CSIRO OCEANS AND ATMOSPHERE
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Potential impacts on zooplankton of seismic surveys

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29 June 2017

APPEA (The Australian Petroleum Production and Exploration Association)

CSIRO Oceans and Atmosphere

Citation

Richardson AJ, Matear RJ and Lenton A (2017) Potential impacts on zooplankton of seismic surveys. CSIRO, Australia. 34 pp.

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Acknowledgments

We acknowledge the funding provided by APPEA for this project. We thank Dr Luke Smith and Matthew Hatch (Woodside) for their support and contribution to this work. We would also like to thank Associate Professor Rob McCauley (Curtin University) for providing advice on how to interpret his study.

Executive summary

Context: While the impact of seismic surveys on marine mammals has been well studied, there has been little work on zooplankton. The study by McCauley et al. (2017) published on the 23 June 2017 is the first large-scale field experiment on the impact of seismic activity on zooplankton. Their study overturns the conventional idea of limited and localised impact on zooplankton. They found that airgun exposure significantly decreased zooplankton abundance, and increased the mortality rate from a natural level of 19% per day to 45% per day (on the day of exposure). These impacts were observed out to the maximum assessed range of 1.2 km. McCauley et al. (2017) state that there is an urgent need to conduct further studies to mitigate, model and understand potential impacts on plankton.

Methods: Here we simulate the large-scale impact of a seismic survey on zooplankton, assuming the mortality rate associated with airgun exposure reported by McCauley et al. (2017). Our approach models a hypothetical survey on the edge of the Northwest Shelf during summer. The survey area was 80 km by 36 km in water 300-800 m deep and the survey was conducted over 35 days. To simulate the movement of zooplankton by currents, we 0.5 million particles into a hydrodynamic model (CSIRO's Ocean Forecast Australia Model). Zooplankton particles could be hit multiple times by the airgun if they were carried by currents into the future survey path. Each particle represents a zooplankton population exhibiting logistic population growth. The greatest limitation in this approach was accurate knowledge of the natural growth and mortality rates of zooplankton. We thus tested the sensitivity of the model to different recovery (growth-mortality) rates, and also the sensitivity of our results to ocean circulation by undertaking simulations with and without water motion. We report the relative zooplankton – the ratio of zooplankton biomass following a seismic survey relative to biomass in the absence of a survey, from 0 (all dead) to 1 (no impact). We report results on four regions relevant to management and of varying size.

Results: Simulations that included ocean circulation showed that the impact of the seismic survey on zooplankton biomass was greatest in the *Survey Region* (0.78, i.e., 22% of the zooplankton biomass was removed) and declines moving to the *Survey Region + 15 km* (0.86), and the *Survey Region + 150 km* regions (0.98, see Table for values); there was no discernible effect on the entire *Northwest Shelf Bioregion*. The time to recovery (to 95% of the original level) for the *Survey Region* and *Survey Region + 15 km* recovery was 39 days (38-42 days) after the start of the survey and 3 days (2-6 days) after the end of the survey.

Simulations with no ocean circulation showed a much greater impact of the seismic survey on relative zooplankton biomass: 0.65 for the *Survey Region*; 0.78 for the *Survey Region + 15 km*; 0.97 (0.97-0.97) for the Survey Region + 150 km; and no discernible effect on the entire *Northwest Shelf Bioregion*. The time to recovery for the *Survey Region* from the start of the survey was 64 days (49-100 days) and from the end of the survey was 26 days.

Discussion: Applying the mortality rate from McCauley et al. (2017), we found substantial impact within the seismic survey area and within 15 km of it. However, these impacts are not discernible at the largest scale of the *Northwest Shelf Bioregion* and are barely discernible within 150 km of the survey area. Zooplankton populations recovered quickly after seismic exposure due to their fast growth rates, and the dispersal and mixing of zooplankton from both inside and outside of the

impacted region. Finally, we make suggestions about how future studies could be designed and optimized using tools developed in the current study – to test the findings of McCauley et al. (2017).

1 Introduction

1.1 Seismic Surveys

Seismic surveys are used to produce detailed images of local geology to determine the location and size of possible oil and gas reservoirs. During a survey, the seismic vessel traverses a series of pre-determined sail lines within a survey acquisition area, generally at a speed <5 knots. As the vessel travels along the survey lines, a series of intense noise pulses are generated by releasing compressed air from the acoustic source (every 7-10 seconds depending on shot point interval), which is directed down through the water column and seabed. The released sound is attenuated and reflected at geological boundaries and the reflected signals are detected using sensitive microphones arranged along hydrophone cables (streamers) towed behind the seismic vessel. The reflected sound is then processed to provide information about the structure and composition of geological formations below the seabed to identify hydrocarbon reservoirs. Seismic surveys are widespread throughout the world and around the Australian coast.

1.2 Impacts of sound waves on marine life

Mammals and fish: Impacts of noise from seismic surveys are of particular concern in marine environments because sound travels faster, further, and with more energy (lower attenuation) in water than in air (Day et al. 2016). There are particular concerns on the impact of seismic sound on marine mammals (Gordon et al. 2004) because they have a well-developed auditory system (Southall et al. 2007). Marine mammals use sound in social interactions, foraging, orientation, and in predator avoidance, and anthropogenic sound can interfere with these functions by altering behaviour and physiology (Southall et al. 2007).

Fish have two auditory systems – the inner ear and the lateral line system (Slabbekorn et al. 2010). Impacts of underwater sound on fish can mask acoustic communication (e.g. in spawning) (Slabbekorn et al. 2010), induce physiological (hormonal) changes (Slabbekorn et al. 2010), and alter behaviour (Pearson et al. 1992, Kastelein et al. 2008, Fewtrell & McCauley 2012). Many fish also have swim bladders, a gas-containing organ used for buoyancy, and those with large swim bladders are potentially more affected by pressure changes (Keevin & Hempen 1997).

Zooplankton: Zooplankton are animals that float and although they can swim, they can’t progress against currents. Most zooplankton are microscopic, but some such as jellyfish can be up to 40 m long. About 75% of the zooplankton are copepods, small crustaceans that are the most abundant multicellular animals on Earth. Zooplankton can be split into those that spend their entire life floating around in the plankton such as copepods (the holoplankton) and those that only spend part of their life cycle in the plankton such as eggs and larvae (young stages) of fish, crabs, lobsters, prawns, seastars, mussels and oysters (the meroplankton).

Less research has been conducted on effects of seismic noise on zooplankton because, unlike vertebrates, zooplankton do not have hearing structures (although they can sense pressure change) and their bodies are generally the same density as the surrounding water so sudden pressure changes associated with seismic activity are presumed to not cause physical damage (Parry & Gason 2006). Few studies have reported negative impacts on zooplankton (including meroplankton or temporary members of the plankton such as fish eggs and larvae, and invertebrate larvae), and none from more than 10 m away from an airgun. Kostyuchenko (1972) found up to a 17% increase in mortality of fish eggs of various species exposed to a seismic airgun source, but no effect beyond 10 m. Kosheleva (1992) reported that plaice eggs and larvae died in great numbers 1 m away from an airgun, but were uninjured further away (cited in Parry et al. 2002). In the spiny lobster *Jasus edwardsii*, there was no impact of an airgun on the quantity or quality of hatched larvae (Day et al. 2016). Dalen and Knutsen (1987) found that captive eggs, larvae and post-larvae of cod exposed to an airgun showed no signs of injury when placed 1 m from the source. In the snowshoe crab, exposure to high levels of sound may retard the development of eggs, although this was from eggs from one individual (Christian et al. 2003), whereas the survival and growth of Dungeness crab larvae are not impacted by airguns discharging within 10 m (Pearson et al. 1994). In a study by Parry et al. (2002) in Bass Strait, there was no significant difference in the abundance of zooplankton behind the seismic survey vessel from their abundance before the passage of the vessel or 2 km distant from the vessel.

Thus, the literature currently suggests that there is limited impact of seismic activity on zooplankton, and any impact present is limited to 10 m from the source (Dalen & Knutsen 1986, Parry et al. 2002, McCauley et al. 2017). Using this 10 m impact range, a study by McCauley (1994) calculated the impact in a seismic survey area assuming plankton mortality of 100% within 10 m of an airgun and argued that the total mortality due to seismic testing would be <1% of plankton in the surveyed area.

1.3 An assessment of the study by McCauley et al. (2017)

1.3.1 Findings

The work by McCauley et al. (2017) is the first large-scale field experiment quantifying the impact of seismic activity on zooplankton. Their experiment was conducted in temperate waters of Southeast Tasmania. Sampling before and after the airgun impact, they used the sonar backscatter to measure changes in zooplankton distribution, net samples to estimates changes in zooplankton abundance, and the proportion of the zooplankton that was dead to estimate the mortality rate associated with the seismic airgun. In their study, copepods dominated the mesozooplankton (0.2-20 mm), and impacts were not assessed on microzooplankton (0.02-0.2 mm) or macrozooplankton (>20 mm). There was some movement of water through the experimental area, and this was considered by calculating the effective distances, so for example the samples that were nominally at 0, 250 and 800 m were effectively at approximately 200, 500, and 1.2 km away from the airgun because of water movement.

McCauley et al. (2017) reports three lines of evidence to show that zooplankton were affected by the seismic source: (i) the proportion of the community that is dead increased two- to three-fold; (ii) the abundance of zooplankton estimated by net samples declined by 64%; and (iii) the opening of a “hole” in the zooplankton backscatter observed via acoustics. These impacts were observed out to the maximum range assessed of 1.2 km, more than two orders of magnitude greater than the 10 m previously assumed (Dalen & Knutsen 1986, Parry et al. 2002, McCauley et al. 2017).

The increase in proportion of dead zooplankton provides the most compelling support for a negative impact of the seismic source on zooplankton. The neutral red staining method for assessing mortality of zooplankton is sensitive and robust (Elliot & Tang, 2009), although the relatively few samples collected reduces confidence somewhat (discussed below in more detail). The use of this method is a novel way for looking at seismic impacts and should be repeated in the future.

In the current work, we have interpreted and applied the results of McCauley et al. (2017) as reported. However, there are three primary questions raised by the results of McCauley et al. (2017), all of which warrant further investigation: viz. 1. Why was there no attenuation of the impact with distance? 2. Why was there an immediate decline in abundance? 3. Was there sufficient replication to be confident in the study findings?

1.3.2 Why was there no attenuation of the impact with distance?

The impulse of acoustic energy created by an airgun (or airgun array) experiences transmission loss as it propagates away from the source. The further from the source, the higher the transmission loss and therefore the lower received level. Therefore, the energy received by marine organisms will be highest closest to the airgun (or airgun array), and decay with distance. In the study by McCauley et al. (2017), there is no consistent decline in the proportion of zooplankton that are dead as distance increases, or as received level decreases. This lack of a clear attenuating impact warrants further investigation.

1.3.3 Why was there an immediate decline in abundance?

The decline in zooplankton abundance is perplexing. If zooplankton were killed, they would not immediately sink from the surface layers, or be rapidly eaten. A drop in abundance would be more likely once the dead zooplankton either sunk to the bottom or were removed by predation.

However, the lower abundance may have been associated with active avoidance of the seismic area by zooplankton. Larger zooplankton could certainly actively swim 10s of metres in an hour leaving a "hole", but the most common copepods in the present study, those of the genera *Clausocalanus* and *Paracalanus*, are small and could only swim <10 m in an hour (Kioboe 2011). If zooplankton did actively swim away, an alternative explanation of the results of the study by McCauley et al. (2017) may be that few zooplankton died because of the seismic survey, but that zooplankton actively swam away from the area, which would leave a higher proportion of dead zooplankton in the region. However, data in McCauley et al. (2017) show that the abundance of small copepods dropped just as much in as it did in larger zooplankton, suggesting that whatever happened, all zooplankton were affected.

1.3.4 Was there sufficient replication to be confident in the study findings?

The conclusions in McCauley et al. (2017) study were based on a relatively small number of zooplankton samples. A total of 24 samples were collected: 2 tows each sampling time x 3 distances from the gun (0 m, 200 m, 800 m) x 2 levels (Control, Exposed) x 2 replicate experiments (Day 1, Day 2). This means that there were only 12 samples collected under conditions exposed to the airgun, 6 on each day of the 2 experiments. The main potential confounding explanation in the study would be that a different water mass entered the area on each day of the experiment and had lower abundance and more dead zooplankton – although this is relatively unlikely it cannot be discounted because of the relatively few samples collected and only two replicate experiments conducted.

1.4 Scope of current modelling work

Here we estimate the spatial and temporal impact of seismic activity on zooplankton on the Northwest Shelf from a large-scale seismic survey, considering mortality estimates of McCauley et al. (2017), and accounting for typical growth rates, natural mortality rates, and the ocean circulation in the region.

The Northwest shelf was chosen following discussions with APPEA, as it is an area of large-scale seismic surveys. We focus on summer when seismic survey in the area are typically conducted. Unfortunately, owing to time constraints, it is not possible to apply our modelling approach to other seasons or regions outside the Northwest shelf, although we will comment on the broad applicability of our findings to other areas. There is also insufficient time to investigate ecosystem impacts on trophic levels above zooplankton (e.g. fish, marine mammals, seabirds).

2 Methods

We simulate the large-scale impact of a seismic survey on zooplankton populations, assuming mortality rates associated with airgun exposure reported by McCauley et al. (2017). Our approach models a typical seismic survey on the Northwest Shelf and simulates zooplankton growth, movement by currents, and mixing of populations over the entire region to assess the impact of a seismic survey on zooplankton populations both within and outside the survey area.

2.1 A generic seismic survey design

To represent a generic seismic survey, a hypothetical survey was developed by APPEA using SurvOPT software. APPEA provided a nominal survey location, located on the Western Australian North West shelf edge of the outer Carnarvon Basin, in water depths ranging from 300 to 800 m. The proposed survey acquisition area was 80 km by 36 km, covering an area of ~2,900 km^2, and was assumed to occur in the summer (Figure 1).

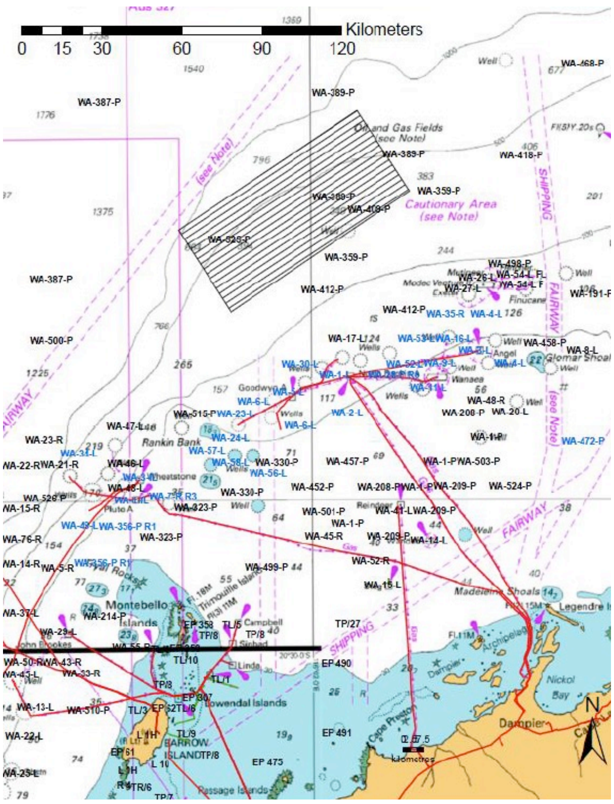


Figure 1. Study region of the Northwest Shelf.

Seismic survey technical specifications have an influence on the temporal and spatial coverage of the survey and were selected to reflect a typical industry standard seismic survey. The proposed modelled survey had a 12 x 7000 km streamer length, 100 m streamer spacing, vessel acquisition speed of approximately 4.1 knots and source shot spacing of 18.75 m (Table 1). The spacing between each adjacent survey line is 600 m, resulting in a total of 60 survey lines. The vessel turn radius was modelled at 3.5 km, resulting in a consecutive line spacing of 7 km with acquisition design reflective of the industry standard racetrack style design (Figure 2).

Table 1. Modelled survey parameters.

Parameter	Modelled Survey
Survey Acquisition Area	2900 km^2
Survey sail line distance	4831.7 km
Survey line distance	80 km
Number of survey lines	60
Range of survey water depth	300 m to 800 m
Survey commencement date, duration	January, duration ~35 days
Airgun capacity	~3,000 – 3200 in^3
Operating pressure	Nominally 13,800 kPa (2,000 psi)
Planned distance between adjacent seismic lines	600 m
Planned distance between consecutive seismic lines	7 km
Shotpoint interval	18.75 m
No. of streamers	12
Streamer length	7 km

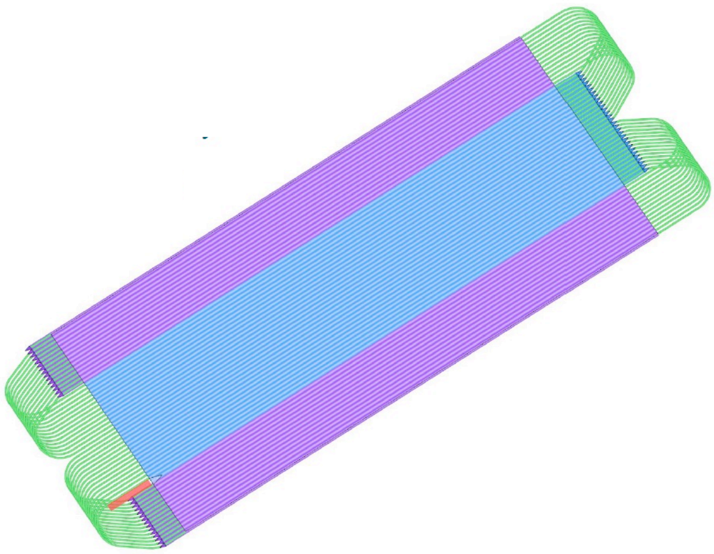


Figure 2. The layout of a typical seismic survey used in the zooplankton modelling.

Operational planning would estimate ~43 days to acquire this survey, which takes into consideration 10% weather down time, 5% infill (re-acquisition due to marine mammal shutdowns or streamer drift) and 5% operational standby (equipment failure or shutdown time for marine mammals). However, for the purposes of this modelling study the proposed survey plan assumed no weather or operational down time and no infill, resulting in a continuous survey duration of approximately 35 days. The survey polygon coordinates and every coordinate and timestamp that the source was active (every 18.75 m for every line) was provided to CSIRO by APPEA as an input into the model.

2.2 Scaling-up findings of McCauley et al. (2017) to a commercial survey

McCauley et al. (2017) used a single 150 cui airgun during their study, substantially smaller than a typical 3000-3200 cui commercial seismic survey array. To account for this the distance that they measured an impact on zooplankton was scaled up to be applicable to a larger survey.

The measured airgun received levels from the 150 cui within McCauley et al. (2017) were extrapolated to a larger 3000-3200 cui commercial survey array using a dataset of measured levels of commercial seismic surveys within the Northwest Shelf as provided by Associate Professor Robert McCauley. The dataset included measured received levels of six commercial arrays (3040-3147 cui) in approximately 180-500 m water depth. Using these measured levels, the 178 dB re 1 µPa PK-PK pressure received level associated with the range of 1.2 km for the 150 cui airgun within McCauley et al. (2017) correlated to an equivalent range of 2,526 m for a 3040-3147 cui airgun array.

The simulated survey in the model reflects a typical survey done in the Northwest Shelf area in the month of January. The simulated survey consists of 60 survey lines that were approximately parallel to the coast in approximately 300-800 m deep water (Figure 2). Each simulated survey line took 12 hours to complete with an additional 2-hour period required to turn the vessel around before starting the next survey line. While performing the survey line, the impact zone was set to be 2.5 km around the seismic source. The seismic impact zone along the survey line was binned into 2 hour periods, thereby creating a fixed impact zone of 2-hour duration before moving to the next impact zone along the survey line (Figure 3). The entire column of water within the impact region was equally impacted.

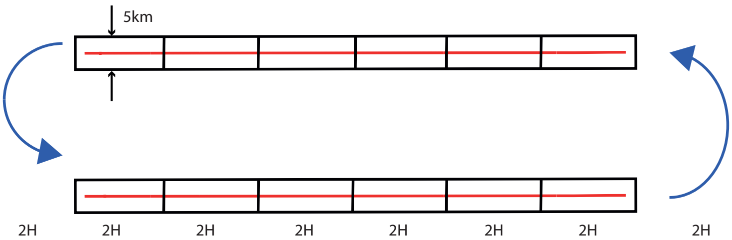


Figure 3. The model implementation of the survey line and impact area in the model. The impact of the survey is applied every 2 hours, shown as black rectangles, the size of this box representing the impact zone around the seismic line (red dashed). Each line takes 12 hours to complete, which is followed by a 2 hour turn around for the seismic ship, before commencing upon the next survey line (7 km apart).

2.3 The particle model

To simulate the movement of zooplankton by currents in the study area, we have used the simulated ocean circulation from CSIRO's Ocean Forecast Australia Model (OFAM) to represent the upper ocean circulation around Northern Australia. The circulation information consists of near global daily averaged horizontal and vertical ocean currents at a horizontal resolution of 0.1 degrees. We have chosen the summer of 2003 as being typical (neither a strong El Niño or La Niña was present). Using this circulation information, we initially seed the domain on January 1, 2003 with particles at

5 depths (5 m, 100 m, 200 m, 300 m and 400 m) uniformly distributed at a horizontal resolution of 0.025 degrees. We start with ~0.5 million particles. From this initial state, particles move with the ocean currents and we record their location every 2 hours from January 1, 2003 until March 1, 2003 to provide tracks for each particle.

We use the particle trajectories and simulated seismic survey to quantify the impact of the survey on the zooplankton population. For each 2-hour period over 12 hours (Figure 3), we determine whether a given particle is located in a seismic impact zone and apply the seismic mortality term if it is. Following this there is a 2-hour period of no seismic surveying as the ship turns to start a new survey line. The particles move with the ocean currents so their locations change with time which cause them to move in and out of the seismic survey impact zone.

The particle tracking approach provides a convenient way to capture the movement of a passive particle in the ocean and enables us to use each particle to represent a population of zooplankton. Hence, each particle represents a population of zooplankton that could potentially be impacted by the seismic survey. For each particle, we consider two different zooplankton populations: 1) a population that is not impacted by the seismic survey; and 2) a population that is impacted by the survey. To quantify the impact of the survey we compute the relative differences between these two zooplankton populations and show the temporal evolution of zooplankton populations.

2.4 The zooplankton model

For both zooplankton populations, we consider a simple equation to represent the temporal evolution of the zooplankton attached to a particle by:

$$\frac{dZ}{dt} = rZ(1 - \frac{Z}{K}) \qquad (1)$$

where the equation gives the change in zooplankton biomass with time and r represents the recovery rate (net growth rate = maximum growth rate minus mortality) of zooplankton to any perturbation and K is the carrying capacity of the zooplankton population (maximum biomass). At steady-state, $Z = K$.

The recovery rate of the zooplankton (r) was set to 0.10 per day. The recovery rate is difficult to estimate as it is the net growth rate considering both maximum growth rate (reasonably well known – see Hirst & Bunker 2003) and the natural mortality rate (dependent upon starvation and predation), which is rarely known in wild zooplankton populations. Typical recovery rates for zooplankton in the laboratory in the absence of predation are around 0.3 (Peña-Aguado et al. 2005). With a typical copepod lifecycle of 13 days at 25°C (Hirst & Kiorboe 2002), our value of $r = 0.1$ would mean that if zooplankton biomass was knocked down to 10% of its carrying capacity, it would recover (within 95% of its carrying capacity) in 4 complete lifecycles. If zooplankton biomass was knocked down to 50%, it would recover in a bit over 2 complete lifecycles. To reflect the uncertainty in recovery, we consider it could range between 0.05 and 0.15 per day.

The zooplankton population is impacted by the survey when the particle passes through a seismic impact zone, at that time we add a mortality term to the zooplankton equation to give:

$$\frac{dZ}{dt} = rZ\left(1 - \frac{Z}{K}\right) - mZ \qquad (2)$$

where m represents the mortality rate on the zooplankton.

2.5 The value of mortality associated with the seismic survey

We estimated the impact on zooplankton mortality of a seismic survey based on the Extended Data Table 2 in the Appendix of McCauley et al. (2017). These data show the results of the neutral red stain method to estimate the proportion of dead zooplankton in the samples. We calculated the mean proportion of dead zooplankton for both Control (0.19, n=12 samples) and Exposed (0.45, n=12 samples) samples across both days (both experiments had similar results), for all three zooplankton functional groups (copepods, nauplii, and other zooplankton had similar results), and for all distances (0 m, 250 m, 800 m had similar results), and giving equal weight to all samples. The extra mortality of zooplankton caused by the seismic activity is thus 0.45-0.19=0.26. This extra mortality operated only on those individuals that were alive before the seismic impact – i.e., 0.81 of the population. Thus, the mortality rate for those that are alive is: 0.26/0.81 = 0.32. This is our best estimate of mortality rate due to seismic activity. We thus calibrated our model so that it produced a decline of zooplankton abundance of 0.32 or 32% over 2 hours of impact by the seismic gun.

Therefore, we implemented the impact of $m = 0.32$ associated with a seismic survey every 2 hours on the zooplankton that is within the exposure distance of 2.5 km either side of the array (Figure 3).

2.6 Zooplankton biomass in the region

To estimate the zooplankton biomass in the Northwest region, we have used data from the Integrated Marine Observing System (IMOS) and compiled by CSIRO (Figure 4). We obtained data collected during summer, using a variety of net mesh sizes, and converted all data to wet mass. We fitted a linear model with the response being biomass (µg per litre) and predictors including mesh size as a factor (73, 100, 168, 318, 330, 500 µm), and water column depth (m) and mean chlorophyll-a (µg per litre) as continuous variables. All predictors were significant and the model explained 68% of the variance in zooplankton biomass. Although we used relative zooplankton biomass in the model (i.e., this underlying mean was removed), the actual zooplankton biomass can be calculated by multiplying the relative zooplankton biomass by this mean background level.

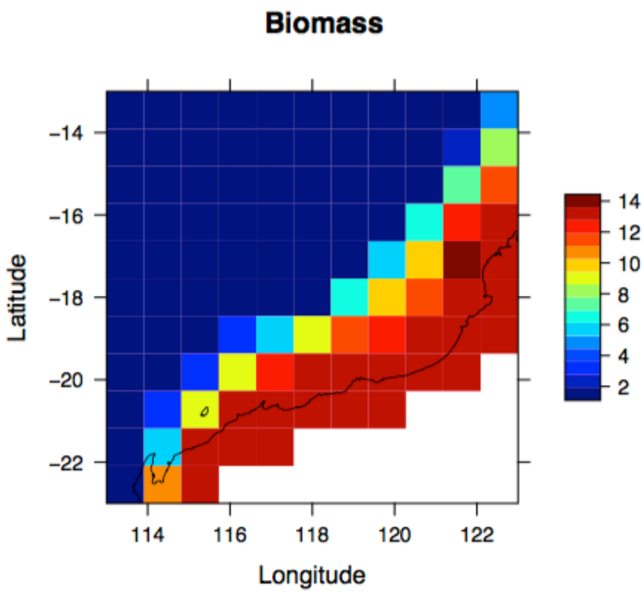


Figure 4. Map of zooplankton biomass (µg per litre) on the Northwest shelf estimated from 459 samples using a linear model with depth, chlorophyll-a and net mesh size (r^2=68%).

2.7 Simulations

Although we have calculated a map of zooplankton biomass in the region, we have not scaled the biomass to this value. Instead, to simplify interpretation, we report the “relative difference” between these two populations (one affected by the seismic survey and one not) to quantify the impact of the seismic survey. The relative zooplankton biomass thus varies from 0 to 1, with 1 being no seismic impact and 0 being death of all zooplankton following seismic exposure. The actual zooplankton biomass at any time can be calculated by multiplying the relative zooplankton value by the mean zooplankton biomass in that location (Figure 4).

In our simulations, we define recovery as happening when the zooplankton population recovers to 95% of its population. As the logistic equation never reaches the carrying capacity (K) (it asymptotes), we have defined the effective recovery period to be the time it takes for the population to reach 95% of K. To make the model results relevant to APPEA, we report results on four management units: viz. the *Survey Region*; the *Survey Region + 15 km*; the *Survey Region + 150 km*; and *the Northwest Shelf Bioregion* (Figure 5). Our first set of simulations included ocean circulation, and the second set had the ocean circulation switched off to quantify the importance of ocean circulation.

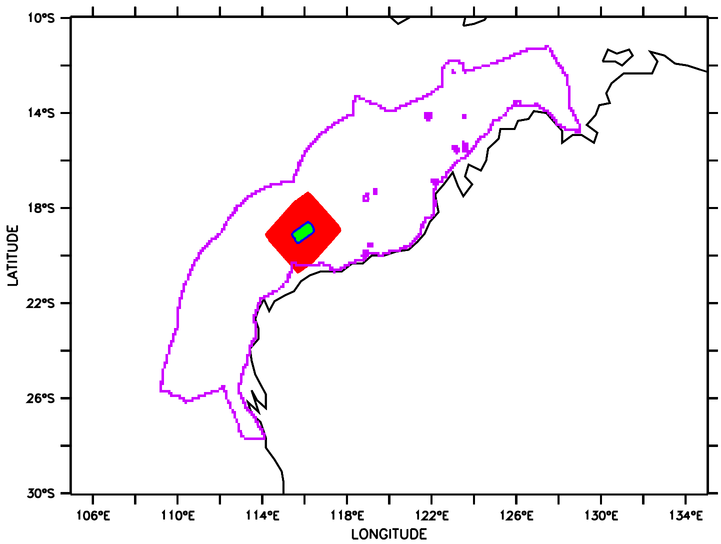


Figure 5. The impact regions for the seismic survey. The purple line represents the boundary of the Northwest Bioregion; the red shading represents the far-field impact region defined as 150 km from the survey line; the blue shading represents the near-field impact region defined as 15 km from the survey line; and the green represents the impact region of the survey defined as the survey line with a 2.5 km impact zone.

We also combine all particle trajectories to produce a spatial map of the impact every 2 hours and present snapshots throughout the survey and recovery period.

3 Results

3.1 The behaviour of simulated zooplankton

To help visualise the behaviour of the simulated zooplankton, we show an example of the temporal evolution of a zooplankton population that is impacted by a seismic survey in the first 2 hours of the simulation (Figure 6a). We can see that the simulated zooplankton particle is knocked down to 0.68 of its initial value (i.e. based on the exposed mortality, $m = 0.32$) by the simulated seismic survey. The value of the recovery rate sets how rapidly the zooplankton population recovers from the impact of seismic survey (Equation 2). A zooplankton particle impacted once by the survey recovers to 95% of its original biomass in 11, 18 and 41 days for recovery rates of 0.05, 0.10, and 0.15 per day respectively (Figure 6b).

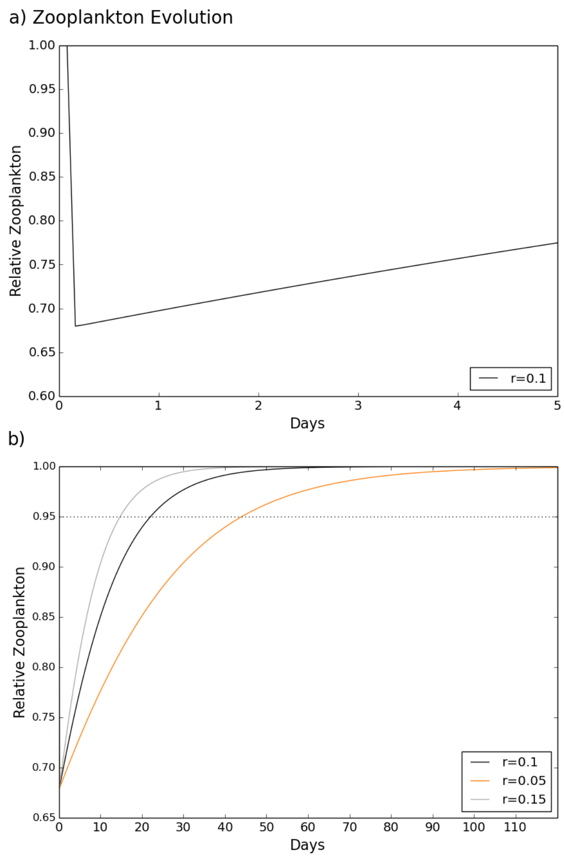


Figure 6. Simulated temporal evolution of the relative zooplankton biomass for the case where a seismic survey impacts the zooplankton for the first 2 hours of the simulation. a) The response over 5 days using a recovery rate of 0.1 per day. b) The same zooplankton evolution for an expand time scale of 120 days along with two additional simulations using recovery values (r=0.05 and 0.15 per day). The dashed line represents when zooplankton biomass has recovered to 0.95 of its original or pre-impacted level.

Sometimes zooplankton particles are hit multiple times by the airgun if they are carried by currents into the future path of the survey. If this happens 9 days apart, the zooplankton has recovered to near its original value before it is exposed again (Figure 7a). However, if this happens 1 day apart, the zooplankton biomass is knocked down to a much lower level (Figure 7b).

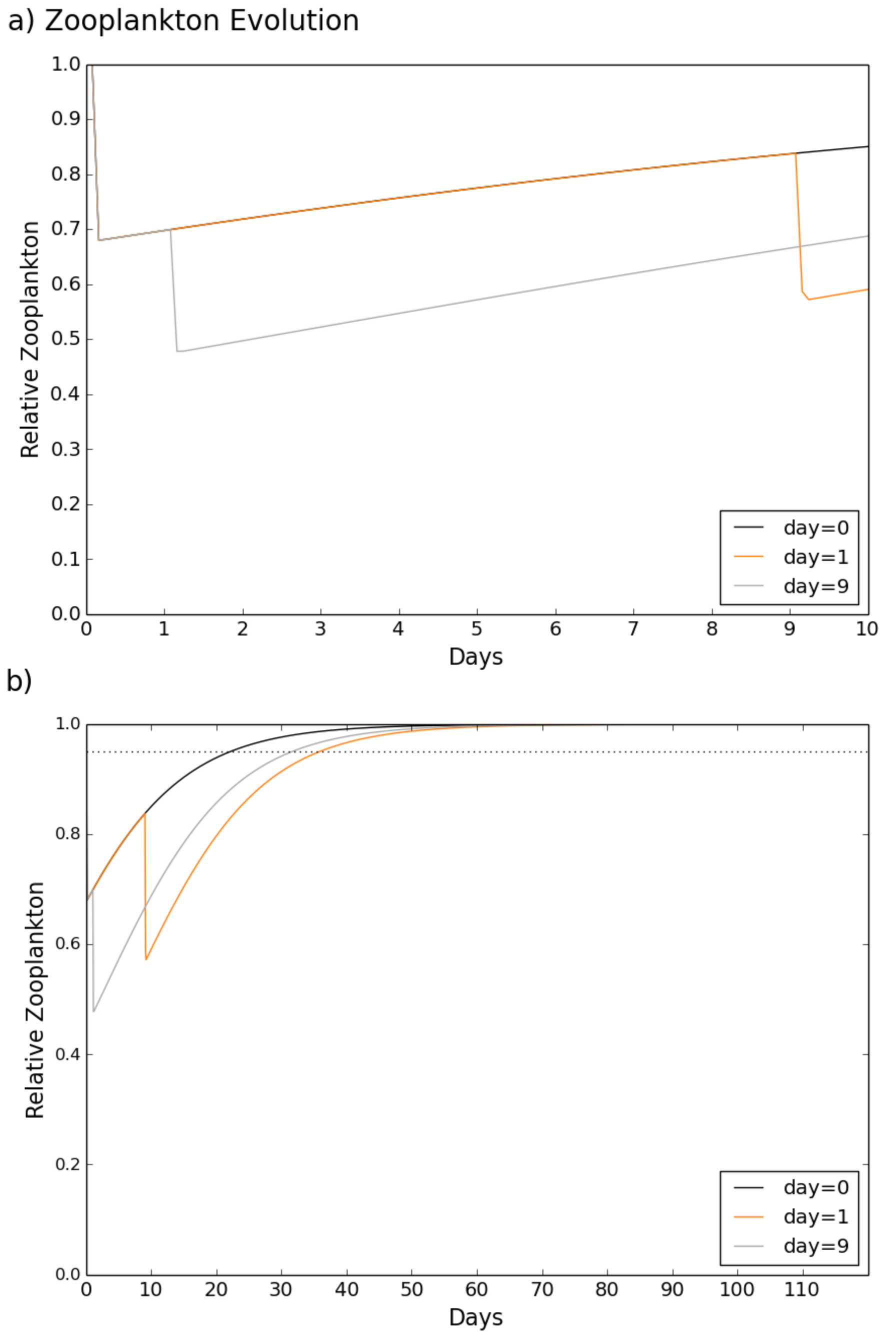
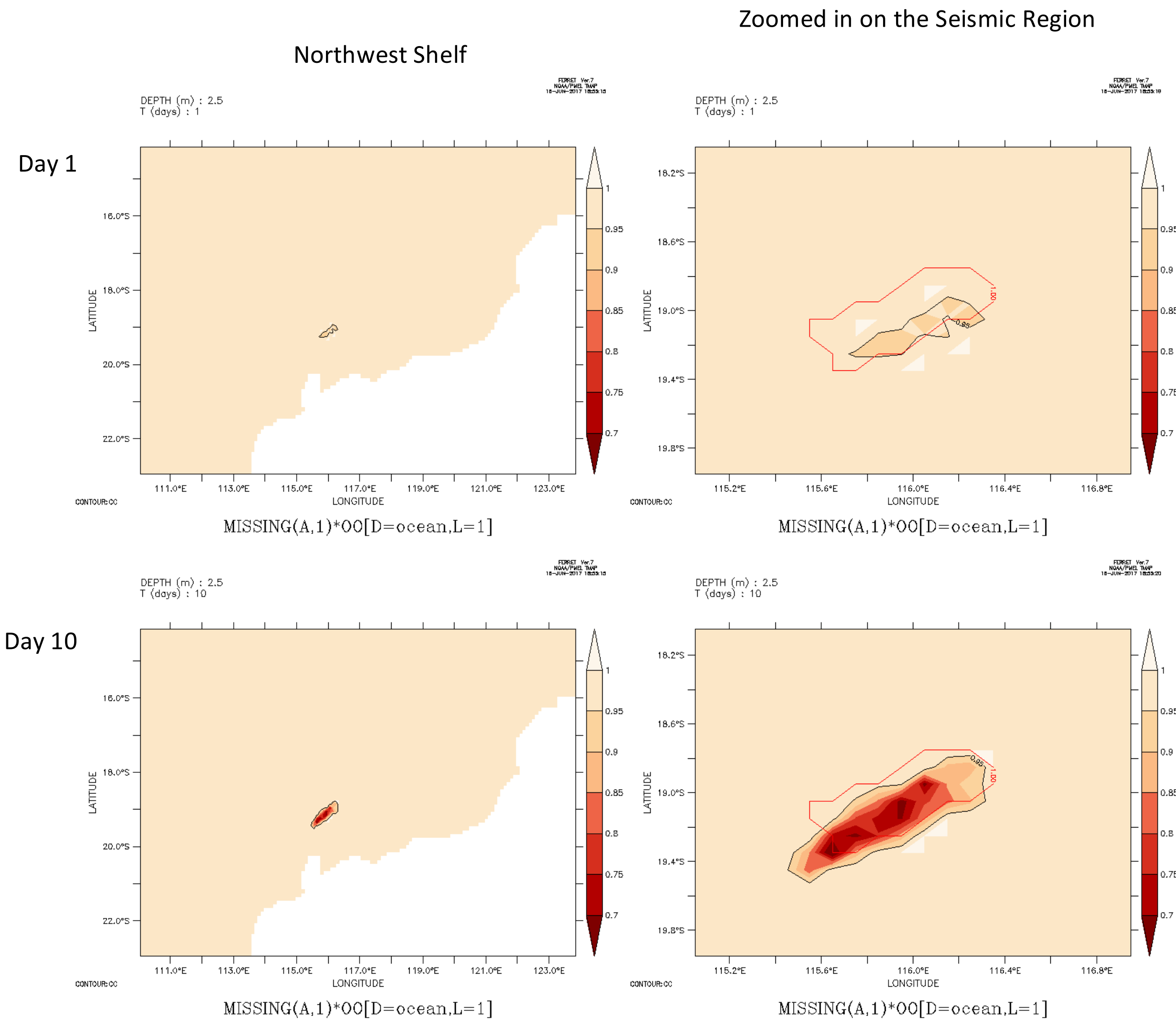


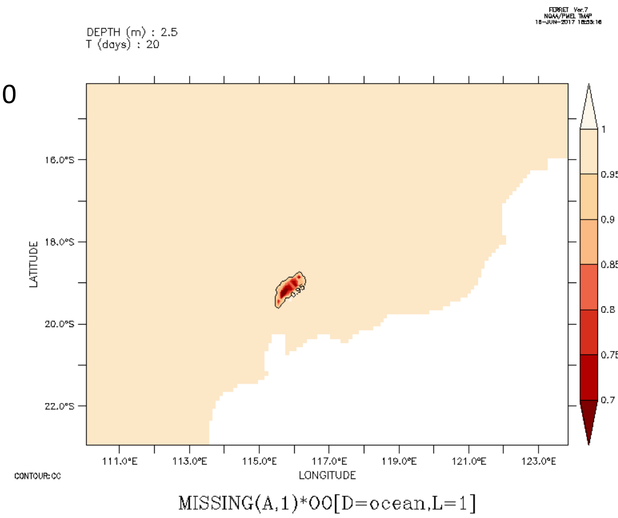
Figure 7. Simulated temporal evolution of the relative zooplankton biomass (with $r = 0.1$) for the case where a seismic survey impacts a zooplankton particle twice: on Day 0 and Day 1 and on Day 0 and Day 9 versus the simulation with the impact only on Day 0. b) Same as a) but extending the timescale to 120 days.

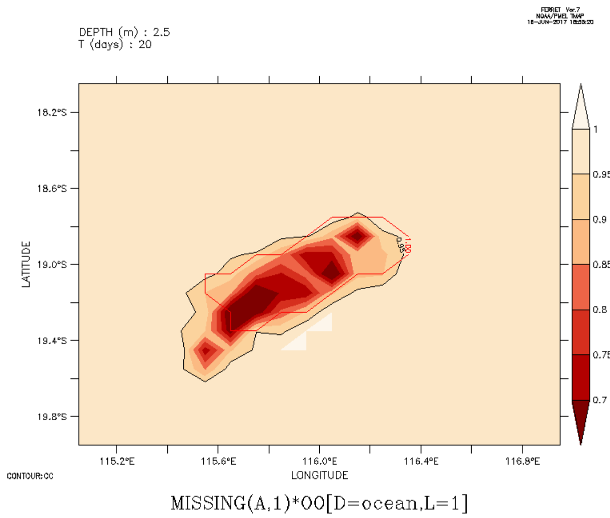
3.2 Impact maps over time

The impacted patch of water grew in spatial extent during the 35-day seismic survey and extended beyond the survey extent (Figure 8; see movies at https://www.appea.com.au/wp-content/uploads/2017/07/mov1.gif and https://www.appea.com.au/wp-content/uploads/2017/07/mov2.gif). The impact zone expands in area until around Day 20 and the impacted zooplankton particles are transported south and west of the seismic zone. By Day 60 the zooplankton has recovered to pre-impact levels.

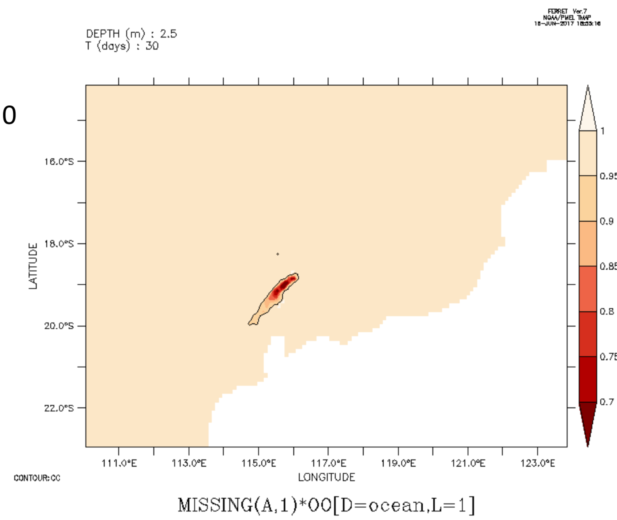


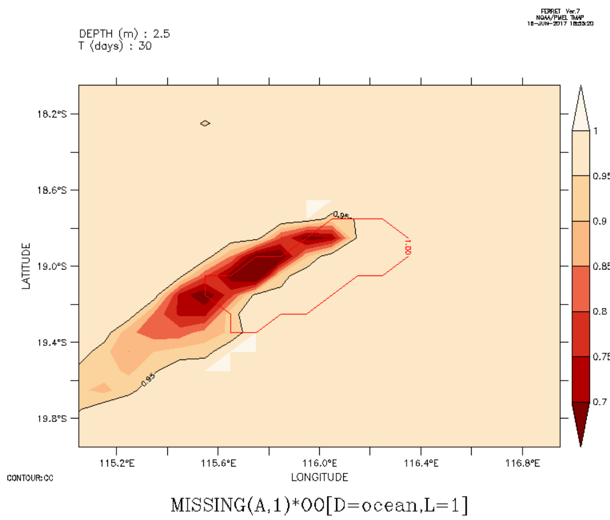
Day 20



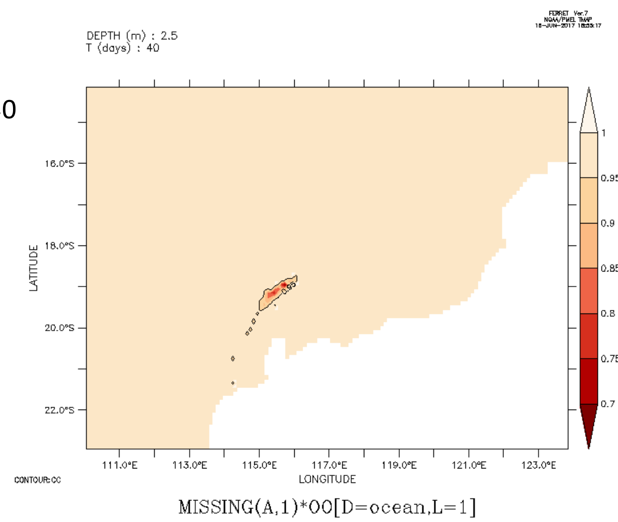


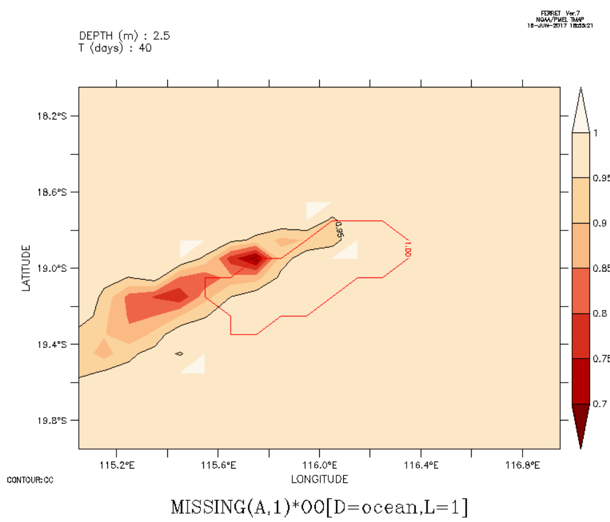
Day 30





Day 40





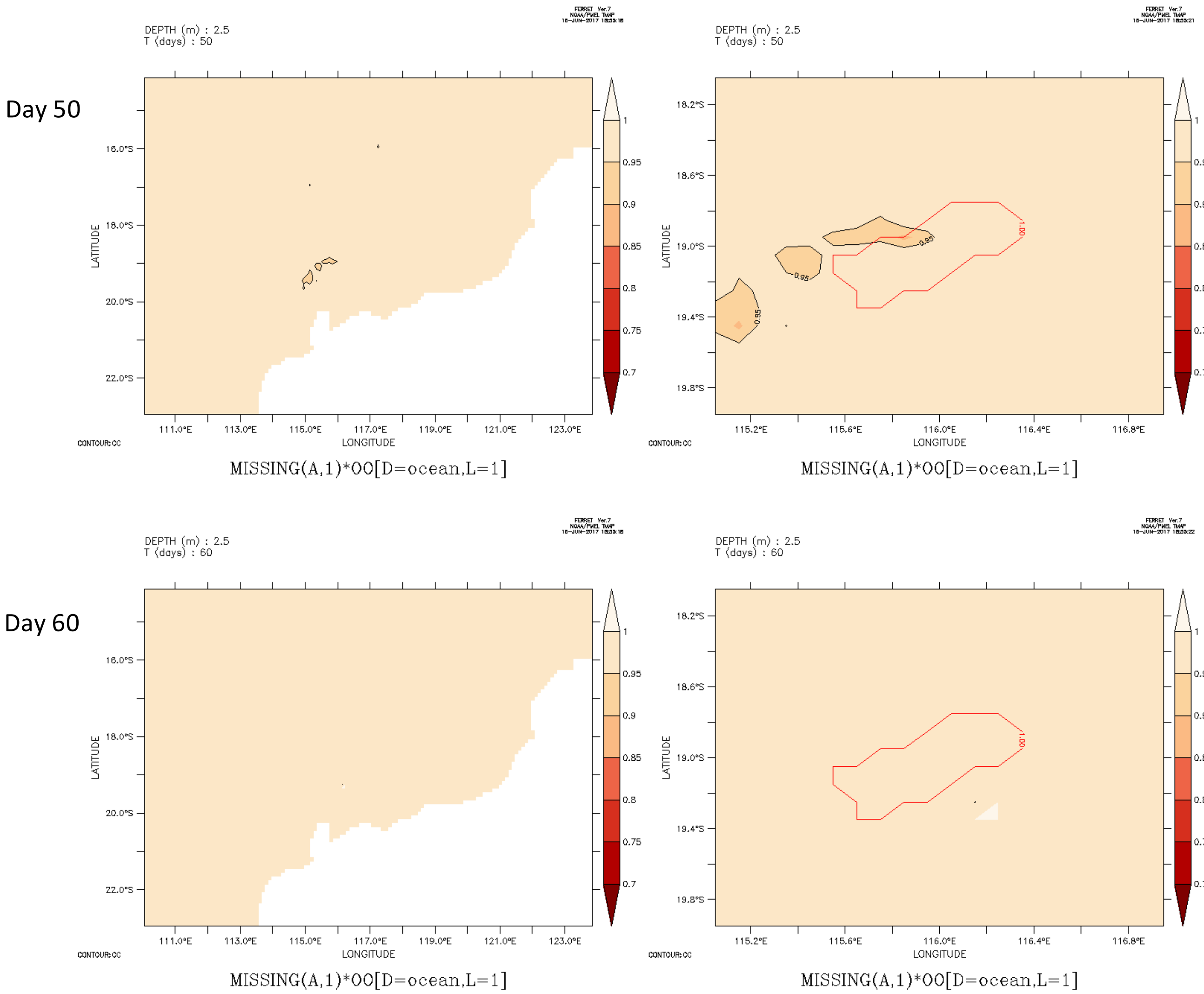


Figure 8. Impact maps for a recovery rate r=0.1 for 10 day intervals at the size of the Northwest Shelf (left) and the zoomed into the Survey Region (right). The red contour line denotes the approximate location of the seismic survey and black contour line denotes a decline in the impacted zooplankton to 0.95 of the non-impact population. The seismic survey was conducted from Day 1 to Day 35. Movies of this simulation are available from APPEA (http://).

Within the survey region, ~1-2% of the total number of particles are impacted in any 12-hour period (Figure 9), the time required to survey one line. There is little difference between the simulations with and without circulation, although the total number of particles impacted in the simulation including circulation is less variable than the simulation with no circulation. The number of particles in the survey area is approximately independent of circulation – i.e. over that timespan on average what comes in, goes out, keeping the total number of particles similar. When the survey stops at Day 35 the are no more impacts.

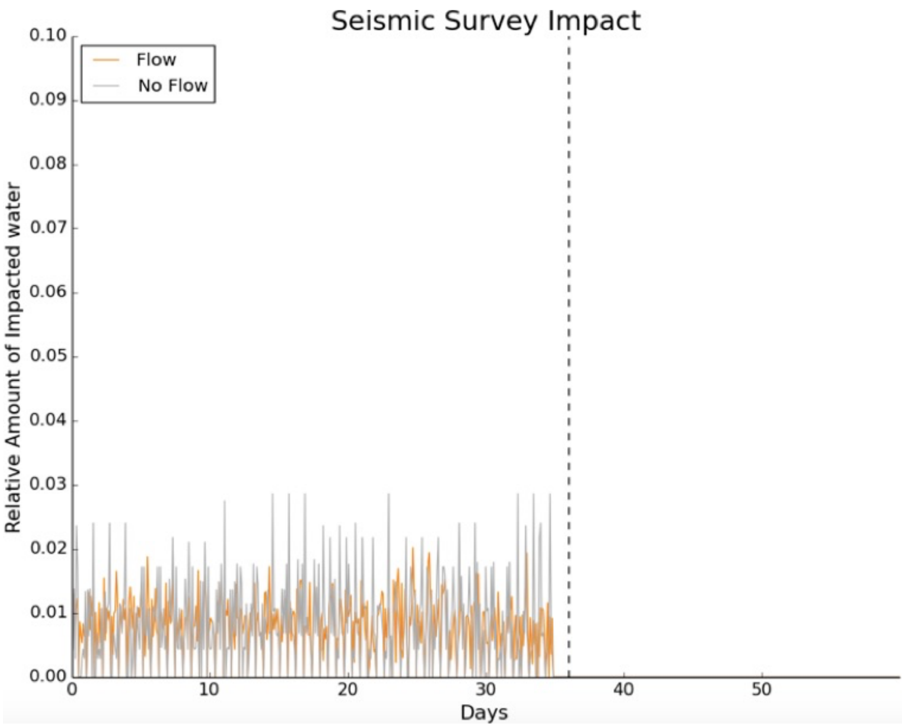


Figure 9. The relative amount of impacted water (the fraction of particles impacted) within the seismic survey region, for simulations with flow (including circulation) and no flow (no circulation).

3.2.1 Frequency distribution of relative zooplankton biomass over time

The frequency distribution of zooplankton biomass (exposed relative to non-exposed) in the seismic survey region for 10-day time periods (Figure 10). At any time period, most of the particles in the survey region are not impacted by seismic noise (i.e., relative biomass values close to 1). The distribution is strongly left-skewed distribution, with a small number of particles (<2%) with relative biomass values down to nearly 0.4 (i.e. 40% of the zooplankton biomass). At the start and end of the simulation, most of the particles are not impacted, and the maximum number of heavily impacted particles are from Days 20 to 40. Near the end there are only a few particles with large impact; once a particle has been heavily impacted (i.e., <0.6) it is slow to recover.

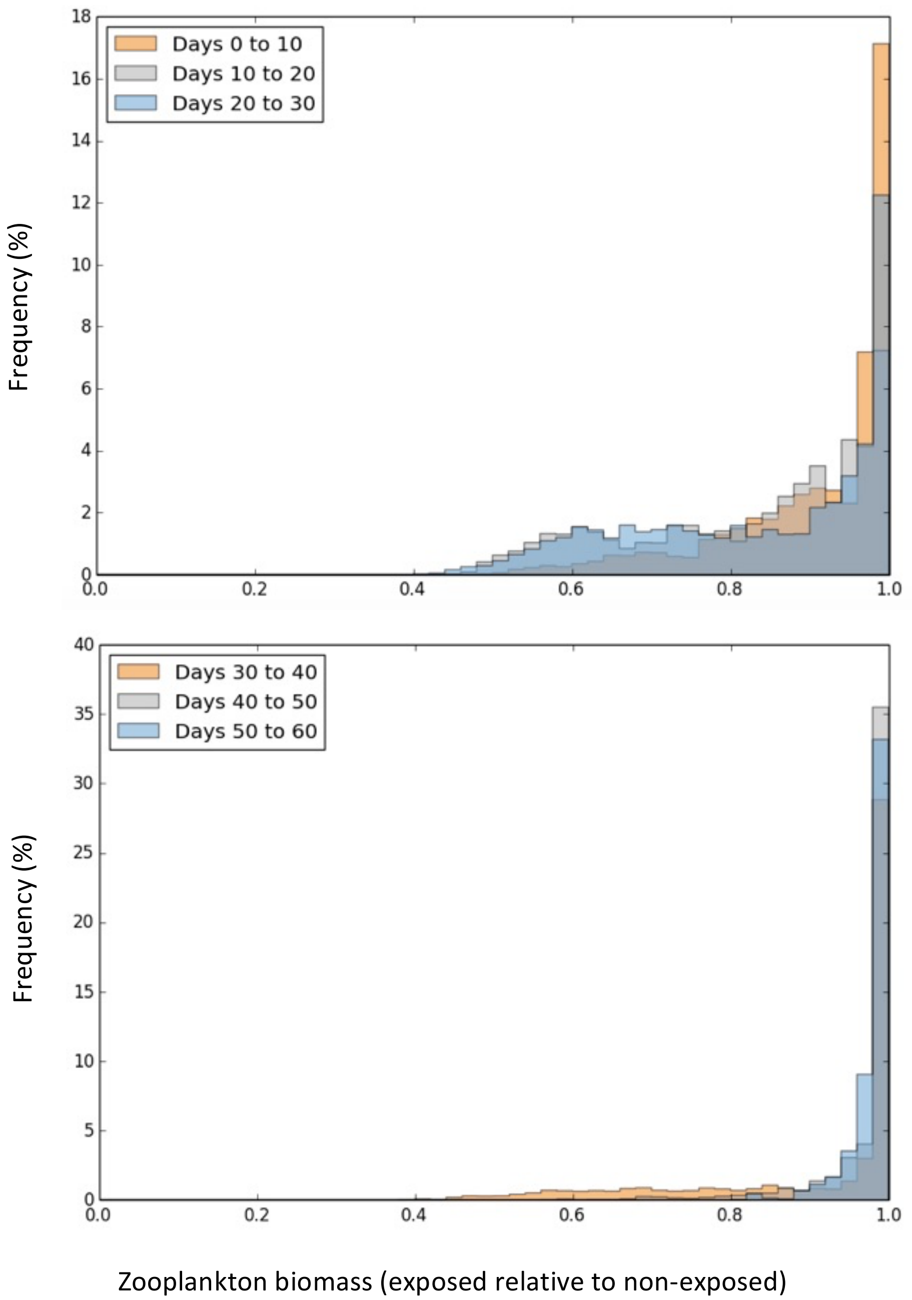


Figure 10. The frequency distribution of zooplankton biomass (exposed relative to non-exposed) in the seismic survey region for 10-day time periods.

3.2.2 Temporal evolution of zooplankton biomass in management regions

Including ocean circulation

The impact of the seismic survey on zooplankton biomass in the four management regions and considering ocean circulation is greatest in the *Survey Region* and declines moving to the *Survey Region + 15 km* and the *Survey Region + 150 km* regions (

Figure 11). The largest effect of the seismic survey on relative zooplankton biomass was: 0.78 range: 0.75-0.81) for the *Survey Region*; 0.86 (0.84-0.88) for the *Survey Region + 15 km*; and 0.98 (0.98-0.98) for the *Survey Region + 150 km*; and there is no discernible effect on the entire *Northwest*

Shelf Bioregion (relative zooplankton biomass close to 1). The zooplankton biomass generally shows a decline until Day 22, and it then increases until the end of the survey on Day 36. This reflects the movement of water through the survey region and the recovery of the zooplankton as they move into non-impacted areas. As the impacted zooplankton move out of the survey region, the most impacted zooplankton are no longer in the survey region and this causes the overlapping of the lines representing the 15km+ and survey region in Figure 8.

The time to recovery for simulations with circulation was relatively quick: for the *Survey Region* and *Survey Region + 15 km* recovery occurred by day 39 (38-42 days) or 3 days (2-6 days) after the completion of the survey.

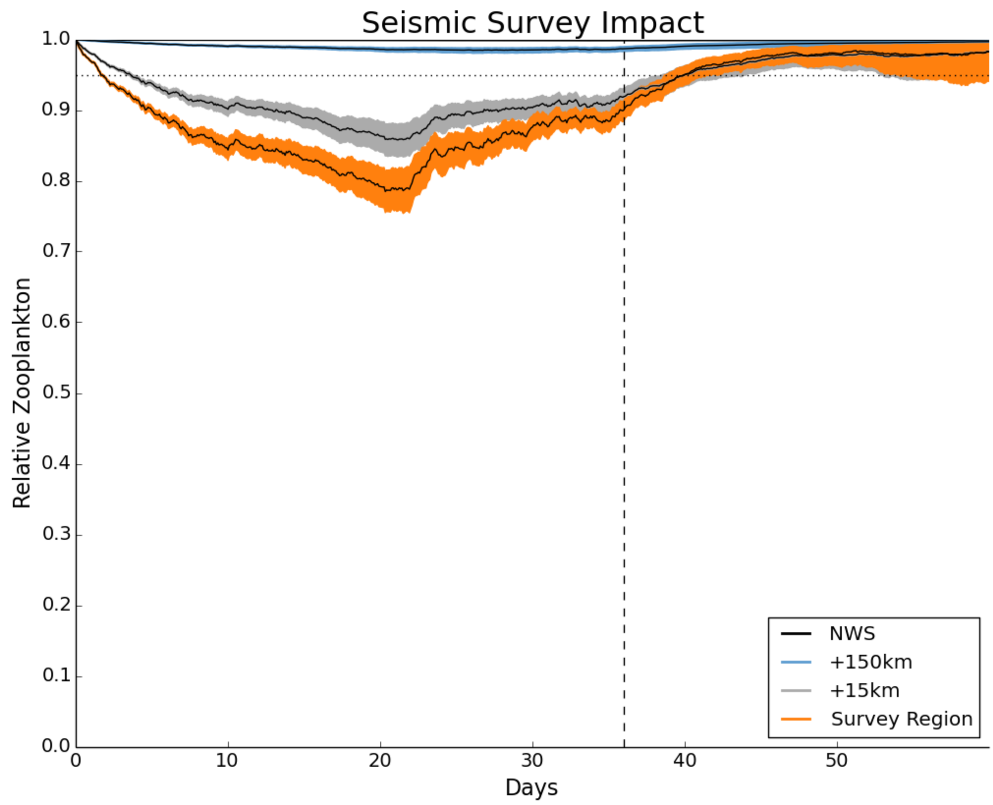


Figure 11. The temporal evolution of the relative zooplankton biomass compared to the non-impact simulation for four management regions (*Seismic survey*, *Seismic Survey + 15 km*, *Seismic Survey + 150 km* and the *Northwest Shelf Bioregion*). The shading for each region comes from the simulations using recovery values r of 0.05 and 0.15 per day, with the 0.1 per day value denoted by the black line in the middle of the shaded regions. The dotted line represents when zooplankton biomass has recovered to 0.95 of its pre-impacted level and vertical dashed line denotes the completion of the survey.

Without ocean circulation

Simulations without ocean circulation had a much greater impact on zooplankton biomass (Figure 12). The largest effect of the seismic survey on relative zooplankton biomass was: 0.65 (0.50-0.73) for the *Survey Region* around Day 36 (the end of the survey period); 0.78 (0.83-0.72) for the *Survey Region + 15 km* on Day 22; 0.97 (0.97-0.97) for the Survey Region + 150 km on Day 25; and no discernible effect on the entire *Northwest Shelf*.

The time to recovery in the *Survey Region* occurs on day 64 (49-100 days) or 26 days after the completion of the survey (13-64 days). For the *Survey Region + 15 km* recovery occurred on day 57 (45-70 days) or 21 days (9-34 days) after the completion of the survey.

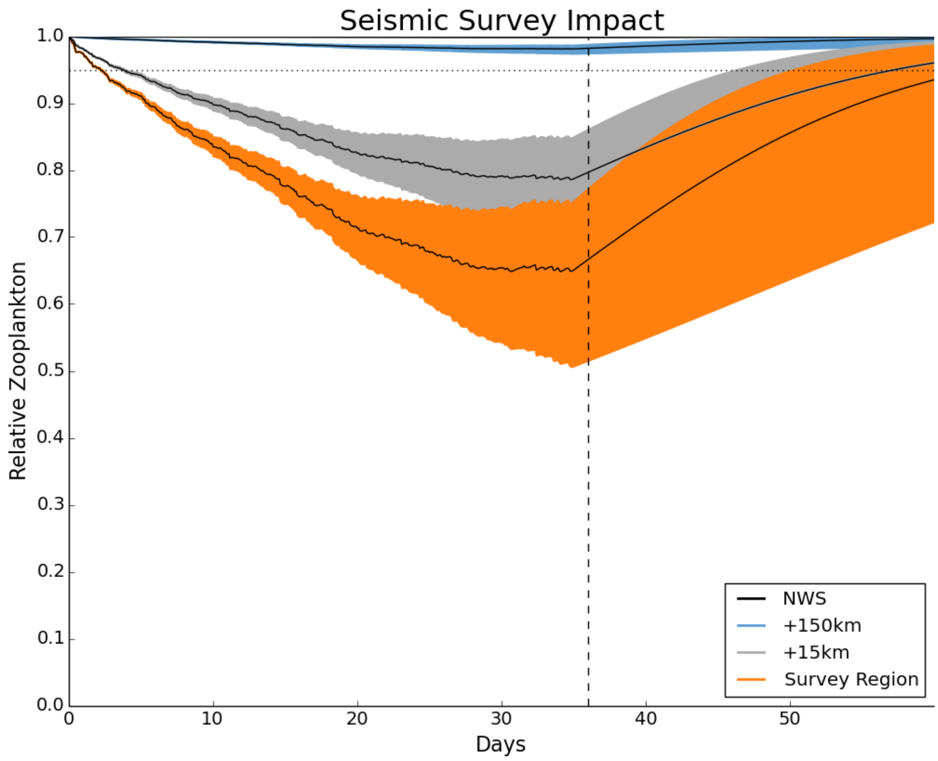


Figure 12. As in Figure 10, but without ocean circulation. The temporal evolution of the relative zooplankton biomass compared to the non-impact simulation for four management regions (*Seismic survey*, *Seismic Survey + 15 km*, *Seismic Survey + 150 km* and the *Northwest Shelf Bioregion*). The shading for each region comes from the simulations using recovery values r of 0.05 and 0.15 per day, with the 0.1 per day value denoted by the black line in the middle of the shaded regions. The horizontal dotted line represents when zooplankton biomass has recovered to 0.95 of its pre-impacted level and vertical dashed line denotes the completion of the survey.

4 Discussion

4.1 Major findings

We found there was substantial impact of seismic activity on zooplankton populations on a local scale within or close to the survey area, with a maximum decline of 22% in zooplankton populations in the survey area, 14% within 15 km of the survey area. However, on a regional scale the impacts were minimal: 2% within 150 km, and not discernible over the entire *Northwest Shelf Bioregion*. We also found that the time for the zooplankton biomass to recover to a pre-seismic survey inside the seismic area and within 15 km was only 3 days following the completion of the survey. The relatively quick recovery was due to the fast growth rates of zooplankton, and the dispersal and mixing of zooplankton from both inside and outside of the impacted region.

4.2 Applicability to other areas and potential for minimizing seismic impact on zooplankton

Our work was conducted in one area (the Northwest shelf), in one season (summer) and based on the oceanography of one representative year (2003). The findings should therefore not directly be applied quantitatively to other regions with different oceanographic conditions. However, we believe that there are a number of insights that we can draw from this work that might help inform survey design to minimize seismic impact on zooplankton. These insights also highlight which regions, water depths, and seasons there might be more impact on zooplankton populations. We would stress, however, that a detailed study of a particular region would be needed to quantify the spatial and temporal impacts in a particular region and season.

First, surveys conducted in regions with more dynamic ocean circulation are likely to have less net impact on zooplankton. We found that switching off the ocean circulation led to a much larger reduction in zooplankton populations because they remain static. Second, surveys conducted into or across prevailing currents would ensure zooplankton particles would be less likely to be impacted multiple times by a seismic gun. Here the impact on zooplankton were greatest when ocean circulation carried zooplankton particles in the same direction as the seismic survey, as the zooplankton were exposed multiple times to the airgun. Third, surveys conducted in regions off the shelf edge are likely to have less absolute impact (although the same relative impact), as zooplankton biomass is generally lower offshore. Fourth, in seasons with lower zooplankton biomass (e.g., in winter in temperate regions), there is likely to be less absolute impact (although the same relative impact). Last, conducting seismic surveys during the day rather than the night might minimize impact on zooplankton, assuming there is attenuation of the seismic signal with depth (although this was not found in McCauley et al. 2017), as there are fewer zooplankton near the surface during the day because zooplankton vertically migrate in the water column to balance food intake and predation risks, and are generally deeper during the day.

As the oceanographic conditions are unique in different regions of Australia, the models and approach developed here should be applied in other regions.

4.3 Future work

The study by McCauley et al. (2017) was the first large-scale study of the impacts of seismic activity on zooplankton. It overturns current thinking that impacts on zooplankton are minimal, although admittedly our current knowledge is based on very few studies. However, as in all areas of science, new ideas can only gain acceptance once they have been repeated and confirmed. We suggest that it is imperative to replicate the findings of McCauley et al. (2017) in an independent, rigorous, large-scale study. A follow-on study should replicate the field experiment by McCauley et al. (2017) to confirm and quantify the negative impact of seismic activity on zooplankton.

Our suggestion would be to design an experiment that would focus on zooplankton, rather than addressing potential ecosystem-wide impacts. We suggest that investigation of seismic impacts on higher trophic levels such as micronekton, fish and seabirds and the effect on carbon sequestration, microbial breakdown and trophic efficiency would better be addressed after the impact on zooplankton was confirmed. It is beyond the scope of the current project to design fully a field experiment, but we suggest that such a study would best be undertaken in an area of high zooplankton biomass, weak currents, a large and stationary seismic source, with comprehensive zooplankton sampling to a greater distance from the seismic source and over time, and using the models (such as those developed in the current study) to best design the experiment (see Appendix A for more details).

4.4 Model caveats

As with all modelling studies, there are many caveats associated with our study. First, the oceanographic circulation for the Northwest Shelf was taken from a single year (2003) and a single season (summer). Here, we did not consider inter-annual and seasonal variations in ocean circulation. Second, although we make some generalizations, the applicability of this study to specific regions should be done with some reservations, considering the local and regional oceanography. Further, zooplankton growth rates are slower in colder regions, and so the recovery rate of zooplankton populations following exposure to seismic activity is likely to be slower. Third, we did not consider impacts on other parts of the ecosystem – not considering these might have implications for the recovery rate of zooplankton. For example, if phytoplankton were also killed during seismic surveys, then zooplankton might recover more slowly than expected because they have no food to eat. But if vertebrate (fish) and invertebrate (other zooplankton) predators of zooplankton were killed, then zooplankton might recover more quickly because they are not eaten. Fourth, there is limited information on the mechanism by which zooplankton are affected by seismic activity, and this limits how we can model it. We do not know whether all life stages (eggs, larvae, juveniles, adults) are equally impacted. In light of this lack of knowledge, we have modelled zooplankton simply, using the logistic equation. However, the energy must attenuate as one moves away from the source. Fifth, we used a simple zooplankton model with no behaviour such as diel vertical migration. Diel vertical migration is likely to lead to greater mixing of zooplankton populations and potentially a reduction of the impact of seismic activity on zooplankton. Last, we did not include any attenuation of the seismic impact, to be consistent with McCauley et al. (2017).

Appendix A Suggestions for future work

To replicate the findings of McCauley et al. (2017) in an independent, rigorous, large-scale study, we make the following suggestions. It will be important to conduct a more detailed analysis of the optimal experimental design prior to any field campaign.

4.4.1 An area of high zooplankton biomass

An area in Australia should be chosen where zooplankton biomass is high, as it would provide the maximum opportunity of finding impacts. As part of the Integrated Marine Observing System (IMOS), the Zooplankton Ocean Observations and Modelling (ZOOM) task team has assembled all the zooplankton data around Australia and is currently building statistical models of biomass. These will be available in the near future.

4.4.2 An area of weak currents

Our current findings show that impacts on zooplankton of a seismic source are greater when currents are weak and there is less mixing of water masses. Existing hydrodynamic models around Australia (e.g. CSIRO's Ocean Forecast Australia Model) can be used to select a limited subset of areas with sluggish currents, and identify the optimal time of year that a field experiment could be conducted. This limited subset of areas and seasons could then be assessed on other criteria, including zooplankton biomass, logistics, and areas of seismic survey interest.

4.4.3 A large and stationary seismic source

Interpretation of the experimental findings is made more difficult when both the seismic source and water are moving. One suggestion might be to keep the seismic gun in one place, and track any water movement. Imposing a large and stationary seismic impact in operation for an extended period would ensure a large effect on the zooplankton (for example, reducing the biomass to below 50%), which would be more easily observable and the recovery could be tracked through time.

4.4.4 Comprehensive zooplankton sampling to a greater distance from the seismic source and over time

The sampling of zooplankton in the field experiment by McCauley et al. (2017) was limited in space and time, making the study suggestive rather than definitive. A definitive study would require more comprehensive zooplankton sampling.

As McCauley (2017) collected only 24 zooplankton samples (12 Control, 12 Impacted) for assessing the proportion of the zooplankton that were dead from a seismic survey, with 2 samples collected at each of 3 distances from the seismic source, they found impacts were saturated out to an effective distance of 1.2 km. Rather than have inadequate replication (2 replicates) at each distance, we suggest sampling more distances (say every 100 m from the source to 1 km and then every 200 m to 2.4 km) and only 1 sample at each distance, which would better resolve the impact and the attenuation distance. Several days of sampling are needed before the experiment begins to allow a robust estimate of the amount of zooplankton in the region and its daily fluctuations. A significant gap in the study by McCauley et al. (2017) was that it did not track the recovery of zooplankton populations. Daily sampling over an extended period (say 3 weeks) would track zooplankton recovery (biomass) and provide an improved estimate of the largest unknown in the current study concerning the impact of seismic activity – the net growth rate (growth – mortality) that we assumed varied from 0.05 to 0.15 d^{-1}.

The neutral red method staining method used in McCauley et al. (2017) is sensitive and robust (>98% staining efficiency) (Elliot & Tang, 2009) and should be used in any subsequent study. It is important that during the study the flowmeter works properly, as the inability to use the flowmeter data in the study by McCauley et al. (2017) weakened the findings.

4.4.5 Using the models developed in the current study to best design the experiment

In addition to finding an area of weak current, models developed and used in the current study can be used to design and conduct the experiment. For example, the models could be used to determine how many days and the drogue, frequency of sampling and how long to run the experiments. Models could also be used to estimate the real-time oceanography on flow of water to optimize drogue deployment.

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