ after the survey than may otherwise have been the case. Interestingly, similar deviations in sawshark catch rates were not reflected in the gillnet sector across the region. We have no way of reconciling this anomaly given the available data and thus urge caution in interpreting the result for this species. No obvious changes were observed in catch rates for other species in the lead up to the seismic survey suggesting that the interpretation of other species catch rate changes are more robust.

Results from the current study support previous work in which the effects of seismic surveys on catch seem to vary among studies, species, and gear types. Engås et al. (1996) hypothesised that the reduction in Atlantic cod and haddock catch rates from commercial longlines and trawls was most likely the result of fish moving away from the seismic area due to avoidance behaviour, but this may instead be due to decreased responsiveness to baited hooks associated with an alarm behavioural response (Skalski et al. 1992) or impacts related to fishing the same area for over two weeks. Most other studies on fish have found positive, inconsistent, or no effects of seismic surveys on catch rates or abundance (Løkkeborg et al. 2012, Miller and Cripps 2013, Peña et al. 2013, Thomson et al. 2014). It seems likely that the effects on fishing may be transitory, primarily occurring during the sound exposure itself (Skalski et al. 1992); this is supported by results from the fish behaviour aspect of our study (Section 4.2) in which flathead showed an increase in swimming speed during the seismic survey but no evidence of long-term displacement away from the array. For marine invertebrates, no potential effects of seismic signals on catch rates or abundances have been detected for cephalopods, bivalves, gastropods, decapods, stomatopods, or ophiuroids (Wardle et al. 2001, Parry et al. 2002, Christian et al. 2003, Parry and Gason 2006, Courtenay et al. 2009).

4.4 Strengths & Limitations

One of the main strengths of the GMEM project is its use of open water environments. By using the organisms’ actual habitat, we observed natural responses to seismic airguns and avoided artefacts that can be introduced by aquaria or cages. Previous research on seismic impacts on scallops and fish has often been limited regarding application to real-world scenarios. The use of aquaria or cages can lead to a misinterpretation of results, particularly related to behaviour, for several reasons, all of which have been well-documented in other studies (Parvulescu 1964, Gray et al. 2016, Rogers et al. 2016): 1) sound reflects off tank walls causing interference, 2) organisms are unable to escape, and 3) real sound sources usually cannot be used. For example, avoidance behaviour can be difficult to detect in a laboratory if the sound source is not obvious to the test organism (e.g. due to reverberation) (Celi et al. 2013). Measurements taken in enclosed spaces for pressure and displacement amplitude provide inappropriate comparisons relative to open marine conditions due to
reflections off surfaces and their interference with wave propagation as well as the invalidation of the particle motion relationship to pressure due to being in the near-field (Gray et al. 2016). Our study, along with recent work by Day et al (2016a, b), used open water conditions to provide insights into the possible responses of marine organisms to marine seismic surveys.

The variables measured in the current study are intended to be commercially relevant, not to reveal mechanisms underpinning potential effects. Catch is the most useful variable to the fishing industry, and we measure this using direct (e.g. commercial scallop dredge, historical catch data) or indirect (e.g. fish movement and migration) methods. This ensures that results from the current study are directly applicable to the fishing industry (but see ‘Recommendations’ below).

Although a strength of the current study is the use of field conditions, this was also the source of various challenges associated with working wholly in the field:

- Numerous gummy sharks and swell sharks left the study area before the seismic survey even started, thereby precluding statistical tests on the effects of seismic on these species’ movement.
- The AUV originally deployed to collect images from before the seismic survey returned unsuitable data, thereby precluding scallop baseline data from statistical tests using AUV imagery.
- The lack of prior information about scallop distributions and abundances meant that the first environmental survey was tasked with not only collecting appropriate baseline (i.e. ‘before’ data) but also with identifying suitable study sites with scallop beds.
- There was uncertainty as to when the seismic survey would be passing overhead which made sound monitoring observations difficult due to limited available recording time and ended initial plans to monitor scallops in situ during seismic operations.
- Inclement weather caused several days of planned fieldwork to be lost which reduced the amount of time available to resolve equipment issues, tag fish, and identify scallop beds.

Sound exposure was monitored during the seismic survey at four different locations and depths using moored hydrophones coupled to digital recorders, and associated modelling of sound propagation was undertaken. Appropriate calibration of hydrophones is crucial to obtain accurate measurements of sound, and this becomes particularly challenging at low frequencies where wavelengths are longer than available calibration tanks. In addition, the enclosure of hydrophones in acoustic recorders is now common but poses issues for calibration (Hayman et al. 2016). Specifically, the ARU is detached from the external data acquisition unit and the analogue signal is digitised before it can be read, which means that it cannot be easily calibrated against a reference voltage and other calibration devices. See Przeslawski et al. (2016) for further details on calibration techniques used in the current study.

4.4.1 Interpretation of non-significant results

In ecological research, it can be challenging to interpret a lack of significant results (Browmand 1989) such as those obtained by the GMEM project. This failure to reject a null hypothesis (i.e. negative result) does not mean that there are no effects of a given treatment (i.e. seismic exposure), but rather that no effects were detected in that particular study. For example, the current study did not prove that seismic surveys have no impact on commercial scallops. Rather, it showed that seismic survey GA-352 did not have any measurable impact on the parameters that were successfully measured on Bass Strait commercial scallops (catch, mortality, morphometrics, fatty acid and sterol assemblages). The GMEM study did not investigate a range of sub-lethal and physiological variables (e.g. Day et al 2016a) nor did it investigate other sound exposures or scallop populations.
4.5 Recommendations

The main recommendations based on the current study are to focus future research efforts on understanding the mechanisms underpinning impacts due to marine seismic surveys, as well as to explore reasons (e.g. multiple stressors) for differences among studies (e.g. the current study and Day et al. 2016a). We found no evidence consistent with airgun exposure causing adverse effects on fish or scallops using a variety of methods (tagging, historical data, imagery, dredging), but recent evidence from Day et al. (2016) indicates that nearby exposure to seismic airguns can indeed have pronounced effects on lobsters and scallops. In the interests of clarity and resolution, it is tempting to simplify each of these studies as showing impact or no impact, but there is then the associated danger of ‘cherry-picking’ data to support particular agendas. Instead, the reality seems much more complex and warrants an avoidance of simplified or sensationalised claims (Hughes 2014), as well as focussed research to identify conditions in which marine seismic surveys may impact certain organisms.

It is now recognised that the lack of standardisation in terminology and measurements related to sound exposure is one of the main limitations in providing a broadscale assessment of potential impacts of underwater noise (Hawkins et al. 2015, Ainslie and De Jong 2016). Variation in metrics and methods used to quantify sound exposure makes comparisons among studies challenging if not impossible. In particular, the calibration of hydrophones attached to autonomous recording devices requires a standardised technique so that measurements are not only accurate but comparable among studies. Until such standardisation is achieved and adopted, the findings of research on the effects of air guns and other sound sources in the marine environment will only apply to individual studies, and the general applicability of these studies to other marine seismic surveys, regions or taxa will remain questionable. Particle motion, in particular, needs to be more widely considered in sound impact research, particularly on fish and invertebrates (Hawkins et al. 2015).

Data from the current study may also be used to further explore spatial and temporal patterns of fish movement, catch and scallop abundance and condition. The GMEM project yielded a wealth of environmental and biological data from acoustic receivers, dredging, biochemical analyses, and historical records, all of which were used for a very explicit purpose here to identify potential impacts of a single marine seismic survey. Although outside the scope of the GMEM project, such data can also be used to understand ecological relationships, notably to improve our knowledge of boom-and-bust fisheries (e.g. scallops). For example, AUV imagery revealed that commercial scallops did not occur in areas with dense numbers of doughboys, the invasive screwshell (*Maoricolpus roseus*), or fileshells (*Limatula strangeii*). Although similar anecdotal observations have been previously recorded (e.g. Haddon et al. 2006), the sheer volume of high-quality imagery obtained from the AUV in the current study warrant further rigorous and focused studies on the potential exclusion of commercial scallops due to habitat or food competition.

4.5.1 Multiple stressors

One of the most interesting hypothesis stemming from the current study and Day et al. (2016a) is that multiple stressors may lead to a tipping point at which impacts of seismic surveys may then be observed. Temperature is perhaps the most promising concurrent stressor to target due to its potential role in the 2010 mortality event (Appendix C). In addition, 2015 was the warmest year on record, with the average global temperature across ocean surface areas 0.90°C above the 20th century average of 13.9°C (NOAA 2016), and eastern Australia is a known climate warming hotspot (Oliver et al. 2013), with range shifts and community cascades already evident (Johnson et al. 2011).
The effects of multiple abiotic and biotic stressors and associated interactions should be considered in any impact assessment of sound effects (Hawkins et al. 2015), but to date there has been no research targeting potential interactions between low-frequency impulsive sound and other potential stressors. Interactions between stressors can be broadly classified into three types: (1) additive effects in which stressors independently affect an organism such that their combined effects are simply the sum of the individual effects (this includes instances when one or more stressors do not have a significant effect), (2) antagonistic effects in which one stressor offsets the effect of the other, and (3) synergistic effects in which stressors interact such that their combined effects are greater than the sum of their individual effects (Folt et al. 1999). Synergistic effects are particularly concerning regarding marine impacts; for example, single stressors related to sound exposure may show no effects in isolation but when combined with other stressors (e.g. temperature, food competition) effects may become pronounced (Przeslawski et al. 2015). If such interactions are not considered, potential effects may be underestimated or overestimated based on whether the interaction is synergistic, additive, or antagonistic (Crain et al. 2008).

### 4.5.2 Interdisciplinary approach and expertise

Understanding the effects of seismic surveys on marine organisms requires knowledge of physics, biology, and ecology. Specifically, experts are needed in acoustic measurements to understand how to accurately measure intense low-frequency sound; underwater sound physics to accurately model sound source and transmission; biology to measure and interpret behavioural or physiological response, statistics to identify significant impacts related to seismic airguns, and field logistics to ensure appropriate data collection and documentation (R. McCauley, unpublished report ‘Framework for studies into response of plankton, marine invertebrates and fish to marine seismic surveys using air gun sources’). Importantly, no single person or even group can meet all the required expertise, and interdisciplinary and cross-agency scientific collaboration is crucial.

In addition to the interdisciplinary scientific collaboration required in seismic impact studies, there is a broader need for improved communication between stakeholders (to identify the need for the study), scientists (to appropriately design the study), petroleum industry (to provide information about timing and location of seismic surveys) and fisheries (to provide information about the catch of key fisheries). This collaborative approach is essential in order to appropriately, and cost-effectively, conduct rigorous in situ studies on the effects of marine seismic operations on fish and invertebrates.

### 4.5.3 Protocol for marine mortality events

Due to the lack of rigorous time-series biological data, we cannot establish a definitive link between shellfish mortality and warming waters in 2010. Unfortunately, baseline data is not readily accessible for most regions, let alone a discrete area in which a die-off may occur. However, valuable data such as total catch, size, and health are collected during pre-season or reconnaissance surveys and can be used as post hoc baseline data in the event of mass mortality. Because of the potential value in such data, fisherman should continue to keep accurate and consistent logs during pre-season surveys and any other time they are able to do so.

Once a mortality event is noted, procedures outlined in the National Investigation and Reporting Protocol for Fish Kills (www.agriculture.gov.au/animal/aquatic/guidelines-and-resources) should be followed to ensure that the appropriate data are being collected without compromising existing fisheries and recreational activities. The National Investigation and Reporting Protocol for Fish Kills hinges on members of the public or fishing community immediately reporting a fish kill incident to the relevant federal or state hotline (national hotline is 1800 675 888). The caller provides the known
location and extent of the die-off, species, number of dead animals, weather conditions, and water quality observations. The responsible agency (e.g. state or territory environmental protection agency, department of primary industries or fisheries, Department of Agriculture and Water Resources) then determines if a full investigation is warranted, and accordingly assembles a response team led by an incident coordinator. The subsequent investigation stage involves the deployment of the response team to collect data and samples to determine the magnitude and cause of the mortality event. Importantly, all the original observer of the mortality event does in this process is to ring the hotline. Without robust and consistent data among multiple regions and times, the continued cause of scallop mortality events and their boom-and-bust nature will remain speculative, hindering management efforts and fisheries success.

4.6 Conclusions

The GMEM project represents an important step in expanding our knowledge in relation to marine seismic surveys and potential environmental impacts on Australian marine invertebrates and fish. Results will inform future environmental plans seeking approval to undertake a seismic survey, as well as the assessment of environmental plans by regulatory authorities such as the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA).

Data from this study are publicly available and will be useful to both the fisheries and petroleum industries to increase their knowledge of the potential impacts of marine seismic surveys on commercially important species. Acquisition of baseline environmental data will facilitate future monitoring and an understanding of the natural variability in scallop and other stocks and how this may relate to environmental changes. Such knowledge will lead to improved management practices and development of mitigation strategies in the petroleum industry to enhance fisheries sustainability and even increase productivity.

The current study and Day et al. (2016a) substantially advance our understanding of impacts by showing that seismic airguns can negatively affect scallops (Day et al. 2016a), but this may not always translate to effects on catch (current study). Results from recent scallop studies need to be interpreted in the context of other stressors (e.g. temperature in Caputi et al. 2015, Courtney et al. 2015) as well as unknown mortality events (e.g. Day et al. 2016a).

Although there are limitations with some of the analyses (e.g. large variance in scallop catch, no imagery data from before the seismic survey, limited shark data for behavioural analysis), the multiple components of the project provide a robust and evidence-based assessment of the potential effects of a marine seismic survey on fish and scallops.
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Appendices

The following appendices are available on the Geoscience Australia website at: http://www.ga.gov.au/metadata-gateway/metadata/89626

- **Appendix A** Sound Monitoring Report (Gardline Marine Sciences Pty Ltd)
- **Appendix B** Sound Modelling Report (SVT Engineering Consultants)
- **Appendix C** Environmental Modelling Report (Geoscience Australia)
- **Appendix D** Dredging Report (Geoscience Australia)
- **Appendix E** AUV Report (Geoscience Australia)
- **Appendix F** Fish Behaviour and Catch Analysis Report (CSIRO)
- **Appendix G** Survey Crews and Project Board Members