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Monitoring coastal dolphins within the Reef 2050 Integrated Monitoring and Reporting Program:

Final Report of the Dolphins Team in the Megafauna Expert Group

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The Great Barrier Reef Marine Park Authority acknowledges the continuing sea country management and custodianship of the Great Barrier Reef by Aboriginal and Torres Strait Islander Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

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Executive Summary

Three species of coastal dolphins are commonly found throughout the Great Barrier Reef (the Reef), the Australian snubfin dolphin, *Orcaella heinsohni*, the Australian humpback dolphin, *Sousa sahulensis*, and the Indo-Pacific bottlenose dolphin, *Tursiops aduncus*. This report focuses on these three species, acknowledging that many other cetacean species also inhabit the Reef.

The objectives of the coastal dolphin team are to produce a desktop report which includes:

- Current status of the relevant elements of the Reef, including an evaluation of primary drivers, pressures and responses using the Driving Forces, Pressures, States, Impacts, Responses (DPSIR) Framework;
- Priority indicators for monitoring the key values associated with these elements;
- Potential sources of data;
- Assessment of the adequacy of existing monitoring activities within each theme to achieve the objectives and requirements of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP);
- Recommendations for the design of an integrated monitoring program as a component of RIMReP, specifically considering:
  - The information requirements for each key element of the Reef to ensure that appropriate data and information are being collected to meet the fundamental objectives of RIMReP;
  - The spatial and temporal sampling design to ensure that greatest value can be extracted from the data collected;
  - The logistics of the design to ensure that it can be implemented efficiently;
  - Likely funding required to implement the recommended monitoring design; and
  - (RIMReP Expert Group Project Megafauna EOI 0504117).

The DPSIR Framework and terminology were used to develop a schematic diagram of the relationships among drivers, pressures and the state of coastal dolphin populations in the Reef. The diagram also includes a set of activities that link drivers to pressures. Pressures applicable to coastal dolphin populations are organised into three categories: pollution, extraction and environmental change.

The status of coastal dolphins in the Reef is discussed, where snubfin dolphin numbers along the Queensland coast are comparable to those found in other Australian states, and humpback dolphin numbers along the Queensland coast appear higher than those found in other Australian states. Additionally, despite humpback dolphins appearing quite widespread compared to snubfin dolphins, current abundance estimates indicate that in sites where both species are found, snubfin dolphins appear more abundant than humpback dolphins.

Priority indicators for monitoring key coastal dolphin values are:

1 Abundance
2 Distribution
3 Contaminants

4 Proportion of calves in groups
5 Environmental variables

Population-level indicators will be based on changes to state variables in the DPSIR framework, with an emphasis on those which can be estimated from realistic data sources and statistical analyses. We propose measuring changes in:

1. Abundance (based on capture-recapture analyses);
2. Spatial occupancy (based on both descriptive statistics of maximum spatial extent and statistical modelling products); and
3. Recruitment (based on descriptive statistics, such as proportion of calves in groups, and capture-recapture recruitment analyses).

In addition to measuring changes in population level indicators, we note that:

1. Multiple indicators can be combined in a weight of evidence analysis, placing highest weight on indicators that have lowest uncertainty and highest *a priori* biological value (e.g. recruitment); and
2. We propose also monitoring absolute concentrations of contaminants in dolphin tissue samples when indicated by changes in contaminant concentrations in parts of the Reef.

For integrated long-term monitoring of coastal cetacean populations along the Reef, we propose:

1. Long-term monitoring of a set of sites along the Reef by robust design capture-recapture methods;
2. A one-off spatial survey for abundance and spatial distribution in the northern Reef (north of Port Douglas);
3. Continuation and expansion of the Great Barrier Reef Marine Wildlife Strandings Program and StrandNet (to be described by a separate working group); and
4. To consider a follow-up of the spatial survey should the northern reef continue to degrade, and initiate further research on contaminant loads carried by dolphins should water quality deteriorate.

As specified in *A Coordinated National Research Framework to Inform the Conservation and Management of Australia's Tropical Inshore Dolphins*' ('Framework'; Department of Environment 2015), the primary enabling objective for coastal dolphin research in Australia is: **Objective 1 - Indigenous Engagement:** *Foster effective and informed partnerships with Australia's Indigenous communities to enable sustainable conservation management of tropical inshore dolphins*. It is therefore acknowledged that appropriate Traditional Owner and Indigenous ranger engagement will be essential to implement all aspects of this coastal dolphin project.

Contents

1.0 Introduction

The *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan) (Commonwealth of Australia, 2015) establishes the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) to help measure and report progress, and guide adaptive management towards achieving the outcomes, objectives and targets of the Reef 2050 Plan. The Reef 2050 Plan will be reviewed on a five-year cycle with an initial mid-term review to be completed in 2018. RIMReP has established a number of expert groups, including the megafauna working group, which consists of several specialised teams, including coastal dolphins.

Three species of coastal dolphins are commonly found throughout the Reef, the Australian snubfin dolphin, *Orcaella heinsohni*, the Australian humpback dolphin, *Sousa sahulensis*, and the Indo-Pacific bottlenose dolphin, *Tursiops aduncus*. This report focuses on these three species, acknowledging that many other cetacean species also inhabit the Reef.

1.1 Objectives

The objectives of the coastal dolphin team are to produce a desktop report which includes:

- Current status of the relevant elements of the Reef, including an evaluation of primary drivers, pressures and responses using the Driving Forces, Pressures, States, Impacts, Responses (DPSIR) Framework;
- Priority indicators for monitoring the key values associated with these elements;
- Potential sources of data;
- Assessment of the adequacy of existing monitoring activities within each theme to achieve the objectives and requirements of the RIMReP; and
- Recommendations for the design of an integrated monitoring program as a component of the RIMReP, specifically considering:
    - The information requirements for each key element of the Reef to ensure that appropriate data and information are being collected to meet the fundamental objectives of the RIMReP;
    - The spatial and temporal sampling design to ensure that greatest value can be extracted from the data collected;
    - The logistics of the design to ensure that it can be implemented efficiently;
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    - RIMReP Expert Group Project Megafauna EOI 0504117.

2.0 The Driver, Pressure, State, Impact, Response Framework

The Driver, Pressure, State, Impact, Response (DPSIR) cause-and-effect framework is described in general terms by Figure 1 (from DPSIR terminology guide). The DPSIR Framework has been adopted to provide a multidisciplinary and integrative analysis to inform assessments of cumulative effects. The DPSIR terminology guide describes a common vocabulary and prescribes lists of drivers, pressures, values and states that form a common conceptual basis for the various expert working group reports.

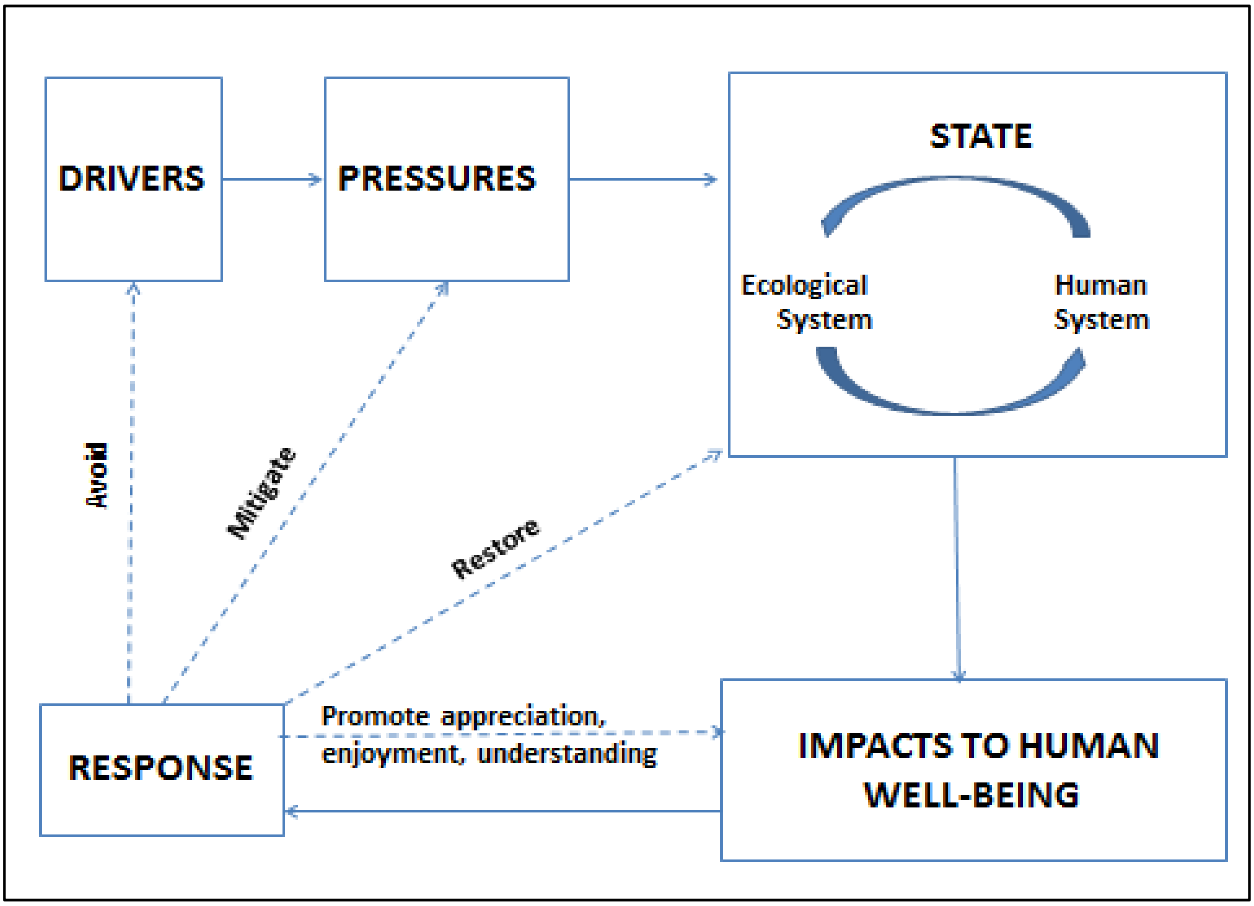

Figure 1: Driver Pressure State Impact Response Framework (from DPSIR terminology guide).

2.1 DPSIR Model for Coastal Dolphins

The DPSIR Framework and terminology were used to develop a schematic diagram of the relations among drivers, pressures and the state of coastal dolphin populations in the Reef (Figure 2). Pressures applicable to coastal dolphin populations are organised into three categories (pollution, extraction and environmental change) to make the causal links in the diagram more explicit. Values and responses will be discussed separately.

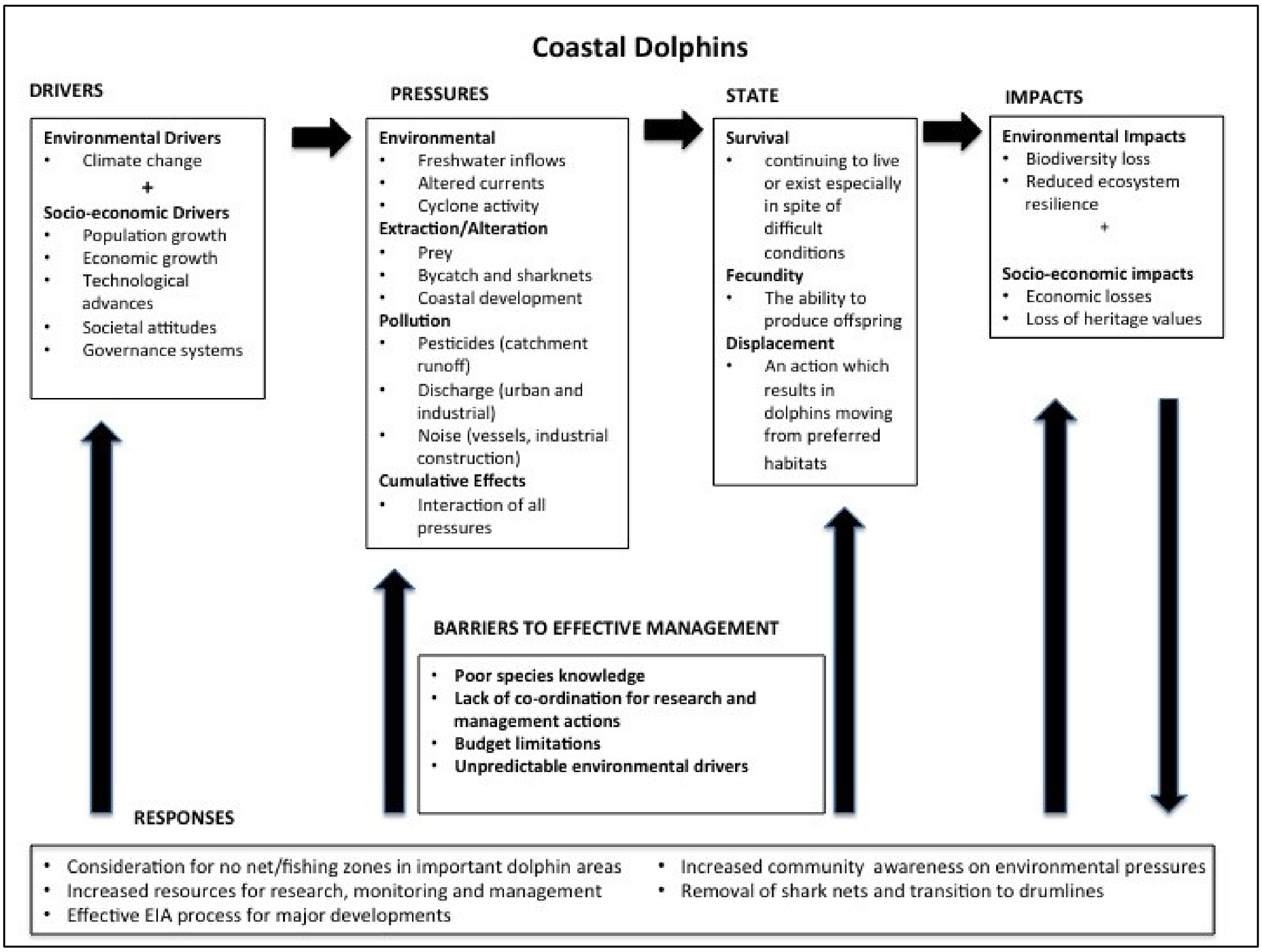

Figure 2: Schematic diagram of the relations among drivers, pressures and the state of coastal dolphin populations in the Great Barrier Reef.

2.1.1 Drivers

Drivers are overarching causes that can drive change in the environment (Great Barrier Reef Marine Park Authority, 2014; Great Barrier Reef Marine Park Authority, 2017). Six drivers of change have been adopted for the Reef system (and consequently coastal dolphins), all of which operate across a range of scales (both in time and space), and are interlinked (Great Barrier Reef Marine Park Authority, 2017):

1. Climate change
2. Population growth
3. Economic growth
4. Technological developments
5. Societal attitudes
6. Governance systems

Importantly, drivers cause changes in the nature of different activities/users, which in turn result in a range of pressures.

2.1.2 Pressures

Pressures (often referred to as threats) are the change mechanisms (e.g. processes or activities) that result from drivers (Great Barrier Reef Marine Park Authority, 2017). For coastal dolphins, pressures have been arranged into three broad categories:

1. Pollution;
2. Extraction; and
3. Environmental change.

Pollution includes marine debris, noise pollution, spills of oil or other contaminants; and urban, agricultural and industrial discharge.

Extraction includes incidental catch in fisheries, incidental catch in shark control devices and vessel strike. Extraction or displacement of prey may be of major importance to these top-order predators.

Environmental change includes altered ocean currents and increased freshwater inflows from prolonged or heavy rainfall or altered catchments. Environmental change that affects the abundance or distribution of prey species may be of particular concern.

Table 1 of the Framework (Department of Environment, 2015) lists *threats* to dolphin populations, while vulnerability assessments for the three coastal cetacean species are provided by the Great Barrier Reef Marine Park Authority (the Authority).

2.1.3 State

Within the DPSIR framework, the state is the way of describing the condition of the value, either quantitatively or qualitatively, thus enabling a measurement of change in the health or quality of that value (Great Barrier Reef Marine Park Authority, 2017). The state of a dolphin population is presented as a combination of three components of population dynamics: survival (i.e. continuing to live or exist especially despite difficult conditions), fecundity (i.e. the ability to produce offspring) and displacement (i.e. permanent emigration of a biologically meaningful proportion of a sub-population from their familiar habitat to another, unfamiliar habitat). The state of coastal dolphin populations in the Reef is more fully described below after brief reviews of the Australian context and existing research in the Reef.

2.1.4 Impacts

Impact is the change in human well-being that results from a change in the state of a value (regardless of whether that value is biophysical, socioeconomic or heritage) (Great Barrier Reef Marine Park Authority, 2017). For coastal dolphins, impacts have been arranged according to:

1. Environmental Impacts; and
2. Socio-economic Impacts.

2.1.5 Values

Values are those aspects or attributes of an environment that make it of significance (Strategic Assessment Report, Great Barrier Reef Marine Park Authority, 2014), where within the RIMReP values include attributes of both environmental and human systems. Three sets of values have been adopted for the purposes of RIMReP:

1. Biophysical (i.e. biodiversity value)
2. Socioeconomic
3. Heritage (i.e. cultural importance to Indigenous communities and world heritage values)

Coastal dolphins are important to all three sets of RIMReP values.

2.1.6 Possible responses to mitigate pressures or restore the state of the ecological and human system

Possible responses to changes of state include consideration of fisheries' netting practices in important dolphin areas; effective Environmental Impact Assessment processes for major developments; removal of shark nets and replacement with drumlines; increased resources for research, monitoring and management; and increased community awareness of pressures on dolphin populations.

3.0 Current Status of Coastal Dolphins in the Great Barrier Reef

Three species of coastal dolphins are commonly found throughout the Reef – the Australian snubfin dolphin, the *Orcaella heinsohni* (Beasley et al., 2005); the Australian humpback dolphin, *Sousa sahulensis* (Jefferson and Rosenbaum, 2014); and the Indo-Pacific bottlenose dolphin, *Tursiops aduncus* (Ehrenberg, 1833). The Australian snubfin dolphin (hereafter referred to as snubfin dolphin) and Australian humpback dolphin (hereafter referred to as humpback dolphin) are target species for monitoring in RIMReP.

Both the humpback and snubfin dolphins are listed as 'Vulnerable' by the International Union for Conservation of Nature (Parra et al. 2017, Parra et al. 2018) and are migratory species and Matters of National Environmental Significance under the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act, 1999). The Indo-Pacific bottlenose dolphin (*Tursiops aduncus;* hereafter referred to as bottlenose, has similar listings except that it is listed as 'Data Deficient' by the International Union for Conservation of Nature and Woinarski et al. (2014), and not considered a Matter of National Environmental Significance. Although the bottlenose dolphin has not been identified specifically as a target species for monitoring in RIMReP, the methods used to monitor coastal dolphins will likely detect and identify bottlenose dolphins (and other cetacean species such as spinner dolphins, *Stenella longirostris*). These additional species should also be included in monitoring reports.

In 2013, *A Coordinated research framework to assess the national conservation status of Australian snubfin dolphins (Orcaella heinsohni) and other tropical inshore dolphins* was developed by the Commonwealth Government (http://www.marinemammals.gov.au/research-and-activities/workshops/australian-inshore-dolphin-workshop). As part of this framework development, an associated document entitled *Current Status of Inshore Dolphins in Northern Australia* comprehensively described the biology, distribution and habitat, population status, threats and conservation status of snubfin, humpback and bottlenose dolphins in Australian waters, and references much of the available literature on them (as of 2013). Further material on humpback, snubfin and bottlenose dolphin status in the Reef is also provided by the Authority vulnerability assessments. Relevant material to coastal dolphin status along the Reef has been included in the discussion below, as well as new information not previously reported in the status report.

Figure 3 shows the locations of existing research on coastal dolphins in the Reef. We distinguish between capture-recapture studies and broadscale observational (occasional) studies. Table 1 describes the research on each of these sites: Table 1A describes the dates of research and whether data are available for modeling together with robust design capture-recapture data from proposed future surveys (see Appendix 1 for a description of robust design models); Table 1B describes the data collected on each site and whether it has produced estimates of abundance based on rigorous statistical analyses, or based on counts of individually identified animals or simply summaries of sightings; and Table 1C references the studies reported in Table 1A and 1B.

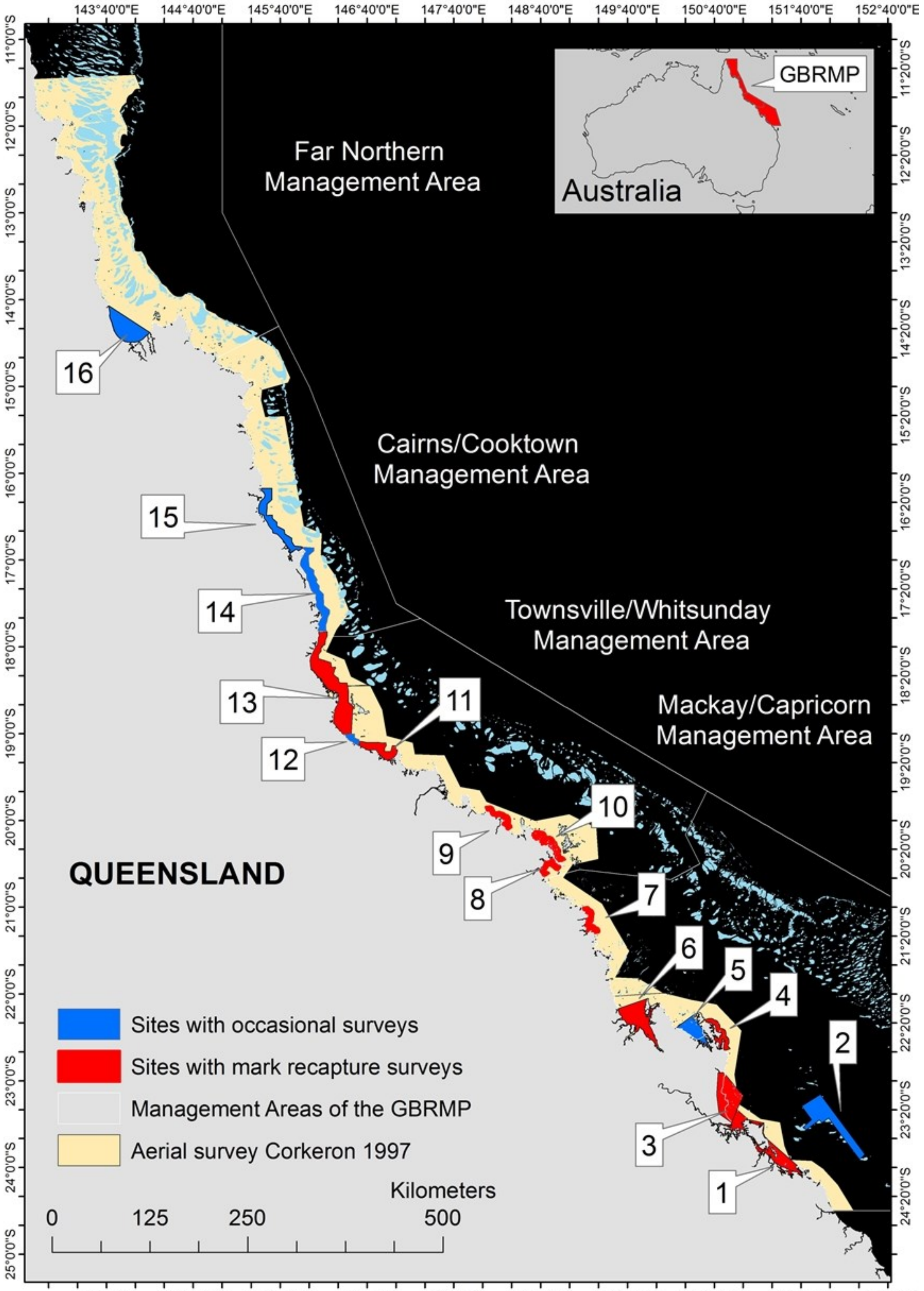

Figure 3. Map of locations of existing research on coastal dolphins in the Great Barrier Reef. The site numbers shown identify the sites in Table 1 (A, B, C).

Table 1A: Sites of existing research, dates of research, consistency with robust design and availability of data

Map ID	Site Name	First surveyed	Last surveyed	Robust design[1]	Primary samples	Data available
1	Port Curtis	01-2006	09-2011	compatible	4-5	yes
2	Capricorn Bunker Group	09-2010	10-2010	compatible	2	yes
3	Keppel Bay	01-2006	09-2011	compatible	4-5	yes
1+3	Rodds Bay to Port Alma	05-2014	09-2016	by design	5	yes
4	Port Clinton	05-2008	08-2010	compatible	3	yes
5	Shoalwater Bay	08-2010	08-2010	compatible	2	yes
6	Broad Sound	08-2013	09-2013	compatible	2	yes
7	Mackay	08-2016	08-2016	by design	3	yes
8	Repulse Bay	07-2014	08-2016	by design	3-4	yes
9	Bowen	08-2016	08-2016	by design	3	yes
10	Airlie Beach	07-2014	08-2016	compatible	4	yes
11	Cleveland Bay	01-1999	10-2002	incompatible	4	maybe
11	Cleveland Bay	05-2016	09-2016	by design	1	yes
12, 14, 15	Sanders Beach north to Port Douglas	08-2016	10-2016	Not CR	1	yes
13	Girringun	08-2012	10-2016	CR (yearly)	1	yes
16	Princess Charlotte Bay	08-2013	08-2014	Not CR	2	yes

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[1] See Appendix 1 for a description of robust design models

Table 1B. Abundance estimates where available, individuals if data matched but not analysed or records of sightings. Where multiple estimates exist, means and mean coefficients of variation are reported.

Map ID	Site Name	Snubfin			Humpback			Bottlenose		
		Statistic	**Estimate**	**CV**	**Statistic**	**Estimate**	**CV**	**Statistic**	**Estimate**	**CV**
1	Port Curtis	Estimate	0	NA	Estimate	81	0.06	Individuals	0	NA
2	Capricorn Bunker Group	Individuals	0	0.00	Individuals	0	0.00	Individuals	>100	NA
3	Keppel Bay	Estimate	114	0.05	Estimate	100	0.04	Individuals	52	NA
1+3	Rodds Bay to Port Alma	Estimate	122	0.17	Estimate	154	0.06	Estimate	0	NA
4	Port Clinton	Estimate	0	NA	Estimate	64.1	NA	Sightings	>200	NA
5	Shoal Water	Individuals	6	NA	Individuals	17	NA	Sightings	0	NA
6	Broad Sound	Sightings	2	NA	Sightings	6	NA	Sightings	0	NA
7	Mackay	Estimate	0	NA	Individuals	12	0.19	Estimate	29	0.38
8	Repulse Bay	Estimate	111	0.21	Individuals	67	0.57	Estimate	0	NA
9	Bowen	Individuals	18	NA	Individuals	54	0.16	Estimate	17	0.40
10	Airlie Beach	Individuals	>20	NA	Individuals	>20	NA	Sightings	0	NA
11	Cleveland Bay	Estimate	69	0.14	Estimate	46.7	0.21	NA		NA
11	Cleveland Bay	Estimate	133	0.20	Estimate	86	0.10	Individuals	13	NA
12, 14, 15	Sanders Beach to Port Douglas	Individuals	29	NA	Individuals	65	NA	Individuals	33	NA
13	Girringun	Individuals	8	NA	Individuals	42	NA	Individuals	16	NA
16	Princess Charlotte Bay	Individuals	0	NA	Individuals	14	NA	Individuals	0	NA

Table 1C. References to reports of research on the set of sites.

Map ID	Site Name	Reference	Document reference
1	Port Curtis	Cagnazzi, Daniele 2010	http://epubs.scu.edu.au/theses/344/
2	Capricorn Bunker Group	Cagnazzi, Daniele (unpublished)	NA
3	Keppel Bay	Cagnazzi, Daniele 2010	http://epubs.scu.edu.au/theses/344/
1+3	Rodds Bay to Port Alma	Cagnazzi, Daniele 2017	http://epubs.scu.edu.au/theses/344/
4	Port Clinton	Cagnazzi, Daniele 2010	NA
5	Shoal Water	Cagnazzi, Daniele (unpublished)	NA
6	Broad Sound	Cagnazzi, Daniele (unpublished) report to WWF	NA
7	Mackay	Cagnazzi, Daniele (unpublished) report submitted	NA
8	Repulse Bay	Cagnazzi, Daniele (unpublished) report submitted	NA
9	Bowen	Cagnazzi, Daniele (unpublished) report submitted	NA
10	Airlie Beach	Cagnazzi, Daniele (unpublished)	
11	Cleveland Bay	Parra, Guido J. et al. 2006	10.1016/j.biocon.2005.10.031
11	Cleveland Bay	Beasley (2017)	NA
12, 14, 15	Sanders Beach to Port Douglas	Beasley (2017)	NA
13	Girringun	Beasley et al. (2017)	NA
16	Princess Charlotte Bay	Beasley et al. 2013; 2014)	NA

3.1 Distribution

3.1.1 Snubfin dolphin

Along the Reef coast, snubfin dolphins have been confirmed to occur in the following locations:

- Capricorn coast — Fitzroy River to Shoalwater Bay (Cagnazzi, 2010, Cagnazzi et al., 2013);
- Northeast Queensland Coast including Hinchinbrook/Cardwell, Halifax Bay, Cleveland Bay, Bowling Green Bay, Pioneer Bay and Repulse Bay (Parra, 2006, Parra et al., 2002, Parra and Corkeron, 2001, Parra et al., 2011, Parra et al., 2006a, Parra et al., 2006b, Beasley et al., 2013, Beasley, 2015, Beasley, 2017); and
- Far Northern Queensland Coast: Princess Charlotte Bay and Bathurst Bay (Parra et al., 2006b).

3.1.2 Humpback dolphin

Through vessel and aerial surveys, humpback dolphins have been confirmed to occur along the majority of the Reef coastline (Corkeron et al., 1997b), with detailed studies being undertaken in the following locations:

- Capricorn coast — Fitzroy River to Shoalwater Bay (Cagnazzi et al., 2013; Cagnazzi et al., 2011);
- Northeast Queensland Coast including Cairns/Port Douglas south to Mission Beach, Hinchinbrook/Cardwell, Halifax Bay, Cleveland Bay, Bowling Green Bay, Pioneer Bay and Repulse Bay (Parra, 2006; Parra et al., 2002; Parra and Corkeron, 2001; Parra et al., 2011; Parra et al., 2006a; Parra et al., 2006b; Beasley et al., 2013; Beasley, 2015; Beasley, 2017); and
- Far Northern Queensland Coast: Princess Charlotte Bay and Bathurst Bay (Parra et al., 2006b).

3.2 Abundance

3.2.1 Snubfin dolphin

Recent estimates from Queensland (Beasley et al. 2017: unpublished) and Cagnazzi (2017: unpublished), indicate that substantial local snubfin dolphin populations occur along the Queensland coast and are of the same order of magnitude as those found in other Australian states.

3.2.2 Humpback dolphin

There is currently no range-wide, or Australian, assessment of the abundance of humpback dolphins. Estimates of humpback dolphin abundance from mark-recapture studies of photo-identified individuals are also only available for a few selected populations across Australia (Parra and Cagnazzi, 2016).

Recent estimates from Queensland (Beasley et al., 2017: unpublished and Cagnazzi, 2017: unpublished), indicate that substantial local populations of humpback dolphins occur along the Queensland coast and are of the same order of magnitude as those found in other Australian states. Additionally, despite humpback dolphins appearing quite widespread compared to snubfin dolphins, current estimates indicate that in sites where both species are found, snubfin dolphins appear more abundant than humpback dolphins.

3.3 Population Trends

3.3.1 Snubfin dolphin

Estimates of population size trends across the species' range are unknown. No trends were detected in Cleveland Bay from 1999 to 2002 (Parra, 2005). A multi-year, comprehensive study (2006-ongoing) in Keppel Bay, Central Queensland, showed that between 2006 and 2010 abundance estimates of snubfin dolphins remained stable around 74 (65-84) individuals, before starting to decline slightly in 2011 to 68 (64-72) individuals in 2013 (Cagnazzi, 2013). The decline in abundance estimates was associated with re-occurring summer flooding in this region since 2010.

3.3.2 Humpback dolphin

Estimates of population size trends across the species range are unknown (Parra and Cagnazzi 2016). Surveys in Cleveland Bay, Queensland from 1999 to 2002 showed low population sizes (34 - 54 individuals) and no obvious trends. A comprehensive multi-year study from 2006 to 2011 along the central Queensland Coast showed that abundance estimates declined throughout the study in Keppel Bay and Curtis Region from 115 and 84 individuals in 2007 to 104 and 45 in 2011, respectively (Cagnazzi, 2013). The decline in the abundance estimate was associated with a large flood event in 2010, and the concurrent expansion of the Port Curtis port facilities (Cagnazzi, 2013).

3.4 Movements

There is little information on large-scale movements of snubfin or humpback dolphins throughout their range, primarily because study areas have been relatively small and widely separated. Studies along the Capricorn-Curtis coast and Great Sandy Strait (both covering an area of 1000 square kilometres) represent one of the best-studied areas in Australia. Through this study, movements up to 130 kilometres for humpback and 60 kilometres for snubfin dolphins have been recorded (Cagnazzi, 2011).

Examination of photo identification data between study sites separated by several hundred kilometres such as Whitsundays-Curtis Coast (approximately 450 kilometres) and Curtis Coast-Great Sandy Strait (approximately 230 kilometres) in Queensland (Cagnazzi and Parra unpublished), and Roebuck Bay-Beagle Bay (approximately 150 kilometres) and Beagle Bay-

Cygnet Bay (approximately 250 kilometres) in Western Australia (Brown unpublished data) did not reveal any individual matches (Parra and Cagnazzi, 2016).

3.5 Fecundity and population viability

Fecundity, or the rate of production of offspring, is an important factor in the viability of a population. A population viability model including extinction risk under different scenarios, parameterised using genetic data and ten years of mark-resighting data, was specifically developed for humpback and snubfin dolphin (Cagnazzi Daniele and Michael Maccarthy unpublished data). Parameters for the model were estimated from the literature, but due to incomplete knowledge of snubfin and humpback dolphin life histories, it was necessary to substitute several values from related species or assume them from other cetacean modelling studies. The model was most sensitive to uncertainty in the sex ratio, inter-birth period, and both adult and calf survival probabilities. Population decline was predicted only when calf survival probability was set to its minimum value of half of adult survival (~0.9). High calf mortality was indicated as the key factor in the decline of a population of bottlenose dolphins in Bay of Islands, New Zealand (Dawson et al. 2008).

Calf is the life stage most susceptible to environmental change and detrimental human factors. Unfortunately, few reports on Australian coastal dolphins pay attention to either the rate of production or survival of calves. This is in part because the natural markings of dolphins do not stabilise for a number of years after birth and capture-recapture models cannot be built on data from calves. While it is not proposed to design a study specifically to study the birth rate or survival of calves, it is proposed to count and record the number of calves sighted in each group and incorporate these data in an analysis of recruitment (see ‘Potential sources of data for monitoring’ below).

3.6 Population genetic structure

Between 2008 and 2011, biopsy samples of humpback and snubfin dolphins were collected to improve the understanding of the population genetic structure of these species within Australian waters. These samples were collected from five regions within the Reef (Gladstone, Keppel Bay, Whitsundays, Cleveland Bay and Hinchinbrook Channel) and three regions outside the Great Barrier Reef Marine Park (the Marine Park) (Moreton Bay, Tin Can Bay and the Great Sandy Strait) (Parra et al. 2018).

Resulting data suggest that humpback and snubfin dolphin populations along the Reef are genetically differentiated into at least two distinct genetic clusters, correspondingly to the Northern-Central (Hinchinbrook, Cleveland Bay and Whitsundays) and Southern Reef (Keppel Bay and Port Curtis).

Estimates of contemporary migration rates between sampled locations and putative populations of humpback dolphins were estimated to vary between one per cent and three per cent per generation (about 20 years) (Parra et al. 2018). Spatial genetic structure in humpback dolphins occurs at distance classes of approximately 382-509 kilometres (Parra et al. 2018).

High migration rates were estimated only for neighbouring sampling locations less than 200 kilometres apart (i.e. Keppel Bay-Port Curtis and Hinchinbrook-Townsville and Whitsundays). Similar results were observed for snubfin dolphins, with two main populations corresponding to the northern-central Reef (Hinchinbrook, Cleveland Bay and Whitsundays) and one for the southern Reef (Keppel Bay). No resident population of snubfin dolphins was found between these two locations. Spatial genetic structure in snubfin dolphins was estimated to be in the order of approximately 600 kilometres (Parra and Cagnazzi, in prep).

3.7 Anthropogenic contaminants

Biopsy samples collected between 2010 and 2011 in Gladstone, Keppel Bay and Whitsundays (southern Reef) were used to assess the levels of the common anthropogenic contaminants: HexaChloroBenzene (HCB); DichloroDiphenylTrichloroethane (DDT); PolyChlorinated Biphenyl (PCB); and Polycyclic Aromatic Hydrocarbon (PAH) (Cagnazzi, 2017). HCB and DDTs were found at levels considered not dangerous to a dolphin's health (Jepson et al., 2005), PCBs and PAHs were found at levels that, based on field and laboratory tests, may cause suppression of the immune system and also impairment of reproduction (Cagnazzi et al., 2013). In particular, three humpback dolphins (two in Port Curtis and one in Fitzroy River) and two snubfin dolphins (in Fitzroy River) were found with levels of PCBs that exceeded the proposed threshold value (that is, the sum of PCB threshold value is 11,000 nanograms per gram lipid weight; the dose at which an adverse effect would be observed with a probability of 10 per cent), derived for bottlenose dolphins in relation to foetal and neonatal mortality associated with maternal PCBs exposure (Schwacke et al., 2002). Additionally, one humpback dolphin (Port Curtis) and one snubfin dolphin (Fitzroy River) exceeded the proposed threshold value (the sum of PCBs is 17,000 nanograms per gram lipid weight) for adverse health effects in marine mammals (Jepson et al., 2005; Kannan et al., 2000) also associated with immune system alterations (Ross et al., 1996). One humpback dolphin from Port Curtis showed PCB levels of 77,000 nanograms per gram lipid weight, associated with carcinoma (i.e. a type of cancer that starts in cells that make up the skin of tissue lining organs, such as the liver or kidneys) in California sea lions (*Zalophus californianus*) (Ylitalo et al., 2005). Although the use of PCBs, DDTs and HCB in Australia has been banned since the late seventies, they remain a common contaminant in the environment due to their stable nature and limited mobility. Further, it is anticipated that PCBs will continue to be produced as combustion by-products, released during the recycling of materials and building demolitions and potential new sources may enter in Australia under the consent of the Minister for Justice and Customs. From these sources PCBs, DDTs and HCB are readily adsorbed into suspended particles, which can act both as sinks and as long-term sources and can be remobilised into marine ecosystems through many pathways including atmospheric transport, riverine inputs, floods and dredging.

All 14 PAHs tested in this study were above detectable levels. Pyrene and Naphthalene were particularly abundant, which could be attributed to oil shale deposits underlying the region and the exposure of natural mineralogy through continuous dredging of the shipping channels and drilling activities. These are also the most abundant PAHs dissolved in oil waste. Although these elements are not classified as carcinogenic, in high concentrations they are known to have negative effects on marine species (Seuront, 2011). For example, naphthalene, the most abundant PAH found in this study, has been reclassified under the International Agency for Research on Cancer and the US Environmental Protection Agency as potentially carcinogenic. Overall, PAHs levels were similar to those of humpback dolphins from more polluted regions of South East Asia (Cagnazzi et al., 2013).

A total of 39 samples were collected in 2014 and 2015 from the same areas. The levels of PCBs, DDTs and HCBs in the recent samples were on average up to nine, eleven and two times higher (respectively) than of those collected in 2010-11. This significant increase in organochlorine levels was linked to the increased frequency and intensity of flooding events observed in the Reef and associated with global warming. These samples were also analysed for ten heavy metals, in all samples Zinc was at levels associated with infectious or inflammatory processes and, for some samples, Mercury was above the threshold for hepatic damage and liver toleration (Cagnazzi, 2017).

Humpback and snubfin dolphins in the Reef may be predisposed to infectious disease as a result of immunosuppression effects of high levels of PCBs and DDTs. The toxicological risk for inshore dolphins in the Reef is likely to be underestimated considering that only a fraction of organochlorine contaminants were analysed for.

4.0 Priority Indicators for Monitoring Key Values

Methods used to study coastal dolphins are described in Appendix 1. Priority indicators for monitoring key coastal dolphin values are:

1 Abundance;
2 Distribution;
3 Contaminants;
4 Proportion of calves in groups; and
5 Environmental variables

5.0 Potential Sources of Data for Monitoring

Population-level indicators will be based on changes to state variables in the DPSIR framework, with an emphasis on those which can be measured from realistic data sources and statistical analyses. We propose measuring changes in:

1. Abundance (based on capture-recapture analyses);
2. Spatial occupancy (based on both descriptive statistics of maximum spatial extent and statistical modelling products); and
3. Recruitment (based on descriptive statistics, such as proportion of calves in groups, and capture-recapture recruitment analyses).

In addition to measuring changes in population level indicators, we note that:

1. Multiple indicators can be combined in a weight of evidence analysis, placing highest weight on indicators that have lowest-uncertainty and highest *a priori* biological value (e.g. recruitment); and
2. We propose also monitoring absolute concentrations of contaminants in dolphin tissue samples when indicated by changes in contaminant concentrations in parts of the Reef.

6.0 Adequacy of Existing Monitoring Activities

The existing studies in the Reef have been highly variable in time, space, sampling methodology, and relevance to conservation management and assessment. The most recent and important studies have been 1) capture-recapture surveys of humpback and snubfin dolphins from Cleveland Bay (which is the most northerly site and where Parra et al. (2006a) conducted capture-recapture studies from 1999 to 2002), and 2) a suite of surveys starting in 2010 from Bowen extending south to Port Curtis (Cagnazzi, 2010). Figure 3 shows the location, time and duration of these surveys. Together, the capture-recapture studies have a spatial extent that spans approximately 40 per cent of the Reef nearshore. Many of these studies are ongoing.

The maintenance and expansion of the capture-recapture sites will be an important aspect of future Reef conservation monitoring. Eight sites are particularly relevant, given their existing longevity of three to five years, and their spatial distribution being selected according to pilot surveys to find areas of high relative encounters of humpback and snubfin dolphins (Cagnazzi, 2010). The sites were also selected for proximity to potential human impact sites. The latter design feature will complement the DPSIR framework to have a close connection between anthropogenic drivers and impacts to coastal dolphins.

However, the multi-year spatial density of sites is relatively sparse compared to the entire Reef, with approximately 310 kilometres separating the sites at Port Clinton/Rodds Bay from Repulse Bay, and 240 kilometres separating Airlie Beach from Cleveland Bay. Clearly, the largest gap is the paucity of robust information in the northern Reef, from Port Douglas northward.

The current power of the capture-recapture studies to detect biologically meaningful change is likely to be low or moderate. The earliest power analyses of Reef coastal dolphins was by Parra et al. (2006a), who estimated that it would take six years to detect a five per cent annual decline, or two years to detect a 20 per cent annual decline. Such estimates seem over-optimistic, due to the exclusion of multi-model uncertainty. They also contrast sharply with the rule-of-thumb of Barlow and Reeves (2001), who suggest that 10 years of surveys are necessary to detect a 50 per cent decline with high probability. Furthermore, we conducted a simulation-based power analysis (See Appendix 2), using levels of uncertainty consistent with humpback and snubfin capture-recapture studies. The analysis suggests that given the existing levels of uncertainty in abundance estimates and demographic processes, it would take 10 to 14 years to detect a three per cent annual decline with a 90 per cent confidence level and 90 per cent power. As a reference to international criteria, this is slightly larger than the IUCN red-list criteria for ‘vulnerable': 30 per cent decline in 10 years). Varying the temporal intensity of the sampling effort, such as doing surveys every other year or every three years, will have only moderate effects on the total study years needed to achieve an acceptable power. However, this opens up the possibility of there being anomalous or dramatic population swings due to, for example, massive flooding events or port developments (both of which have already been observed and thought to have caused dramatic swings in sightings of dolphins near the Whitsundays; Daniele Cagnazzi, personal communication).

Secondary design considerations can also be effective to increase the reliability of capture-recapture trend estimates, such as increasing the number of within-year capture periods (‘*secondary periods’* in robust design studies). There are also post-hoc modelling considerations that may alleviate some of the variance and uncertainty in abundances estimates, such as using hierarchical models to share information among sites.

Aside from the capture-recapture work, there have been a number of aerial surveys and boat-based systematic transects that include humpback and snubfin dolphin sightings (Corkeron et al., 1997; Beasley, 2016; Beasley et al., 2016). In general, the number of encounters of animals in these studies is low, reflecting the low densities of animals. Aside from the analytical challenge of integrating information from multiple studies, a more pernicious challenge is the low number of encounters. Low encounter rates make it very difficult to perform statistical analyses on animal counts and discriminate between ecologically meaningful relationships with spatial covariates versus purely spurious covariates. We performed a Monte Carlo power analysis to investigate the ability of conventional count-based statistical analyses and model-selection techniques to select and estimate the effects of spatial covariates versus spurious effects, using realistic densities of animals (See Appendix 3). The results suggest that only relatively moderate-size effects (such as a 25 per cent change in the abundance of animals across a covariate space) can be reliably discriminated from purely spurious effects. At low densities, important covariates with small effect sizes (such as a 10 per cent change in abundance) are likely to be statistically shrunk-to-zero and estimated to have no marginal effect. The results motivate the need for spatial sampling designs that give greater sampling weight to areas and habitats with higher densities and thus can increase the encounter rates of animals. Some of the existing broad-based spatial surveys can help suggest regions that deserve a greater sampling weight.

7.0 Recommendations for an Integrated Monitoring Program

7.1 Information requirements for coastal dolphins to meet the RIMReP Objectives

The Reef 2050 Plan objectives relevant to the proposed coastal dolphin integrated monitoring program address ecosystem health, biodiversity, and water quality. Based on the DPSIR framework, evaluation of existing monitoring activities, and information required to meet the objectives of the RIMReP, recommendations for future monitoring have been developed. As mentioned in the introduction, a *Coordinated research framework to assess the national* *conservation status of Australian snubfin dolphins (Orcaella heinsohni) and other tropical inshore dolphins*, was developed in 2013 by the Commonwealth Government**.** This framework was revised in 2015 (Department of Environment, 2015). The four main objectives designated within the revised framework as high priority for Australian coastal dolphins are:

> **Objective 1 - Indigenous Engagement:** *Foster effective and informed partnerships with Australia's Indigenous communities to enable sustainable conservation management of tropical inshore dolphins.* [Enabling Objective]
>
> **Objective 2 - National Distribution Data:** *Provide for access to and analysis of standardised national tropical dolphin data to assess distribution and underpin management and conservation.* [Data Management Objective]
>
> **Objective 3 - Long-term Monitoring:** *Gather and use information over long-term timescales to determine trends, mitigate impacts from threats, and support adaptive management and conservation of tropical inshore dolphins.* [Research Objective]
>
> **Objective 4 - Threat Risk Assessment:** *Identify, map and assess threats to tropical inshore dolphins, understand related impacts, and mitigate risks.* [Research Objective]

Objective 1 is considered an enabling objective, Objective 2 is a data management objective, and Objectives 3-4 are the research objectives. We recommend that an integrated monitoring program for coastal dolphins in the RIMReP conform as closely as possible to the objectives listed above.

Appendix 1 describes methods used to study coastal dolphin populations and design principles for robust design capture-recapture studies.

The principal measurable indicators of the state of coastal dolphin populations in the Reef at any point in time are:

- Abundance (including survival estimates) at a sample of sites;
- Spatial distribution;
- Fecundity (recruitment); and
- Estimates of contaminant concentrations from biopsy samples or freshly stranded carcasses.

7.2 Monitoring change in population demographic parameters

Estimating change in coastal dolphin populations is time and resource intensive due to their typically small local populations, high mobility and movements on and off a sampling area (Brooks et al., 2017).

Using case studies, Taylor *et al.* (2007) demonstrate that the ability to detect declines in marine mammal stocks with current monitoring programs is generally poor, even when the decline is considerable. They concluded that it would be impossible to detect even precipitous declines in most marine mammal populations with present levels of investment, survey technology and design. Marsh et al (2017) summarise the situation in these terms:

- Detecting population trends for marine mammals is possible but requires high technical expertise and access to considerable resources because these animals occur in small numbers, are sparsely distributed and are difficult to capture at suitable rates.
- The effort expended and results obtained in our case studies demonstrate that management intervention should not require the trigger of statistical evidence of reduction in abundance; indeed such a requirement can be a red herring that unduly delays conservation action.

While capture-recapture methods remain the preferred means of estimating demographic parameters for coastal dolphin populations (Brooks et al., 2017; Cagnazzi, 2017; Beasley, 2017), the preceding discussion indicates that detection of a statistically significant decline (i.e. 'state' in the DPSIR framework) should not be required as a criterion for conservation action (i.e. 'response' in the DPSIR framework). Given estimates with suitable precision, a systematic pattern of decline and reasonable argument should be sufficient to indicate that a conservation response should be implemented.

Appendix 2 reports a power analysis for robust design capture-recapture analyses based on the design principles described in Appendix 1.

7.3 Change in spatial distribution and contaminant status

While we propose only a one-off spatial survey of the northern Reef at this stage, continued high water temperature and continued severe decline in the state of the Reef in the area, or observed movement of prey further south, may justify a second spatial survey in the area in future. A power analysis suggests that because the densities of snubfin and humpback dolphins are expected to be low, it will be difficult to accurately estimate and predict large spatial trends in abundance, thus motivating additional surveys and careful thinking about sampling designs. As top order predators, declines in dolphin abundance or their permanent movement to new habitats may signal degradation of the whole ecological system.

Similarly, while here we rely on previous work (see Anthropogenic Contaminants above) to establish current levels of contaminants carried by dolphins, further study may be justified should water quality be observed to decline. Major construction or relatively local reduction in water quality may justify further biopsy sampling and assessment of contamination in the food chain to detect accumulation in these top-order predators. As such, studies may be better targeted to areas where such changes in pressures actually occur or standings are found, and it may be sensible to establish baselines in areas where increases in pressures are anticipated as a consequence of development.

7.4 Spatial and temporal sampling design

For integrated long-term monitoring of coastal cetacean populations along the Reef, we propose:

1. Long-term monitoring of a set of sites along the Reef by robust design capture-recapture methods;
2. A one-off spatial survey for abundance and spatial distribution in the northern Reef (north of Port Douglas);
3. Continuation and expansion of the Reef Marine Wildlife Strandings Program and StrandNet (to be described by a separate working group); and
4. To consider a follow-up of the spatial survey should the northern Reef continue to degrade, and initiate further research on contaminant loads carried by dolphins should water quality deteriorate.

Although the spatial survey is recommended as a one-off at this stage, conditions under which a follow-up survey should be considered are described above. Similarly, although we do not recommend further biopsy sampling at this stage, conditions under which further biopsy sampling should be considered are also described.

Access to Cape York, north of Port Douglas, poses significant logistical and cost issues for long-term capture-recapture monitoring. To adopt this approach would require research crews to spend a month to six weeks on the coast at each of a set of sites for each primary sample. The limited coastal research conducted north of Port Douglas includes photo-identification boat-based surveys in Princess Charlotte Bay conducted by Lama Lama Rangers and James Cook University (JCU) in 2014 and 2015, where only humpback dolphins were sighted (Beasley et al., 2014; 2015: unpublished). However, line transect surveys found both snubfin and humpback dolphins in Prince Charlotte Bay but only snubfin dolphins in Bathurst Bay (Parra et al. 2006).

A spatial sampling approach from a large vessel would yield estimates of the total abundance, spatial distribution and habitat use for each species. Spatial sampling in the northern Reef would provide insight into coastal dolphins' use of reef habitat. Should a follow-up survey be considered in the future, the dolphins' use of habitat in close proximity to the reef may provide an opportunity to monitor the response of the species to continued degradation of the northern Reef. One possible response to continued ocean warming and reef degradation in the north is movement of dolphin populations and their prey further south (Cheung et al., 2013).

7.5 Proposal for long-term capture-recapture monitoring on a selected set of sites

Sampling principles for robust design capture-recapture studies in respect of a single primary sample were briefly described Brooks et al. (2014) in response to the 2013 Framework. They suggest that repeated primary samples on a site may be best taken annually at the same time of year to obviate apparent instability in the estimates that may arise should there be a seasonal pattern of use of the site.

The Framework (2015) includes a section on criteria for selecting key sites for research (Table 2 of the Framework 2015). A major development proposal is an automatic trigger for site selection. This criterion has been applied to the region around the Gladstone port development site (Cagnazzi et al., 2015) and the proposed Abbot Point Coal port facility (Cagnazzi et al., 2016: under review). Studies on such sites generally need to be more intensive and deliberately structured to match planned construction phases than sites monitored for more general conservation management purposes.

The Framework (2015) also identifies a number of sites for priority research (Table 3a of the Framework 2015) among which the following are in the Reef: Fitzroy River, Repulse Bay, Townsville-Hinchinbrook and Bathurst Bay. Bathurst Bay is in the northern Reef and would be included in the area for spatial sampling. This may be one a few sites in the northern Reef where long-term capture-recapture monitoring is viable but special arrangements would have to be made and a pilot study performed.

7.5.1 Site selection for long-term monitoring in the Great Barrier Reef

Table 2 lists a set of sites proposed for long-term monitoring in the Reef. These sites were selected as conforming as far as possible with the site-selection criteria listed in Table 2 of the Framework (2015).

Table 2. List of sites proposed for long-term monitoring of coastal dolphins in the Great Barrier Reef

Proposed site for long-term monitoring	Approximate area (square kilometres)
Cleveland Bay including Saunders Beach	290
Fitzroy River	450
Repulse Bay	396
Bowen	422
Port Clinton	412
Balgal Beach to Missionary Bay	520
Cairns north to Wangetti	390
Bathurst Bay (possible following pilot study and separate proposal)	300

7.5.2 Comment on listed migratory species and biologically important areas

Multiple studies have highlighted the importance of the Marine Park coastal waters for both humpback and snubfin dolphins. In north Queensland (Far Northern Management Area) the reefs or sand flats occur almost continuously from the mainland to the mid-shelf reefs. In these regions, humpback dolphins have been sighted in the outer reef area although in sheltered and protected waters (Corkeron et al., 1997). Overall, throughout the Marine Park humpback dolphins were sighted on average 6.4 kilometres from land or 2.4 kilometres to water shallower than two metres deep at low tide (Corkeron et al., 1997). The distribution of snubfin dolphins overlaps substantially with that of humpback dolphins (Parra et al., 2006) although in north Queensland there are no reports of snubfin dolphins in the outer reef.

South of Cairns the distance between the reef and the mainland increases from 30 kilometres up to 150 kilometres near Bundaberg. In the Central and Southern section of the Reef the Capricorn channel, with a depth of about 50 metres, further isolates the outer reefs from the mainland. South of Cairns the distance of the outer reef to the mainland may act as a limiting factor on the movement of humpback and snubfin dolphins from the coast to the outer reef. The importance of coastal habitat to both species may increase while moving south with the declining availability of sheltered and protected waters.

Both species were reported along the entire coastline but only few sites support relatively large resident populations and are therefore suitable for long-term monitoring. Balgal Beach to Missionary Bay, Cleveland and Halifax Bays, Bowen, Repulse Bay, Port Clinton and Fitzroy River were all indicated at the National Research Framework as preferred sites for research on tropical inshore dolphins. In each of those sites, large aggregations of Australian humpback and snubfin dolphins were observed involved in breeding, foraging and resting behaviours. Movements of individuals between some of these sites (Bowen-Repulse Bay) were also recorded. Based on this information, all the selected sites meet the criteria to be classified as a Biologically Important Areas (BIAs) for both humpback and snubfin dolphins and are therefore appropriate sites for long-term monitoring as part of the RIMReP program. Finally, these sites were also selected based on meeting one or more criteria for determining ‘important habitat’ for Listed Migratory Species, according to the Department of the Environment (2013):

a. habitat utilised by a migratory species occasionally or periodically within a region; that supports an ecologically significant proportion of the population of the species;
b. habitat that is of critical importance to the species at particular life-cycle stages;
c. habitat utilised by a migratory species which is at the limit of the species range; and
d. habitat within an area where the species is declining.

Despite the lack of dedicated surveys, based on anecdotal information and the characteristics of the habitat, Bathurst Bay is also likely to be a biologically important area for at least one of the humpback or snubfin dolphin species.

7.5.3 Cost estimate

An indicative estimate of the cost of completing a primary sample, which includes four secondary samples (see Appendix 1) on a site of 480 square kilometres is provided in Appendix 4 ($138,000). Potential project management costs and costs for Traditional Owner/Indigenous Ranger involvement also need to be estimated and accounted for.

7.6 Proposal for spatial sampling in the northern Great Barrier Reef

7.6.1 Goals

The large-scale spatial survey of the northern Reef aims to provide a one-time snapshot of the abundance and distribution of coastal dolphins, at multiple spatial scales. The design includes systematic transects, double-observer distance sampling, and fine-scale geo-referencing of dolphin groups. The key elements of the design, such as spatial allocation of effort, aim to address major sources of variation in dolphin counts, such as observer error, broadscale latitudinal gradients, and fine-scale associations with habitats.

7.6.2 Design

The broadscale design is the systematic positioning of 30 transects, each 80 kilometres long, distributed from Port Douglas to the tip of Cape York. The design goal is to achieve representative of the latitudinal gradient in species' distribution and abundance. During the dry season when better weather and lower turbidity are expected, we propose that one-half of the transects should be surveyed, starting in the south and moving north while selecting alternating transects for survey. The remaining transects should be surveyed from north to south. The motivation for the staggered sampling is to partially separate spatial and temporal effects (such as changes in turbidity and weather), which may otherwise have a strong confounding effect on the visual detection of animals, and influence the ability to statistically control for observer error.

Appendix 3 reports simulations for a preliminary power analysis of the proposed spatial survey.

The exact layout of individual transects will be random, subject to a balanced spatial sampling design that meets the following criteria and constraints. The most important sampling criteria is to target coastal habitats in accordance with our prior belief that the majority of dolphins make use of those coastal habitats frequently, as well as reef areas because little is known about the dolphins' use of reef habitats.

The target habitats are:

1. Within 10 kilometres of the mainland;
2. Within two kilometres of reef; and
3. Everywhere else

We propose a ratio of effort of 2:2:1 for the three habitats, respectively reflecting the criteria above. Other design criteria pertain to the shape and operational feasibility of transects. Some example transects are shown in Figure 4.

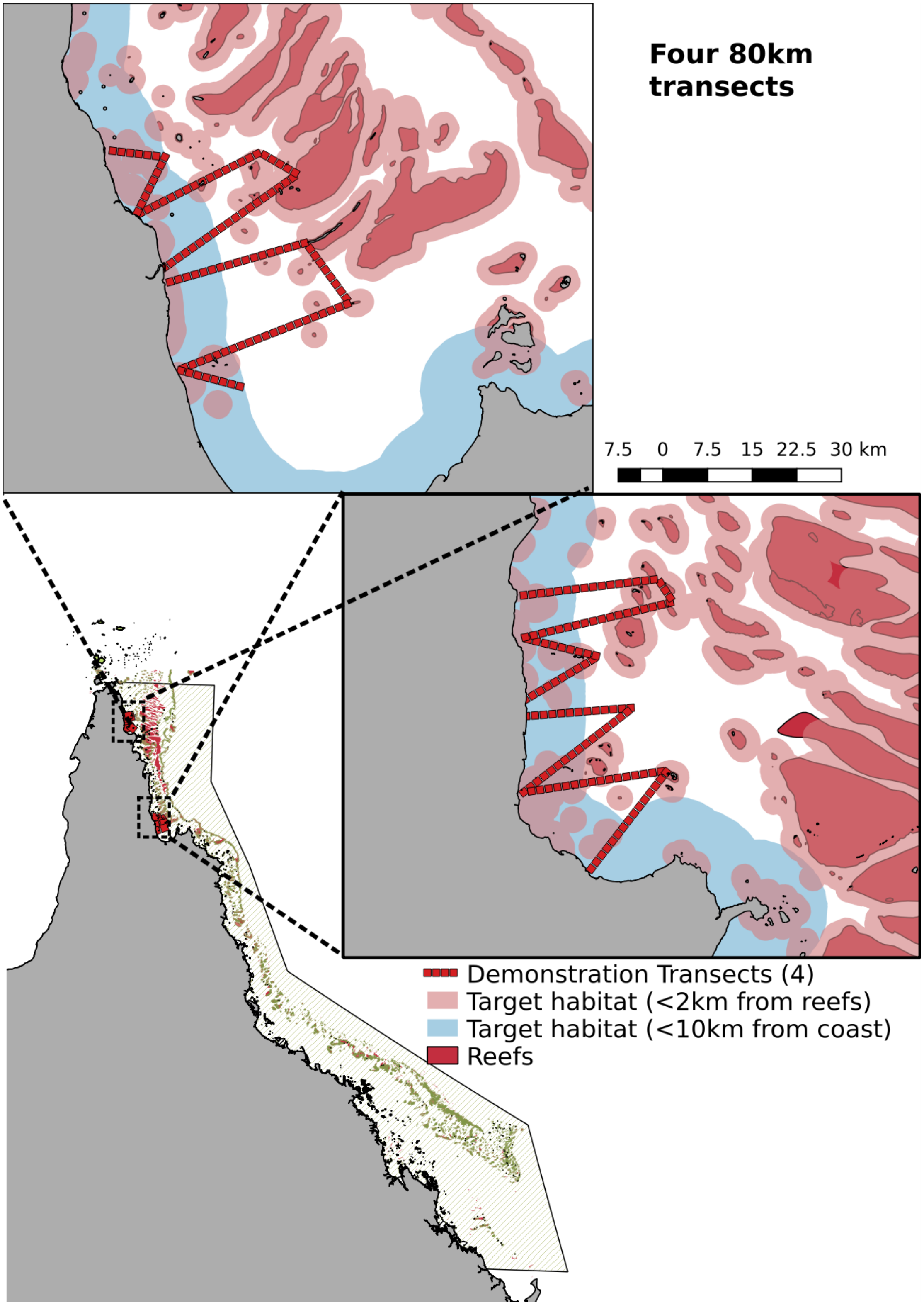

Figure 4. Two examples of four 80 kilometre transect designs, including target habitats that motivate the spatial allocation of effort.

Each survey consists of a double-observer distance sampling protocol, with a deck height of approximately six metres and a truncation distance of approximately 600 metres from the transect line (Dawson et al., 2004). Conditional on detecting a dolphin group, a rotating wing video-surveillance drone will gather additional information on group size, location, species composition, and any sex-age information. Such information will help control for factors that likely moderate detection probability and human observation error, such as species identity (for example, snubfin and humpback are less noticeable than bottlenose dolphins), group-size, turbidity, and distance. There are many other influences on detection error which can be minimised during boat operations at the time of data collection (such as halting boat operations during Beaufort sea-states greater than two).

7.6.3 Statistical analyses at the broadscale

The coarsest analysis will discretise the 30 transects into 1 by 1.2 kilometres spatial units, and aggregate information therein. The response variable will be the species-specific sum-of-counts within 600 metres of either side of the transect line, taking the maximum over both observers. The simplest analysis is a Generalised Linear Model (GLM, plus model selection) regressing sum-of-counts versus mean environmental and spatial covariates. The inference is predicting counts of animals per unit area, called surface density modelling. Although this is coarse, the advantage of this analysis is that the models have unique solutions, are objective (in the sense of requiring little prior information) and the outputs are easily interpretable and communicable.

The disadvantages are that the models are so simplistic that they ignore multiple sources of variation and uncertainty (e.g. non-linearities, spatial autocorrelation). A subtle variation of the above is density surface modelling with observer error modelled as a function of distance and other covariates. This inflates the observed sum-of-counts with expectations of the detected proportion of animals. See Miller et al. (2013) for an overview.

7.6.4 Statistical analyses at the fine scale

At the finest scale of resolution, we propose a Hierarchical Bayesian marked non-homogeneous point-process (MNHPP) model (Banerjee et al., 2015). The response is the precise location of cetacean groups as clusters and the conditional abundance (the ’mark’ per point). Points are considered ‘missing’ due to observer error, which is modelled as a function of distance and other covariates (e.g. group size). Inference is predicting the abundance and clustering of dolphin groups, and estimating the influence of covariates (e.g. depth). The conceptual advantage of the MNHPP model is that clustering is inherently spatial and highly ‘zero-inflated’, and the decomposition of the counts into different processes (occurrence, abundance and observer error) provides estimates that are less biased than univariate generalised linear models, and may be better approximations of reality. Point-process methods are under intensive theoretical research and have proved to be promising when compared to other established ecological species distribution models (Chakraborty et al. 2013; Renner & Warton, 2013). For all of these models' advantages, they are very complex and therefore may require strong prior information to stabilise estimates. Bayesian analyses are, by definition, more subjective, and therefore require careful elicitation of prior information.

These two analytical frameworks (broadscale density surface modelling and finescale point processes) represent two extremes on a continuum of simplicity/bias and complexity/variance. These serve as useful starting points for analyses. However, there are other intermediate methods, like Hierarchical Bayesian spatial Generalised Linear Mixed Models which may have a better trade-off between analytical tractability and realism.

7.6.5 Material and personnel

1. A large vessel with ability to accommodate 12 people, carry a tender, provide a viewing platform for two pairs of observers at least 5.5 metres high, be suitable for retrieving a floating, rotating-wing drone, provide skippers and other support crew and supply food
2. Two rotating-wing drones, battery charger and spare batteries to identify species and count dolphins in groups
3. A tender suitable for dolphin surveys
4. Three pairs of two observers – one pair for each side of the big boat with an exchange crew – some of these will need to be able to skipper the small tender (taken for safety and to check on the drone's measurements)
5. A pilot for the drone
6. A statistician/data manager – to update the design according to the criteria given conditions, monitor protocol, gather all data each day and support the other crews (e.g. the drone pilot, tender crew).

7.6.6 Cost estimate

An indicative cost for the supply of a liveaboard vessel and support vessel (including crew and all fuel) is provided in Appendix 4 ($280,000 plus GST). As described in the appendix, the items in the remainder of the list would need to be costed separately.

7.7 Traditional Owner and Indigenous ranger engagement and involvement

As specified in the Framework (2015), the primary enabling objective is: **Objective 1 - Indigenous Engagement:** *Foster effective and informed partnerships with Australia's Indigenous communities to enable sustainable conservation management of tropical inshore dolphins*. It is therefore acknowledged that appropriate Traditional Owner and Indigenous ranger engagement will be essential to implement all aspects of this coastal dolphin project. Both capture-recapture studies and the spatial survey will require the permission from the relevant Traditional Owner groups/Aboriginal Corporations, as well as appropriate State and Marine Park research permits. It is anticipated that a project information sheet will be sent to all Reef Traditional Owner groups/Aboriginal Corporations well in advance of any surveys being conducted to gain permissions, and provide an opportunity for meetings/presentations to be conducted with groups to answers questions and provide further information. It will be important that opportunities are provided to Traditional Owners/Indigenous rangers to join capture-recapture surveys and the spatial survey where possible, ideally with at least two representatives joining surveys when they are conducted throughout respective sea Country. Any budget costings will need to include allowances for appropriate Traditional Owner/Indigenous ranger engagement and involvement.

8.0 Appendix One: Methods used to study coastal dolphins

Methods to address research objectives 2-4 from the Framework (Department of Environment 2015) are discussed below.

8.1 Spatial sampling methods (Framework Objective 2)

Distance sampling or density surface modeling (e.g. Miller et al., 2013) may be used to study the broadscale distribution of cetaceans and estimate abundance. While this type of approach has been employed elsewhere to study dolphin populations (e.g. Forney et al., 2012; Dawson et al., 2004), studies that have used counts from aerial or boat-based surveys for coastal dolphins are relatively few in Australia. The Northern Territory Department of Land Resource Management conducted helicopter surveys for coastal dolphins along the Northern Territory coast in 2015 and 2016 using spatial sampling (paper in preparation). An earlier fixed wing aerial survey was conducted in Northern Territory waters by Freeland and Bayliss (1989) using distance sampling methods. Other studies include Preen et al. (1997) in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia, and Bilgmann et al. 2017 off the western Eyre Peninsula in the Great Australian Bight.

Very little is known about the spatial distribution of snubfin and humpback dolphins, the extent of their habitat use, or their movements (Framework, 2015). Although capture-recapture studies (described below) provide insight into demographic parameters of dolphin populations (albeit that they can only estimate apparent survival and apparent births), they have little to offer towards understanding spatial distribution or abundance on broader scales such as those described in the preceding paragraph. While the Multistate Closed Robust Design Model (MSCRD, Brownie *et al*., 1993; Nichols and Coffman, 1999; Kendall and Nichols, 2002; Kendall, 2013) can model movements between sites, they rely on observation of a sufficient number of movements of individuals to make informative estimates. This is often not the case with populations using a pair of sites, because population sizes are typically small and it is necessary to capture the same individuals on different sites in consecutive primary samples.

8.2 Capture-recapture methods (Framework Objective 3)

Capture-recapture methods have been widely used to estimate demographic parameters for a number of dolphin species including snubfin, humpback and bottlenose dolphins (Würsig and Jefferson, 1990; Parra et al., 2006a; Nicholson et al., 2012, Palmer et al., 2014; Brown et al., 2016). A general overview of capture-recapture models is found in Amstrup et al. (2005) while more detailed coverage is found in Williams et al. (2002).

Snubfin, humpback and bottlenose dolphin dorsal fins bear nicks and marks that allow identification of individuals from photographs. These identifiers provide a mechanism for population estimation based on capture-recapture methods, where re-sightings of individuals with distinctive natural marks constitute re-captures (Hammond and Thompson 1990). Typically, images of dorsal fins showing nicks and scars on the leading and trailing edges and overall fin shape are employed as the primary means of individual identification, while pigmentation patterns are sometimes used as secondary identifiers.

Closed population models assume that no deaths or emigration nor births or immigration occur during a sampling period (i.e. all members of a local population are present and available for capture in the study area during the sampling period). Open population models assume that there may be both deaths or emigration and births or immigration during a sampling period. Capture-recapture models cannot estimate biological survival separately from emigration and estimate the combined effect of both as apparent survival. Similarly, these methods cannot estimate in-situ births separately from immigration and estimate the combined effect of both as apparent births.

Closed population models are typically used to estimate capture probability and abundance while open population models primarily estimate capture probability and apparent survival, with abundance and apparent births estimated as derived parameters from the data and primary model parameter estimates. An advantage of closed population models, when they can be justified, is that they allow heterogeneity of capture probabilities between individuals or in response to first capture (behavioural response) among the sampled population to be modelled. Un-modelled individual heterogeneity results in a downward bias in abundance estimates. Therefore, capture-recapture studies are primarily concerned with finding the ‘correct’ amount of heterogeneity and model complexity, in order to balance the trade-off between biases from un-recognised sources of heterogeneity versus instability of estimates (high-variance) due to overfitting.

Robust design models may integrate both closed and open population models (the Closed Robust Design; CRD; Pollock, 1982; Kendall et al., 1995; Kendall and Nichols, 1995; Kendall et al., 1997) allowing for heterogeneity to be modelled where necessary and for apparent survival and apparent births to be estimated along with accurate abundance estimates. This is achieved through a sampling design with sampling conducted at two temporal scales. A set of secondary samples is taken over a relatively short period in which deletions from (deaths and emigrants) and additions to (births and immigrants) the population are unlikely to occur to compose a primary sample, with a series of primary samples taken over a longer period in which the intervals between primary samples are such that deaths or emigration and births or immigration are likely to occur.

Apart from the capacity to model heterogeneity, robust design models have two major advantages over other sampling schemes and models: 1) each primary sample can be taken in a relatively short period allowing monitoring crews to sample several sites in each sampling period (often a year or a season); and 2) the proportion of the local population which is offsite and unavailable for capture for the duration of each primary sample can be estimated as temporary emigration. This allows for a better understanding of a series of abundance estimates (animals present and those temporarily absent), and insight into large-scale seasonal or other movements of proportions of the local population on and off the sampling area. Depending on the temporal structure of temporary emigration, abundance estimates may be biased low in the presence of un-modeled temporary emigration.

The Framework referred to above (Department of Environment, 2015) was an update on an earlier Framework (Department of Environment, 2013). Brooks, Carroll and Pollock (2014) wrote a document on methods for implementation of the original Framework (Methods 2014; unpublished) and Brooks and Carroll (2016) wrote a revised document (Methods 2016; unpublished) to reflect recent research and changes in the objectives between the two Frameworks. The section on abundance on selected sites (long-term monitoring) in Methods (2014) was expanded to include short-term preliminary studies but otherwise unchanged in Methods (2016) and describes in some detail why the robust design is chosen as the preferred model for long-term monitoring of coastal dolphin populations and specifies criteria to be employed in the design of sampling schemes for these studies. While we do not repeat that discussion here, we mention it in order to establish a basis for evaluation of capture-recapture studies conducted in the Reef to date. We propose to evaluate the existing capture-recapture research on coastal dolphins in the Reef in terms of its conformity with (or conformability to) a robust design approach to ongoing modeling.

These are difficult species to study due to their sparse distribution, three-dimensional movements, high mobility and cryptic behaviour. Capture-recapture studies based on photo identification of individuals are by far the most often used means of studying Australian coastal dolphins.

8.2.1 Sampling principles for robust design capture-recapture studies: a primary sample

As described in Methods 2014 (p .31), an abundance estimate may be made from the first primary sample in a robust design study, which is simply a closed population study over two or more secondary samples. It is sensible to design a pilot study for short-term assessment of previously unstudied sites with the potential to continue the study as a robust design should further study on the site be justified. Depending on the size of a population, a capture probability greater than 0.2 is a sensible target (statistical power decreases with the size of the population) for robust design studies. The capture probability that may be considered appropriate for a longer-term study may be too low however for an accurate (unbiased and reliable) one-off estimate. Our aim is to generate abundance estimates with the Coefficient of Variation less than or equal to 0.2.

We recommend that the area searched on transect be estimated from an assumed sighting distance (our rule of thumb is sighting distance = half-strip width = 250 metres) and transects be laid out to achieve at least 30 per cent coverage of the study area per secondary sample. This puts parallel transects at approximately 1.5 kilometres apart.

Transects were placed two kilometres apart in Cleveland Bay (Beasley, Table 1) giving 25 per cent coverage of the sample area in each of four secondary samples with an assumed half-strip width of 250 metres. The inclusion of a number of dolphins sighted off-effort in the analysis yielded abundance estimates with a Coefficient of Variation of 0.20 for snubfin and a Coefficient of Variation of 0.10 for humpback dolphins.

Surveys in Bowen, Repulse Bay, Mackay, Port Alma and Port Curtis have been conducted following a standardised parallel line transect survey design. In Bowen, Repulse Bay and Port Curtis transects were placed 1.2 kilometres to each other whereas in Port Alma and Port Curtis transects were placed at a distance of two kilometres (Cagnazzi, Table 1). Assuming a half strip width of 250 metres, these surveys had 33 per cent and 25 per cent coverage respectively (Cagnazzi argues that it is reasonable to assume a half-strip width of 400 metres giving coverage of 53 per cent and 40 per cent respectively). These surveys provided robust and reliable abundance estimates which generally met or exceeded the Coefficient of Variation less than or equal to 0.2 criterion (Table 1).

The intensity of these studies was high and probably close to a practical maximum, especially for the surveys in Bowen, Repulse Bay and Port Curtis. Measures that might be taken to maximise capture probabilities given these coverage rates include employment of experienced, skilled camera operators, and continuing to photograph a group until as many individuals as possible have been captured in good photographs, or the dolphins show signs of boat avoidance.

An advantage of the robust design over other long-term study methods is that it can model heterogeneity of capture probabilities due to individual differences and behavioural response to first capture (Methods 2014). It requires at least four and preferably more secondary samples per primary sample to achieve suitable precision however. With heterogeneity rarely found in studies of these animals, four secondary samples per primary sample seems to be a reasonable compromise between achieving a suitable capture probability in each secondary sample and the expenditure required for each primary sample. An advantage of an even number of secondary samples per primary sample is that, should the capture probability be found to be too low, secondary samples can be aggregated in pairs; two secondary samples is adequate but not optimal for a primary sample.

Study sites are generally smaller than the home ranges of the local populations under study, and the implications of this for the closure assumption within a primary sample are discussed in Methods 2014 (pp. 29-30). Dolphins may enter and leave the study area during a primary sample and, provided such movement is random (does not vary by individuals or groups of dolphins), an abundance estimate will be unbiased if it is interpreted as an estimate of the number that used the sample area during the primary sample period. The rates of movement into, and out of, the sample area within a primary sample is generally unknown and cannot be modeled; temporary emigration refers to off-site absences for entire primary samples. Consequently, although rates of movement are unknown, it seems likely that studies conducted over very short periods will yield lower abundance estimates than longer duration studies, and that primary samples of similar duration be adopted for robust design studies on different sites for consistency.

Many studies have been conducted on sampling areas of between 300 and 500 square kilometres (Cagnazzi et al., 2011; Cagnazzi et al., 2013; Parra et al., 2006a; Beasley et al., 2017; Cagnazzi et at., 2017). This is almost certainly smaller than the area of habitat used by populations that use the site and consequently, such studies rely on most dolphins in the broader area moving onto the sampling area with sufficient frequency to ensure their availability for capture during the course of a primary sample.

Under normal circumstances, depending on weather conditions and whether more than one boat is used, a primary sample would normally be completed in a month to six weeks.

8.3 Other methods (pertinent to Framework Objective 4)

8.3.1 Biopsy sampling

Biopsy sampling may be employed for a variety of reasons: It may be used as a means of individual identification for capture-recapture research (e.g. Constantine et al., 2012); to study genetic diversity, gene flow and demographic history (see below); to estimate rates of movement by distance with close-kin capture-recapture (Bravington et al., 2016); or to investigate toxin loads or concentrations of stable isotopes (Cagnazzi et al., 2013; Parra and Jedensjö, 2014). Biopsy sampling is rarely employed in studies of coastal dolphins due to the expense and effort it requires and to avoid harassment of the animals. However, a long-term study to assess the population structure of humpback and snubfin dolphins in Queensland (Moreton Bay to Hinchinbrook Channel) has been recently completed by Parra, Cagnazzi and collaborators (Parra et al. 2018). This study showed that both species along the Queensland coast are divided into small discrete populations connected by limited contemporary gene flow (m=0.017 to 0.047). Each population is characterised by low genetic diversity, low contemporary effective population size (Ne =11.5–31.2) and a widespread genetic bottleneck 50–150 generations ago.

9.0 Appendix 2: Power analysis for capture-recapture studies

This appendix includes a simulation study to investigate the power of capture-recapture studies to detect trends in abundance of snubfin and humpback dolphins. The exercise was requested to answer questions such as: given a -3 per cent annual rate of change in abundance[2], how many years of capture-recapture sampling are needed in order to confidently detect the trend? The exercise makes use of empirical levels of uncertainty found in recent, intensive capture-recapture studies near the Reef (see Sampling Principles for Capture-Recapture Studies above).

Background

To investigate the power of trend detection, we used the familiar Neyman-Pearson framework called inductive behaviour (Neyman and Pearson, 1933). The scenario is as follows: imagine that a conservation manager wishes to detect a trend, but wants to avoid raising false alarms when there is no trend (a Type-I error), nor miss important declines (a Type-II error). This framework involves prescribing four quantifies: i) a test-statistic (e.g. a trend estimate); ii) a rejection region for the test statistic (e.g. greater than three per cent annual change); and the long-term acceptable Type-I and Type-II error rates. We define the Type-I error as: declaring that the trend estimate is below -3 per cent per year or greater than three per cent per year, conditional on there being no trend (i.e. the manager incorrectly rejects the null hypothesis and raises a false alarm). The long-run frequency of Type-I errors is hopefully capped at a rate called α. We define the Type-II error as: declaring that the trend estimate is greater than -3 per cent (i.e. the manager fails to detect a biologically important trend)[3]. The long-run frequency of Type-II errors is β, and the “power” to detect a trend is $1-\beta$. At each simulation, the manager calculates the trend-estimate and test-statistic from the capture-recapture abundance estimates, and compares the trend to the rejection region and takes one of two actions: enact conservation invention or not.

In this scenario, data are costly to collect, and so the manager must economise effort by controlling: i) how extensive the data are (i.e. the maximum number of years of the capture-recapture time-series); and ii) how intensive the data collection is (i.e. modifying the intervals

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[2] As a point of reference, a consistent 3.5% annual decline accumulates to a 30% decline in 10 years and would meet the IUCN criterion for “vulnerable”.

[3] This exercise differs slightly from the classic Neyman-Pearson (NP) power-analysis. Whereas the classic NP framework is to test the hypothesis the null hypothesis of a trend estimate of zero versus the alternative hypothesis that the trend is not equal to zero, for mathematical simplicity, we only consider two point-hypotheses: H_0: $\beta=0$ vs. H_A: $\beta >= |-3|$.

between subsequent sampling events). Our interest is in how these decisions affect the Type-I and Type-II error rates.

The crux of the exercise is setting the acceptable error rates. For interesting and complex historical reasons (Hubbard et al., 2003; Lehmann, 1950; Lehmann, 1993), the default set-up is to cap Type-I error at less than or equal to 0.05, and then try to maximise power by increasing sample size. However, error rates are only meaningful in the context of costs of incorrect action or inaction (Wald, 1939). For example, the conventional $\alpha = 0.05$ versus a $\beta = 0.2$ places a very high burden of proof on the manager to rule out the ‘no trend’ null-hypothesis, making it very difficult to detect even precipitous declines (Taylor et al., 2007). For conservationists and government resource managers, it is conceivable that missing a negative trend early on will result in much more expensive remedial actions later when the population reaches a critically low level. At the very least, we would argue that a conservationist would set α and β to be equal (and possibly $\beta<\alpha$), implying that the cost of missing a real decline is at least as great as the cost of wrongly enacting conservation activities when there is no decline. Thus, we do not use the α=0.05 convention, and instead suggest using α= 0.1 and β= 0.1: we expect to be wrong at most one time out of 10 in declaring that there is a trend if it does not exist; and, we hope to minimise the error-rate of missing a trend, when there is one, to a target rate of one in 10.

Methods

The simulations consisted of randomly generated time-series of counts of dolphins. The simulations varied according to different conditions; we varied: i) the starting population abundance (132 animals for snubfin, 86.2 for humpbacks); ii) the true exponential annual decline (0 per cent and -3 per cent change per year); iii) the length of the study duration in years (from four to 30 years); and iv) the interval in years between surveys (1, 2, 3, or 4). For each scenario, annual abundances were randomly generated from a log-normal distribution, where the log-mean was set according to the true deterministic trend, and the root-variance was set according to the empirical Coefficients of Variation of abundance estimates from recent robust-design capture-recapture studies at Cleveland Bay, Rodds Bay/Port Alma, Port Curtis, Keppel Bay, Mackay, Repulse Bay, and Bowen. For snubfin, the Coefficients of Variation were: 0.2, 0.05, 0.17, and 0.21 (excluding sites were 0 animals were captured). For humpbacks, the Coefficients of Variation were: 0.1, 0.06, 0.04, 0.06, 0.19, 0.57 and 0.16. The Coefficients of Variation included variation due to sampling error and adjustments for the mark identification rates. For more details about the data sources, please refer to Table 1 in the main document. Due to the variation among Coefficients of Variation per study, we randomly sampled Coefficient of Variation values per simulation, using the above numbers as discrete distributions. The variation and uncertainty in the Coefficients of Variation reflects processes such as missed captures, death, and temporary migration, as per the Pollock's Closed Robust Design sampling procedure and analysis.

Each simulation scenario was repeated 1000 times. Per simulation, a Poisson Generalised Linear Model was run. The Generalised Linear Model used the simulated counts as a response variable and ’years’ as a continuous regression variable. When the true trend was 0 per cent per year, and the estimated trend was greater than three per cent per year or less than -3 per cent per year, we declared that a Type-I error had occurred (raised a false alarm). When the true trend was -3 per cent per year and the estimate was greater or equal to 0 per cent per year, we declared that a Type-II error had occurred (missed a real decline). The expected error rates were calculated as the mean number of Type-I and Type-II errors over all simulations. The goal was to estimate how many years it would take to cap the expected Type-I error rate at 0.1, and lower the Type-II error rate to 0.1. We were also interested in how these rates were affected by the size of the interval between capture-recapture sampling years.

Results

Table A.2.1: Number of years to confidently detect a -3 per cent decline.

Intervals between sampling events (years)	Snubfin	Humpback
1	9.01	9.69
2	10.29	10.61
3	11.96	11.81
4	14.09	13.49

The Table A.2.1 shows the estimated number of years needed to cap the Type-I errors and achieve a power of 0.9 (1-β), stratified by species (starting population abundance) as well as the role of the number of years between successive capture-recapture surveys. With yearly sampling it would take about 10 years of snubfin studies and 12 years of humpback studies to confidently detect a trend of -3 per cent and rule-out false-alarms (in expectation). Increasing the number of intervals between successive samples, from 1 to 4, resulted in 1.2 to 2.7 more years of sampling in order to achieve the same error rates.

The results reflect the empirical data, as well as our choices about acceptable long-run error rates. In contrast, had we chosen to cap the Type-I error rate at 0.05 (i.e. deeming it more important to avoid false-alarms), and set the β to 0.8, then it would take 12 years of consecutive sampling to detect a trend for snubfin, and 16 years for humpbacks.

A final word of warning about the limitations of the simulations and the nature of linear declines: although the power to detect trends did not seem to be drastically affected by the size of the sampling intervals (i.e. only varied within a few years), the simulation exercise assumes a constant rate of decline which is inherently easier to detect than unpredictable and sharp discontinuities. For example, it may be that drastic swings in the environment, such as flooding or intensive port development, concentrate the population change with a few years. Long sampling intervals may miss these dramatic events.

10.0 Appendix 3: Simulations for Preliminary Power Analysis of the Proposed Spatial Survey of the northern Great Barrier Reef

The purpose of this simulation exercise was to provide a semi-quantitative context for the northern Reef spatial survey and its ability to estimate large spatial trends in abundance. The results have influenced design considerations of the proposed large spatial survey of the northern Reef, and future more sophisticated simulations can help refine the necessary design and analytical considerations.

This type of exercise is somewhat reminiscent of conventional power-analyses (e.g. Murphy et al., 2014), but the procedure is modernised to include model-selection uncertainty, which is a major preoccupation of all ecological statistical analyses. Furthermore, the exercise is focused on accurate trend estimation (including bias and variance components) rather than on the outmoded convention of controlling Type-I error rates (e.g. falsely rejecting a “Null Hypothesis” of no trend). Specifically, the analyses compares the square-error of trend estimation versus changes in: i) true effect size, ii) number of transects, and iii) mean density of dolphins (based on estimates of snubfin and humpback dolphins from the Northern Territory; Northern Territory Department of Land Resource Management in prep.).

10.1 In summary, the conclusions are:

- The number of transects should be increased from 25 to 30, with diminishing returns thereafter; at realistic densities of snubfin and humpback dolphins, only moderate-to-large trends (such as a 25 per cent increase/decrease in abundance) may be accurately estimated and distinguishable from spurious effects;
- Completely random sampling of habitats may be inadequate, and the design should increase the sampling weight of strata with higher densities of dolphins.
- The simulations are conservative, in that the densities used were half of the densities of animals in the Northern Territory (we applied a 0.5 correction factor as a cost of extrapolating beyond existing studies into a new area).
- The simulations ignore observer error, spatial autocorrelation, multicollinearity, and other realistic sources of uncertainty and assumption violations, which should further decrease the estimation accuracy. These will need to be considered in a more sophisticated power analysis, and to provide further refinements to the survey design.

10.2 Simulation Design

The baseline simulation scenario included a rectangular spatial grid of 1000 x 80 kilometre (a rectangular analogue of the northern Reef nearshore environment), discretised into n x 80 spatial units, where n was the number of transects. Each spatial unit had a survey area of 0.8 kilometres x 1 kilometre, corresponding to a 1 kilometre segment of transect and an 800 metre strip width. The counts of animals were Poisson distributed within each spatial unit, at a rate consistent with observed densities measured in the Northern Territory for snubfin (9.43x100 square kilometres) and humpbacks (2.63 x100 square kilometres), multiplied by a 0.5 factor (to be more conservative in the face of extrapolation beyond the area of measurement). The distribution of animals varied according to two spatial covariates, with variable effect sizes: i) a continuous-variable latitudinal gradient, and ii) a randomly distributed categorical variable representing ‘reef’, making up 20 per cent of the study area. The latter is an estimate of the background availability of reef habitat. The two covariates had independent multiplicative effects on dolphins' abundance according to five scenarios: x = [1.00, 1.10, 1.25, 1.50, and 2.00] (i.e. the last value corresponded to a doubling of dolphins’ mean abundance across the covariate space). Additionally, there were two spurious covariates: a longitudinal gradient, and a completely random continuous covariate, both of which had no effect on animal abundance. In summary, the simulations varied according to: i) the density of animals (1.315, 4.715 100 square kilometres); ii) number of transects (25, 30, 38, 44, and 50); iii) strength of true covariates’ multiplicative effect (1.00, 1.10, 1.25, 1.50, and 2.00) for two different covariates. This corresponded to a 2 x 5 x 24 factorial design. Each scenario was run for 100 simulations.

The proximate task for each simulation was to estimate the marginal multiplicative effect of the two covariates (latitude and reef) while trying to filter out spurious covariates. Each simulation uses L2boosting (Bühlmann & Yu, 2003) to simultaneously perform both model selection and Poisson estimation using the R package ‘mboost’ (Bühlmann & Hothorn, 2007). This is philosophically very similar to AIC based model selection and estimation: both combine estimation and model-selection by trying to maximise the Expected Likelihood (Akaike, 1998).

The simulation results were summarised by the R statistic: ratio of the true effect size versus the square-root of the mean square error of estimation. When R > 1, then the expected error of estimation is lower than the actual effect size, suggesting some reliability to detect a trend. When R is less than or equal to one, then the expected error of estimation is equal to or greater than the actual effect size, and the procedure cannot be said to reliably detect any trend. Ideally R should be much greater than one. Notice that due to “model selection uncertainty” and selection-competition with spurious effects, the true covariates effects will frequently be missed entirely (i.e. they receive an estimate of zero); therefore, all model selection procedures have an expected bias that is slightly negative.

10.3 Results

The power analysis suggests that given the assumed densities of coastal dolphins (1.315 to 4.715 100 square kilometres), the design and statistical procedure can only provide reliable estimates at moderate effect sizes (such as greater than or equal to 25 per cent change in abundance over the span of a covariate space), as shown in Figure 6 where the R ratio is only greater than one for true effect sizes greater than or equal to 1.25. At densities of 1.315 100 square kilometres (e.g. for humpbacks), the power analysis suggests that for n is greater than or equal to 30 transects, the statistical procedure and design can reliably estimate an effect size of 1.5. However, the R ratios are very small (1-1.5) even for very large effect sizes, such as a doubling of abundance. At higher densities (e.g. 4.715 100 square kilometres for snubfin), there is a greater power to estimate effect sizes, but true effect sizes below 1.25 are undetectable and remain entangled with the error estimation and model-selection uncertainty. For example, the expected bias for low effect sizes were very high, equal to the true effect, which reveals how such small/moderate effects are unlikely to be selected in a model-selection exercise.

The assumptions of the power analysis are highly simplistic, such as excluding observation error, over-dispersion, spatial autocorrelation, and more. These will likely decrease the ability of estimation procedures to reliably estimate effects, and should be the subject of more sophisticated future power-analyses to refine the design of the spatial survey.

Nonetheless, the analysis reveals two pernicious challenges of the spatial survey and analysis which erodes our ability to detect moderate or small effects: i) the low densities of coastal dolphins; and ii) the “model selection problem”, when analysts have multiple competing covariates which may have some or no effect on dolphin densities, and must appeal to a model selection procedure to simultaneously select and estimate effects. The latter is typically ignored in power analyses. The former, however, can be partially addressed by design considerations.

The implication for design considerations are to: i) use at least 30 transects; ii) increase the encounters and detections of dolphins, such as increasing the strip width from 800 metres; iii) avoid completely random sampling of coastal strata (e.g. reefs), and instead increase the weight of sampling effort for those areas of higher dolphin densities. Future power analyses should include more sophisticated analyses (including distance-observer error, more spatial covariates, and different degrees of spatial autocorrelation) in order to benchmark different statistical paradigms, such as linear-models versus point-process spatial models.

Future power analyses will address more sophisticated aspects the analytical framework, such as the power of point-processes models versus simpler Generalised Linear Models to detect changes, and the role of unknowable sources of heterogeneity and violations to model approximations (spatial autocorrelation, high clustering of individuals, non-canonical count distributions).

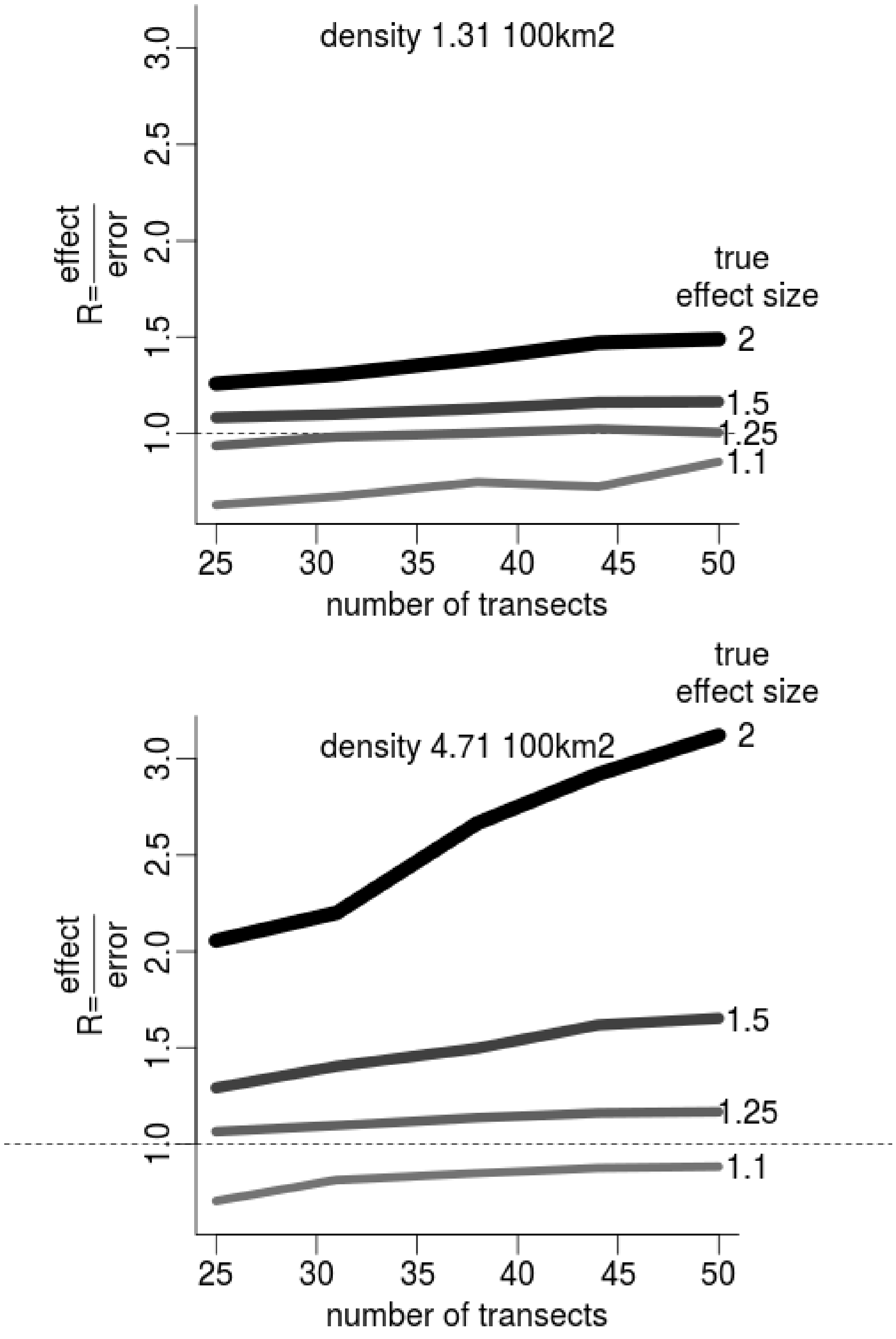

Figure 6. R is the ratio of the true effect size for covariates versus the expected error of estimation (root means square error of estimation). R varies by the number of transects (x-axes), the background density of dolphins (top panel versus bottom panel) and the true effect size (different lines).

11.0 Appendix 4: Indicative costings

11.1 Capture-recapture monitoring of one site for one primary sample

Daniele Cagnazzi has provided a full costing for one primary sample in a robust design capture-recapture survey on a single site (Table A4.1). This is a full commercial costing based on access to funds from major developers and may overestimate the costs that might be expected for monitoring conducted as a research project through a university. University management costs, and costs for Traditional Owner/Ranger involvement, would need to be considered and incorporated into project costs.

Table A4.1. Full commercial cost of a primary sample of four secondary samples on site of 480 square kilometres.

Material/ personnel	Cost item	Unit cost	Number of days	Total cost $
Research Leader	A8 level for 8 hours a day for 3 months	57.34	90	41284.8
Boat 1	Average daily cost based on Cagnazzi experience	450	12	5400
Boat 2	Average daily cost based on Cagnazzi experience	450	12	5400
Boat 1 non water day	Average daily cost based on Cagnazzi experience	250	1	250
Boat 2 non water day	Average daily cost based on Cagnazzi experience	250	1	250
Boat 1 fuel	Average daily cost based on Cagnazzi experience	110	12	1320
Boat 2 fuel	Average daily cost based on Cagnazzi experience	110	12	1320
Skipper 1 water days	Basic commercial rate	350	30	10500
Skipper 2 water days	Basic commercial rate	350	30	10500
House * 8	Based on Cagnazzi experience	250	30	7500
Car1	University rate including fuel	80	34	2720
Car2	University rate including fuel	80	34	2720
Research assistant	With experience in photo-id	32.49	30	7797.6
Research assistant 2	With experience in photo-id	32.49	30	7797.6
Volunteer 1	Some basic knowledge of dolphin work	22.49	30	5397.6
Volunteer 2	Some basic knowledge of dolphin work	22.49	30	5397.6
Food	Based on Australian average weekly spending	104	34	4160

TOTAL	119715.2
15% risk factors	17957.28
TOTAL including risk	**137672.48**

11.1.1 Recommended frequency of monitoring

A biannual sampling interval is recommended to achieve a balance between sampling costs, statistical power and the ability to describe the pattern of observed decline processes.

As described in Appendix 2, statistical power to detect a consistent exponential (percentage) decline (or increase) depends on the intervals between consecutive samples, the size of the starting population and the standard errors of the estimates. Table A.2.1 gives the numbers of years required to detect a 3% annual decline given typical sizes of snubfin and humpback dolphin populations (132 and 86 respectively in existing Reef studies) and the precision achieved in more recent robust design capture-recapture studies. Naturally, the number of years required to detect a consistent decline increases with the size of the sampling interval but, perhaps more importantly, longer intervals mean that a consistent decline may be difficult to distinguish from sample to sample variation, whether this is random or due to varying conditions.

11.2 Dual observer spatial sample in the northern Great Barrier Reef

Blue Planet Marine has provided an indicative cost to supply a suitable liveaboard vessel and a support vessel (six metre Rigid Inflatable Boat in independent 2C survey) for 52 days (including crew and all fuel). This is the first dot point in the list of material and personnel in the above proposal for spatial sampling in the northern Reef. The items in the remainder of the list would need to be costed separately.

This costing is provided as an indicative costing only for the supply of a liveaboard vessel and support vessel (rigid hulled inflatable boat) suitable to undertake and support inshore dolphin surveys between Cairns and Thursday Island, Queensland.

This indicative costing is based on a number of assumptions:

1. 30 X 80 kilometre transects to be undertaken between Cairns and Thursday Island
2. Surveys to be undertaken at a speed of eight knots (15 kilometres per hour)
3. Surveys to be undertaken in sea state Beaufort 2 or below
4. For fatigue management it is assumed that only one survey transect will be completed per day
5. A liveaboard vessel able to comfortably accommodate and feed a minimum of 12 personnel and work in remote areas unsupported on extended charter for a period of up to two months

6. A proven history of operating in the waters of the far northern section of the Reef including operating within unsurveyed reef areas
7. Hold suitable survey for area of operation and number of personnel carried
8. Observation platform with 360 degree view, a minimum eye height above sea level of 5.5 metres eye and suitable to house observers with a double blind configuration.
9. Hold a Great Barrier Reef Marine Park Authority commercial operators permit for the area of operation
10. Hold the appropriate research (the Authority and Queensland State) and animal ethics permits to undertake the survey
11. Supply of a six metre Rigid Inflatable Boat in independent 2C survey to operate from the mother vessel to support research activities
12. Rigid Inflatable Boat to operate a maximum of two hours per day
13. Survey to commence and finish in Cairns
14. 15 transects to be surveyed during the northern passage between Cairns and Thursday Island and 15 transects to be surveyed during the southern passage between Thursday Island and Cairns
15. Suitable for launching and retrieving a drone or multiple drones from the top deck of the mother vessel
16. Have an experienced crew with a detailed understanding of undertaking and supporting research activities and extensive experience operating in remote areas of the Reef
17. Assumption that to operate in under Beaufort 3 conditions you would on average only get four days out of seven suitable to survey
18. Optimum survey time is recommended to be November and December. While January to February have the lowest wind speeds in the region, these months have the highest rain falls (along with March) and therefore increased turbidity within coastal waters, especially near rivers

Based on the power analysis for the optimum number of transects to meet the survey objectives, and based on the assumption of only being able to survey four out of seven days to meet the required Beaufort 3 cut off, then it will take approximately 52 days to complete the 30 X 80 kilometre transects (assuming one transect is completed per suitable weather day).

Indicative cost to supply a suitable live aboard vessel and a support vessel (six metre Rigid Inflatable Boat in independent 2C survey) for 52 days (including crew and all fuel) = $280,000 plus GST.

12.0 References

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