Paua research diver survey: review of data collected and simulation study of survey method

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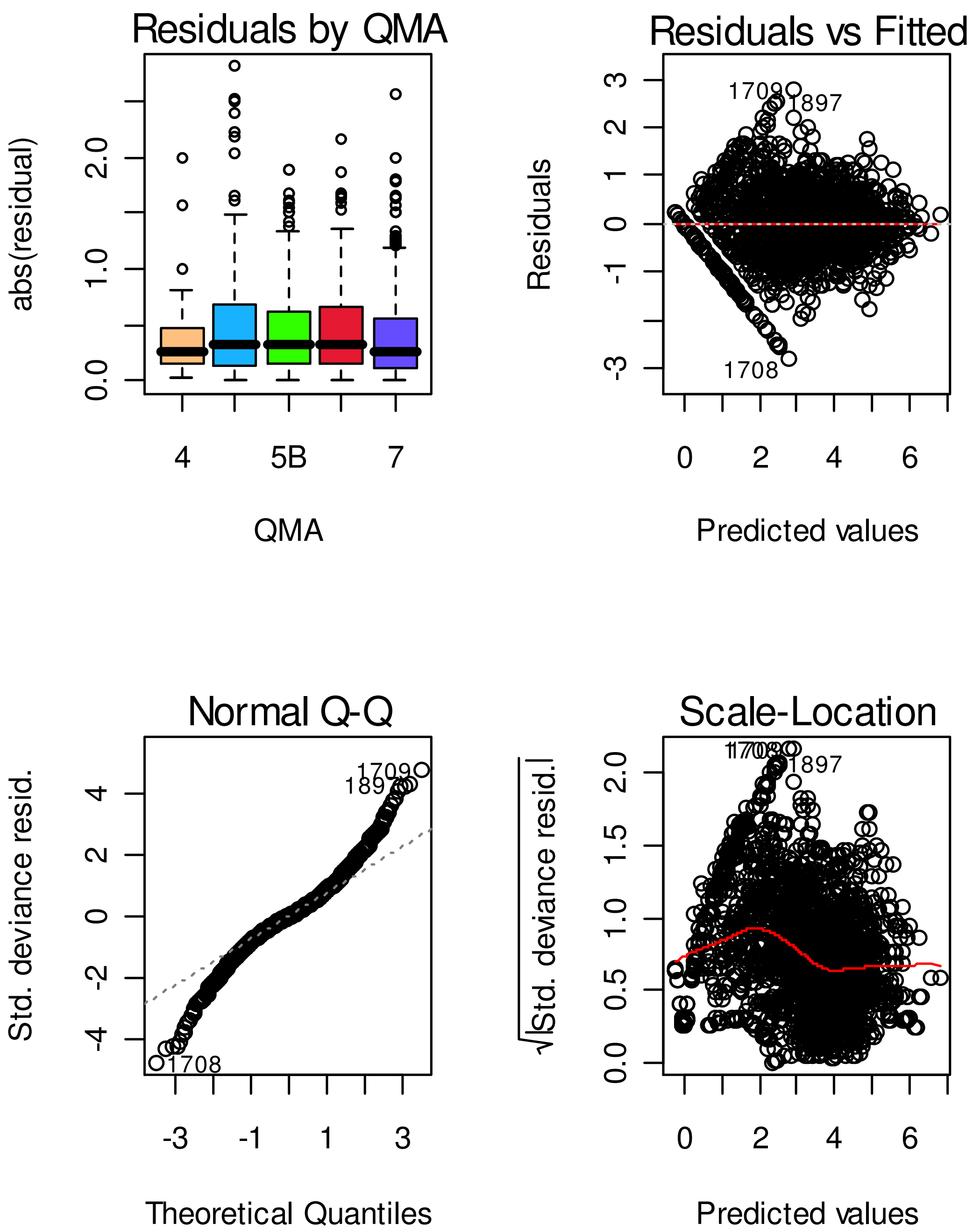

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EXECUTIVE SUMMARY

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Paua research dive surveys, based on a timed-swim method, have been conducted using consistent methods since 1993 and results from the surveys are routinely used in stock assessments. Over that time 2293 individual dives have been recorded across the five QMAs that support major commercial fisheries. The data represent a considerable investment and resource; understanding potential biases in the potential abundance indices is crucial for their use in assessing stock status.

A simulation approach is used to evaluate the utility of the timed-swim survey method for estimating relative paua abundance. This report presents: 1) analyses of the historical research dive survey data to inform the structure of the simulation model; 2) development of a model that simulates paua distributions and diver behaviour during dive surveys; 3) analysis of the behaviour of the simulation model relative to model control parameters; and 4) results of simulations that represent dive surveys across a range of paua densities.

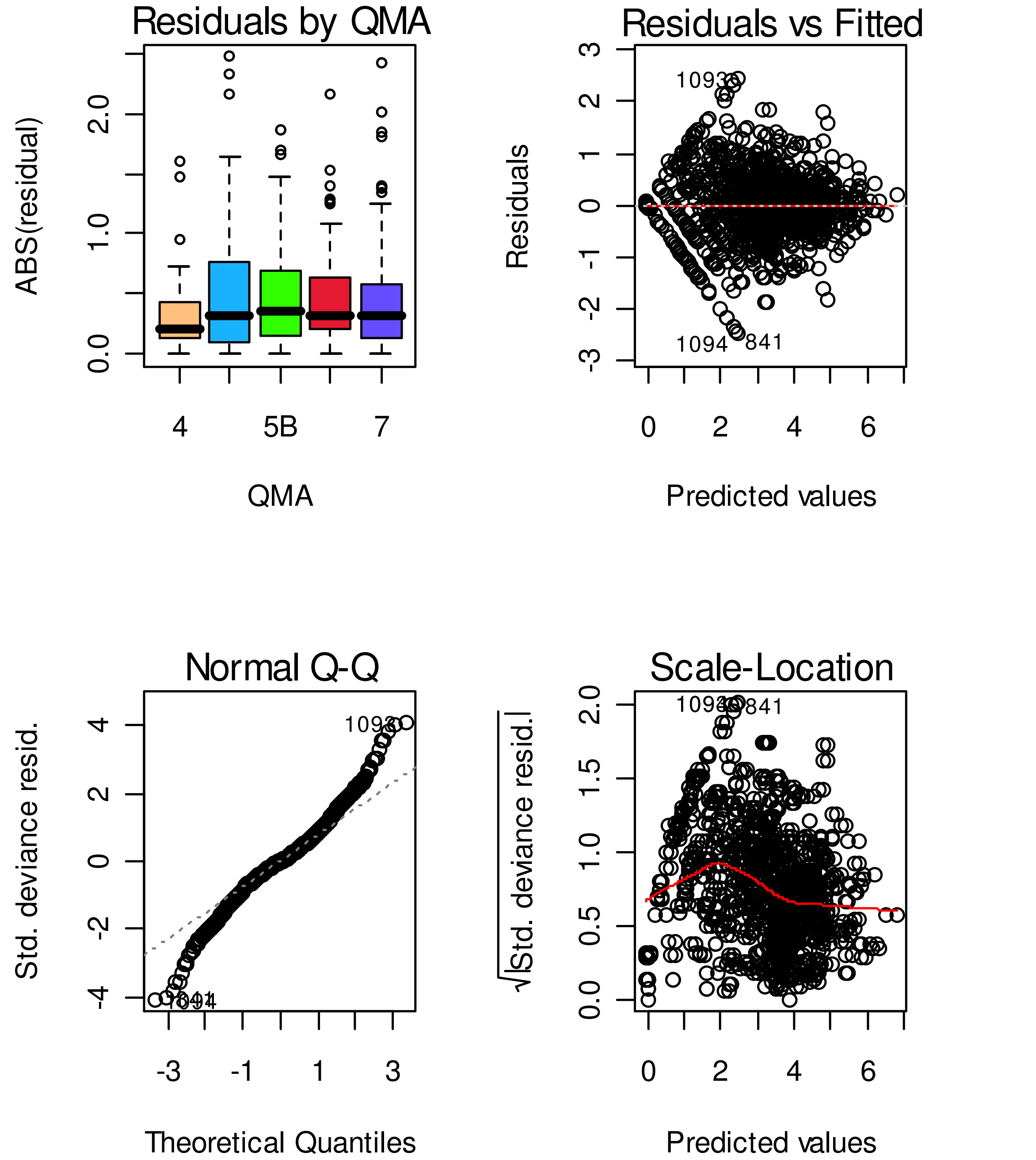
A fundamental issue with the paua research dive survey is that it is based on a fixed search time rather than a fixed search area. Research divers are directed to maximise the number of paua they find during the fixed-time swims, so even if the area searched during a swim were known there would almost certainly be some non-linearity between paua density and the diver paua counts.

Results from the paua diver simulation model produced variable relationships between paua density and simulated paua diver counts. At extreme assumptions the relationships between q (the proportion of paua in the potential search area counted) and density ranged from relatively simple decreasing functions to more complex (i.e., domed) functions. While the extreme assumptions are unlikely, the resultant non-linearity in q may well reflect the underlying pattern in the paua research dive survey. There is no basis in the available data to determine the form of the relationship between q and density. The paua dive survey simulator cannot be validated, and certainly does not capture the full dynamics of the surveys.

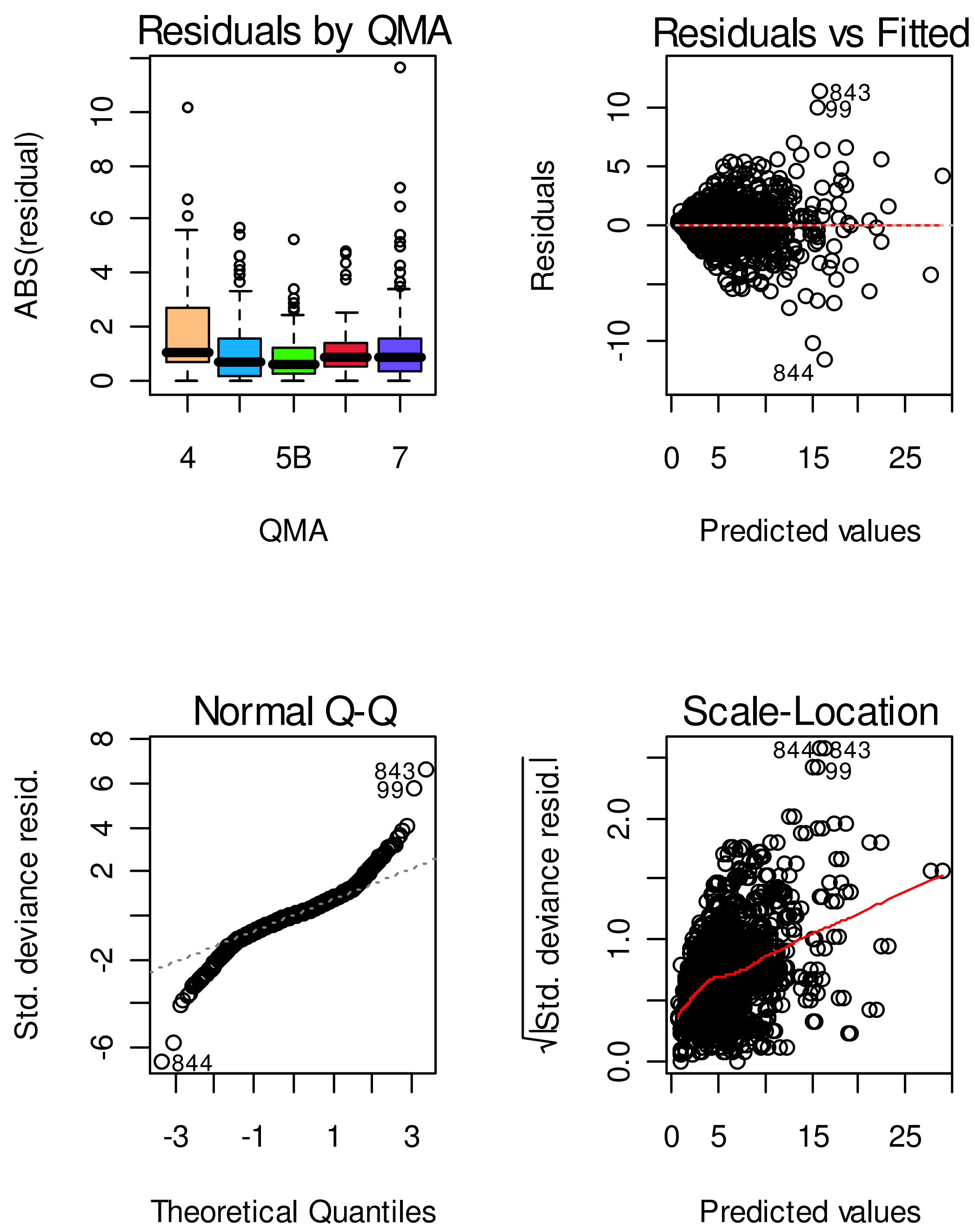
The simulations designed to reflect QMA-level paua dive surveys were based on relatively ideal scenarios: non-linearity in q was minimal; every stratum was sampled during each survey; and the area of paua habitat was constant among simulated sites. Results from these simulations indicate that abundance indices based on 10-minute counts (first 10 minutes on reef), prorated for time processing data and samples, decreases potential bias in the indices. Including diver effects in GLM standardisations is not warranted as that does not improve the performance of the indices. Even under relatively ideal conditions, estimated confidence limits from GLM analyses did not include the simulated relative abundance as frequently as expected.

Ultimately, the relationship between q and paua density is unknown and cannot be determined from available data. This is the greatest limitation of using the paua research dive survey data in stock assessments. Survey results are likely more useful when they are relatively stationary, indicating no change in relative abundance. Where changes in abundance are indicated, survey results should be treated cautiously as they may under- or over-estimate the degree of change.

Non-linearity in the relationship between q and paua density could be investigated through a research programme to compare timed-swim and fixed-area estimates of paua abundance. Such a programme would undoubtedly be large and expensive, and may lead to replacing the current survey with one based on a fixed-area design.



Appendix Figure 2: Diagnostics for GLM fit of log transformed *actual_10min_counts* data with paired swim and diver co-variates.



Appendix Figure 1: Diagnostics for GLM fit of square-root transformed *actual_10min_counts* data with paired swim and diver co-variates.

1 INTRODUCTION

Research dive surveys to assess the relative abundance of paua (*Haliotis iris*) have been conducted in New Zealand since 1991 (e.g., Naylor & Kim 2004), and abundance indices developed from the survey data (RDSI) are routinely used in stock assessments (e.g., Breen & Smith 2008a, McKenzie & Smith 2009). However, there is some concern that the surveys, which are based on a timed swim method, may not provide reliable abundance indices. Andrew et al. (2002) reviewed the survey methodology and recommended changes to the design which have since been implemented. Recently, Cordue (2009) conducted simulations of the paua surveys and concluded that the timed swim approach is not capable of providing reliable abundance indices.

The primary issue with the paua research dive survey is that it based on a timed-swim method whereby the area surveyed is unknown. The rationale for adopting this survey design relates to the severe dive conditions often encountered during surveys. Large surge and swell can limit the ability of a diver to follow line-transect and other survey methods. However, if the area surveyed changes with paua density, changes in survey abundance indices will not be linearly related to paua abundance.

The work presented here uses a simulation approach to evaluate the utility of the timed-swim survey method for estimating relative paua abundance. The scope of the work is defined by the objectives for the project, SAP2009:01 (Appendix Table 1). This document describes: 1) analyses of the historical research dive survey data to characterise them and inform the structure of a simulation model; 2) development of a model that simulates paua distributions and diver behaviour during dive surveys; 3) behaviour of the simulation model relative to model control parameters; and 4) results of simulations that represent dive surveys across a range of paua densities.

2 PAUA RESEARCH DIVE SURVEY DATA

This section describes the protocols for the paua research dive surveys and presents analyses of the survey data. The objective of the data analyses is to characterise paua distributions to inform development of a simulation model that reflects paua distribution and diver behaviour.

2.1 Dive survey protocols

Paua dive surveys have been conducted following a well defined timed-swim protocol since 1993. Some preliminary surveys, conducted in 1991 and 1992 to develop the methodology (McShane et al. 1996), are not included in these analyses. The survey methods were modified during the period 1998 to 2000; however, consistency with the data previously collected was maintained. The survey protocol and data collected consistently since 1993 is described below, with modifications of the protocol noted.

The primary objective of the paua research dive surveys has been to estimate relative abundance indices at the Quota Management Area level (QMA, Figure 1) for use in stock assessments. Each QMA is subdivided into strata and there are between two and six strata in each QMA. With the exception of QMA 5D, the strata essentially encompass the major commercial fishing area within the QMA. The amount of paua habitat within each stratum is unknown and not all strata within a QMA have been routinely surveyed (Table 1), so research dive survey indices (RDSI) are estimated using GLM methods.

Paua strata are further subdivided into sites which are defined by 250 m sections parallel to the shoreline and encompass the reef area to a maximum depth of 10 m. For each survey, sites are selected randomly. In general, each survey comprises between 7 and 15 sites per stratum (Table 1).

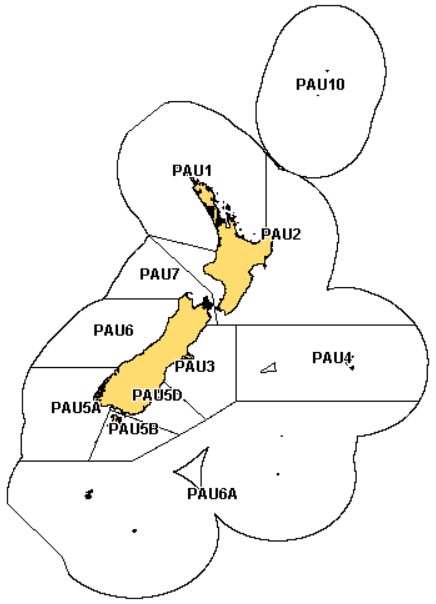


Figure 1: Paua quota management areas.

Table 1: Number of paua research survey dives (paired swims) by QMA, stratum, and year. Year represents the actual year of the survey, not the fishing year used in stock assessments.

QMA	Stratum	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
4			17								57							
	1		11								15							
	2		1								12							
	3		5								15							
	4										15							
7		45		34	37		20	64	42	30	20	61	24	46				
	Campbell											15		3				
	DUrville	14		12			20		20			15	2	13				
	NthnFaces			15				19	8	8	5	10	16					
	Perano	15			15			20		16	15		6	13				
	Rununder	16		2	22			20	10	6		15		11				
	Staircase			5				5	4			6		6				
5A					21					8	23	15		23	26		21	52
	Central																15	
	Chalky				21					8	8			11				10
	Dusky										15				12			15
	George														14			15
	Milford																	1
	SouthCoast											15		12			6	11
5B		14	43	54	3	62	28			83					30	29		
	Codfish	5	11	3			7			7						6		
	EastCape		9	14		11	7			15					13			
	Lords		6	9		20				16					10	2		
	Pegasus		8	3		20				15						11		
	Ruggedy			18	3	11	7			15					7	8		
	Waituna	9	9	7			7			15						2		
5D		10	10		10			30		25			29					
	Catlinse		10					15		10			14					
	Catlinsw	10			10			15		15			15					

Research dives take place from a tender vessel using surface-supplied air. The air hose is 100 m long which limits the area a diver can cover. Two divers simultaneously survey the area, one on either side of the tender vessel. This results in paired-dive data for each site.

Appendix Table 1: Objectives for project SAP2009:01.

1. Analyse all available Research Diver Survey data and assess the extent to which the existing RDSI index is a reliable index of abundance.
    a. It is anticipated that some form of spatial modelling will be required to mimic the activities of the divers (based on their protocols and practice) and their interaction with various sized patches of paua in various distributions (based on hypotheses about how patch distribution respond to exploitation and/or change with density)
    b. Models should take into account variability in the extent of suitable habitat in each coastal strip
    c. Models should assess likely departures from a linear relationship between abundance and the RDSI using both extreme assumptions (as in Patrick Cordue's study) and assumptions likely to more closely reflect reality.

It is likely that substantial discussions with NIWA (especially Reyn Naylor) will be required to build models that reflect the actual dive surveys; during working group discussions, it became clear that divers did not work precisely as described in their protocols.

2. Make recommendations on how to improve the suitability of the existing RDSI index using:
    a. data that are already collected or held on databases
    b. data that could be collected with modest marginal cost.

3. Assess the extent to which the current and any proposed revised RDSI are useful as indices of relative abundance for the current Bayesian stock assessment model:
    a. Our working assumption is that the RDSI will have at least some non-linearity.
    b. Models or simulations should assess the extent to which stock assessment modelling using RDSI as an index of relative abundance is likely to lead to misleading advice on the status of stocks, recent trends, and future prognosis (i.e., we would like to go beyond a demonstration that there is non-linearity in the RDSI index to assess the implications of that non-linearity).

4. If Research Diver Survey data are likely to lead to poor stock assessments and management advice, make recommendations on future approaches to monitoring the relative or absolute abundance of paua as an input to stock assessment models. Some comparability with existing time series would be desirable, recognising that we would not wish to continue a time series if it bore no relationship to paua abundance.

Increasing the number of replicate dives in each stratum decreased the "year" effect c.v.s, but the resultant confidence limits were less consistent, encompassing the simulated relative densities less frequently than expected. These results suggest that larger survey sample sizes are more likely to lead to erroneous conclusions about changes in stock abundance because confidence in estimated trends is overestimated.

The simulations designed to reflect QMA-level paua dive surveys were based on relatively ideal scenarios: non-linearity in q was minimal; every stratum was sampled during each survey; and the amount of paua habitat was constant among simulated sites. Results from these simulations indicate that abundance indices based on 10-minute counts (first 10 minutes on reef), prorated for time processing data and samples, decreases potential bias in the indices. Including diver effects in GLM standardisations is not warranted as that does not improve the performance of the indices. Even under relatively ideal conditions, estimated confidence limits from GLM analyses did not include the simulated relative abundance as frequently as expected.

Ultimately, the relationship between q and paua density is unknown and cannot be determined from available data. This is the greatest limitation of using the paua research dive survey data in stock assessments. Survey results are likely more useful when they are relatively stationary, indicating no change in relative abundance. Where changes in abundance are indicated, survey results should be treated cautiously as they may under- or over-estimate the degree of change.

Non-linearity in the relationship between q and paua density could be investigated through a research programme to compare timed-swim and fixed-area estimates of paua abundance. Such a programme would undoubtedly be large and expensive, and may lead to replacing the current survey with one based on a fixed-area design.

8 ACKNOWLEDGMENTS

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Each swim (a single diver at a specific site) is a 10 minute survey, though the definition of the "10 minutes" has changed. In earlier survey years, divers started the 10 minute clock when the first paua was encountered and continued the survey for 10 minutes (modified when large paua patches were encountered, as described below). In later survey years the clock was started as soon as the diver was on suitable reef habitat, and two "clocks" were used. The first clock ran for 10 minutes from when the diver first encountered the reef and the second clock ran for 10 minutes from when the first paua was encountered. Thus, the later swims include information on "time to first paua" so that paua counts can be standardised to the total time on reef habitat.

Before 1988 divers recorded only the number of paua patches observed in each of six patch size categories, and total counts are inferred from these observations. For later surveys, the number of paua in each patch was recorded. Paua are considered to be in the same patch if they are separated by less than two body lengths. The timing clocks are stopped when patches of 20 or more individuals are processed. For smaller patches the clock continues while paua are collected and patch data recorded. For each patch encountered, a maximum of four paua are collected to represent the size structure of the area.

The primary objective for divers conducting the paua research surveys is to maximise the number of paua they find.

2.2 Data processing

All paua dive survey data were obtained from NIWA (Reyn Naylor, pers. comm.) in the form of Excel spreadsheets. Data from each QMA were in separate files, and formats varied among the QMA. The data were collated into consistent formats and some error checking was done. For example, when data on paua counts for individual patches were available this was summarised and checked against the number of patches by patch category for the swim. Also, inconsistencies in recording information such as *time-to-first* were corrected.

Not all information was available for all the QMAs. There were no visibility codes recorded for PAU 7 and no paua fine scale statistical area codes recorded for PAU 4. Additionally, a small number of missing fine scale statistical area codes in other QMAs were interpolated from the paua site codes and statistical area codes that were available.

The variability of data formats and inconsistency in recorded data among the QMA is clearly the result of changes in the data that have been collected and the components of that data that are used for developing RDSI for stock assessments. Some information that is collected is not recorded in the data bases (e.g., degree of difficulty, algae cover, patch counts after the first 10 minutes). A consistent data structure should be developed for all the data and a single data base maintained.

The number of research paua dive survey records, by information type, are shown in Table 2. *Time-to-first* data records include information on the time the first paua was encountered and the number of paua counted after the first 10 minutes of the swim. *Patch count* data records have information on the number of paua in each patch encountered during the first 10 minutes of the swim. *Actual paua counts* are observations where all paua encountered during the swim were counted. The *all dives* observations include the *actual paua counts* observations and data records where only the numbers of patches by patch size category were recorded.

Table 2: Number of paua dive survey observations (individual swims) by QMA, year, and data type: "all dives" is the entire data set; "actual paua counts" are observations where all paua were counted; "patch counts" are observations of the size of each patch; and "time to first" are observations where the time that the first patch was observed is recorded.

	All dives					Actual paua counts					Patch counts					Time to first				
Year	4	7	5A	5B	5D	4	7	5A	5B	5D	4	7	5A	5B	5D	4	7	5A	5B	5D
1993		90		28	20															
1994	34			86	20															
1995		68		109																
1996		74	42	6	20															
1997				124																
1998		40		56			40					40								
1999		128			60		128			60		128			60		50			
2000		85					85					85					85			
2001		60	16	166	50		60	16	166	50		60	16	157	50		60		166	48
2002	114	40	46			114	40	46			114	10	46			113	40			
2003		122	30				122	30				50	30				122			
2004		48			58		48			58		4			59		46			56
2005		92	46				92	46				26	46				92	46		
2006			52	60				52	60				52	53				52	60	
2007				58					58					52					58	
2008			42					42					42					42		
2009			104					104					104					104		

2.3 Characterising paua research dive surveys

A number of analyses of the paua research dive survey data were conducted to characterise the surveys and to determine differences among the QMA and among strata within QMAs.

The following terminology is used to describe the paua survey data:

single dive: Data from a single diver's swim

paired dive: Data from the two diver swim at a single site

total_count: Total number of paua in swim (may be greater than 10 minutes), where all paua were counted

10min_count: Total number of paua in first 10 minutes of swim, where all paua were counted

inferred_count: Total number of paua in swim (may be greater than 10 minutes), where the number of paua are estimated from patch size categories

all_count: Combined *total _count* and *inferred_count* data

Where the "count" observations are based on combining the data from a paired dive, the prefix "paired" is used to name the observations (eg. *paired_10min_count*)

2.3.1 Distribution of patch sizes

Beginning in 1998, data on the number of paua in individual patches were collected (*Patch Counts*, Table 2). This information can be used to describe the distribution of patch sizes by QMA as well as the distribution of patch sizes within an individual swim.

The mean patch size for each patch size category shows little variation among the QMAs for patch categories less than 6 (Table 3). Average patch size by patch category tends to be slightly less in PAU7 than the other areas. For patch size category 6, the PAU 4 and PAU 7 mean counts are larger than for the other QMA but samples sizes are small.

One of the objectives of the simulation analyses conducted for this project was to investigate how the paua research dive survey data can best be used to estimate relative abundance indices for stock assessments. Simulations conducted to address this question were based on versions of the dive survey simulator that exhibited only minor non-linearity in q. As such, the simulation results may be useful to understand the general performance of alternative abundance indices, but they should not be taken to reflect the actual relationship between q and stock abundance.

Other features of the series of simulations to investigate the performance of alternative relative abundance indices included: a population structure with six strata and variable area and paua density among the strata; diver effects simulated; and GLM analyses to generate relative abundance indices. These simulations were tuned to generate survey observations similar to those from the paua research diver survey in terms of the average number of patches and average patch size and the variance in these observations among dives. The performance of alternative abundance indices was primarily assessed through the consistency in the confidence intervals estimated from the GLM analyses – that is, the probabilities that the 95% confidence intervals on relative abundance indices (year effects) contained the simulated values. The GLM analyses included fits only to paua counts based on the first 10 minutes on the reef.

Including diver effects in GLM standardisations of the simulated paua count data did not improve the consistency of the relative abundance indices. The set of simulations that investigated diver effects had similar abundance trends among the strata and hence only minor non-linearity in the relationship between q and stock abundance. GLM estimates of diver and year effects had minimal bias. The estimated c.v.s of the "year" effects were larger for GLM models fitted to paired diver observations than for models fitted to individual diver observations either with or without diver effects. The larger c.v.s resulted in year effect confidence limits that were more consistent. That is, the probabilities that the 95% confidence limits encompassed the simulated values were closer to 0.95 for the GLM fits to the paired diver observations. These results suggest that including diver effects in GLM standardisations does not improve the performance of the relative abundance indices. The paired diver counts are not independent observations and fitting GLMs to the combined data resulted in the most consistent abundance indices.

Diver effects were the only covariates considered in the diver survey simulations using GLMs to estimate relative abundance. Another potential covariate, a visibility code, was not assessed because analysis of the research dive data indicated it did not significantly reduce the residual variance in the paua counts. Other information collected during the research dive surveys (e.g., algal cover, degree-of-difficulty) is not routinely entered into the database, but may improve GLM fits. These data should be included in a paua research dive survey data base that maintains all data from this survey.

The mean GLM estimates of the "year" effect c.v.s were consistently lower for models fitted to the "raw" 10-minute count data than for models fitted to the 10-minute count data adjusted for processing time (i.e., counting, recording, and collecting paua). The relative performance of those two potential abundance indices was variable in terms of the consistency in their confidence limits. However, when the range in simulated densities was large, the confidence limits for the adjusted-count abundance indices were substantially more consistent in that the probabilities that the 95% confidence intervals included the simulated values were closer to 0.95. With high variation in mean density among surveys, the average processing time will also be highly variable and can add significant bias to the abundance indices if not accounted for.

For all simulated scenarios the relative abundance index confidence limits included the simulated values less frequently than expected, even where the simulated paua counts (adjusted for processing time) had minimal bias (i.e. 2% bias). For scenarios that were simulated with greater bias, through larger density decreases in strata with lower initial abundance, the GLM estimated confidence intervals were only slightly less consistent than for the scenarios with less bias.

simulation analyses presented here should be taken as reflecting some of the potential behaviours of the RDSI, not as reflecting what the true behaviour would be.

Results from the paua diver simulation model produced variable relationships between paua density and simulated paua diver counts. At extreme assumptions, that is the number of patches is constant across densities or the patch size is constant across densities, the relationships between q and density ranged from relatively simple decreasing functions to more complex (i.e., domed) functions. While the extreme assumptions about patch distribution are unlikely, the resultant non-linearity in q may well reflect the underlying pattern in the paua research dive survey. There is no basis in the available data to determine the form of the relationship between q and density. The paua dive survey simulator cannot be validated, and certainly does not capture the full dynamics of the surveys.

Ultimately, the only way to determine the relationship between the timed-swim paua survey q and paua density would be through an intensive research project. This would require paired observations of timed-swim paua counts and some form of fixed-area (i.e., line-transect or other method) paua counts. Given the apparent small-scale variability in paua density, as suggested by the variance of between diver paua counts at individual sites, such an experiment would undoubtedly be large and expensive. Relationships between survey q and paua density may vary with habitat or substrate type which would increase the scope of any research project to address this question.

The paua Bayesian stock assessment model has the capacity to estimate a non-linear relationship between the RDSI and stock abundance. However, it would be unrealistic to assume that the true underlying relationship could be discerned through an integrated stock assessment analysis. There are a number of reasons for this: the underlying form of the relationship is unknown; the abundance indices have high associated uncertainty; and information in the other data sources (e.g., length frequencies) is unlikely to be informative about the relationship. Further simulations could be conducted to assess the ability of paua stock assessment model to detect non-linear trends in q, but these would suffer the same limitations as the current study. That is, the extent to which the simulations reflect reality would be unknown.

A number of issues with the initial paua research dive survey were identified by Andrew et al. (2000). That report reviewed many of the assumptions underlying the timed-swim survey method and potential biases in relative abundance indices derived from the survey data. Andrew et al. (2000) recommended a number of modifications to the survey which have been implemented as incremental changes to the methodology so that a consistent time series of data was maintained. Key changes in the survey methods included: counting the number of paua in each patch; recording the number of paua encountered during the first 10 minutes a diver is on suitable reef area (in addition to the number encountered during the 10 minutes after the first paua is encountered); and prorating paua counts per timed-swim to adjust for time spent processing patch data. The modifications of the survey design removed some of the problems with the survey, in particular by standardising the search time. However, as pointed out by Andrew et al. (2000) "the assumptions regarding search efficiency remain at the core of the timed swim method and are insoluble."

Simulations designed to emulate the scenarios modelled by Cordue (2009) generated results similar to those found in that study. Two scenarios of how paua patches change with paua density were simulated: the number of paua per patch was constant or the number of patches was constant. The simulations conducted by Cordue (2009) were based on theoretical considerations about the interaction of paua research diver behaviour and paua density, whereas the simulations reported here were based on a mechanistic approach. Both studies found a range of non-linear relationships between diver paua counts and density. Applying corrections to paua counts for processing time did not always decrease the non-linearity between counts and density and tended to increase the c.v.s of the observations. Results from this study suggest paua counts based on the first 10 minutes on the reef performed better than those based on the 10 minutes after the first paua were encountered in terms of non-linearity in q.

Before collecting data on the number of paua in each patch, only counts of paua patches by patch size category were made. For these data, the mean number of paua in each patch category (Table 3) is used to estimate the number of paua in each swim (*inferred_counts*).

The *patch counts* dive survey data also provide more detailed information on the distribution of patch sizes (Table 4). A patch size of 1 is consistently the most common patch size, representing from 43% of patch observations in PAU 5A to 63% of observations in PAU 7. For patch sizes of 40 paua or more (categories 5 and 6), the percent of observations ranges from 0.4% for QMA 7 and QMA 5B to 3.3% for QMA 4 (Figure 2). Although the distribution of patch sizes is variable among strata, there is still a fair degree of consistency within each QMA (Table 4).

Table 3: Mean paua counts by patch size category and QMA. Sample sizes are given in parentheses.

	Patch size category (range of number of paua in category)					
QMA	1 (1-4)	2 (5-10)	3 (11-20)	4 (21-40)	5 (41-80)	6 (81+)
5A	1.7 (2115)	6.9 (443)	14.6 (223)	28.5 (115)	53.3 (58)	126.0 (23)
5B	1.5 (2004)	6.6 (256)	14.4 (90)	28.3 (33)	54.3 (9)	- (0)
5C	1.5 (1778)	7.0 (208)	14.4 (98)	28.7 (63)	52.3 (18)	105.0 (12)
4	1.6 (2030)	6.9 (355)	14.5 (151)	28.1 (75)	52.6 (48)	150.5 (41)
7	1.5 (7107)	6.7 (592)	14.1 (167)	27.0 (61)	50.8 (19)	166.4 (13)
All	1.5 (15034)	6.8 (1854)	14.4 (729)	28.1 (347)	52.7 (152)	140.3 (89)

Table 4: Distribution of patch size by QMA and stratum. Nobs- the total number of patches sampled.

			Patch size							
QMA	Stratum	Nobs	1	2	3	4	5-10	11-20	21-40	40+
4		2700	0.481	0.150	0.075	0.046	0.131	0.056	0.028	0.033
	1	644	0.467	0.146	0.067	0.045	0.160	0.051	0.031	0.033
	2	463	0.406	0.119	0.097	0.045	0.140	0.080	0.043	0.069
	3	846	0.474	0.164	0.069	0.060	0.134	0.053	0.026	0.020
	4	747	0.548	0.157	0.075	0.031	0.099	0.048	0.017	0.025
7		7959	0.631	0.153	0.068	0.042	0.074	0.021	0.008	0.004
	DUrville	3723	0.605	0.161	0.073	0.052	0.082	0.020	0.007	0.001
	NthnFaces	2366	0.689	0.150	0.053	0.028	0.056	0.014	0.006	0.004
	Perano	637	0.559	0.130	0.082	0.041	0.088	0.060	0.016	0.025
	Rununder	760	0.632	0.167	0.062	0.036	0.078	0.014	0.009	0.003
	Staircase	473	0.634	0.108	0.093	0.038	0.087	0.027	0.008	0.004
5A		2977	0.430	0.144	0.079	0.057	0.149	0.075	0.039	0.027
	Central	234	0.389	0.132	0.060	0.073	0.184	0.107	0.026	0.030
	Chalky	555	0.494	0.141	0.068	0.056	0.133	0.059	0.029	0.020
	Dusky	721	0.379	0.153	0.083	0.055	0.150	0.096	0.050	0.035
	Five fingers	120	0.283	0.108	0.092	0.050	0.150	0.092	0.108	0.117
	George	641	0.431	0.133	0.097	0.050	0.145	0.076	0.042	0.027
	Milford	11	0.364	0.000	0.000	0.273	0.273	0.000	0.000	0.091
	South Coast	695	0.472	0.161	0.073	0.059	0.150	0.052	0.024	0.009
5B		2392	0.597	0.126	0.063	0.052	0.107	0.038	0.014	0.004
	Codfish	217	0.553	0.111	0.097	0.083	0.097	0.028	0.028	0.005
	East Cape	337	0.629	0.107	0.071	0.042	0.080	0.053	0.012	0.006
	Lords	351	0.613	0.128	0.037	0.034	0.108	0.037	0.026	0.017
	Pegasus	399	0.627	0.115	0.055	0.048	0.105	0.045	0.005	0.000
	Ruggedy	838	0.563	0.148	0.064	0.055	0.129	0.030	0.011	0.000
	Waituna	250	0.632	0.104	0.068	0.064	0.080	0.040	0.012	0.000
5D		2177	0.577	0.133	0.064	0.042	0.096	0.045	0.029	0.014
	Catlinse	906	0.521	0.138	0.066	0.049	0.108	0.062	0.035	0.020
	Catlinsw	1271	0.618	0.130	0.062	0.037	0.087	0.033	0.024	0.009

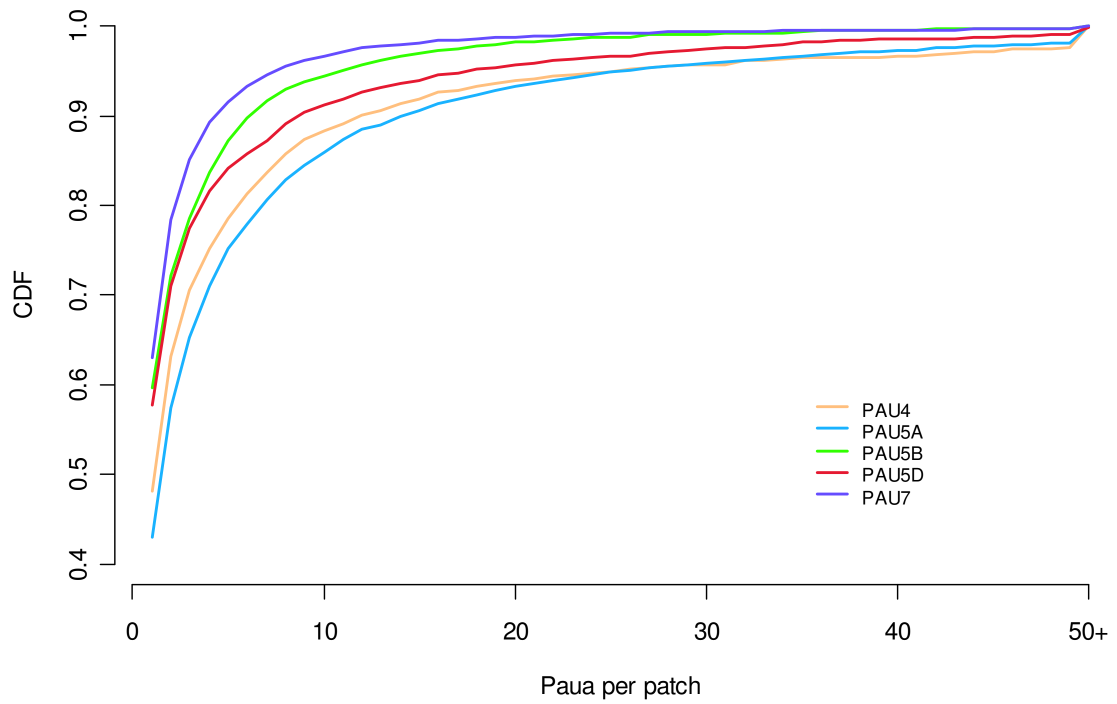

Figure 2: Cumulative density function (CDF) of the number of paua per patch by QMA.

2.3.2 Within swim patch size variance

For individual dives, there is a strong relationship between the mean number of paua per patch and the standard deviation of the number of paua per patch, though the relationships are somewhat variable among the QMAs (Figure 3). The within-swim patch size c.v.s are highest for PAU 4, lowest for PAU 5B, and least variable for PAU 7 (Table 5, Figure 3).

Table 5: Quantiles (10th, 25th, median, 75th, and 90th) of the distribution of the c.v.s of the number of paua per patch within individual dives, by QMA.

	10th	25th	50th	75th	90th
PAU 4	0.74	0.90	1.24	1.68	2.04
PAU 5A	0.00	0.39	0.86	1.22	1.55
PAU 5B	0.00	0.35	0.77	1.09	1.41
PAU 5D	0.00	0.55	1.04	1.53	1.98
PAU 7	0.33	0.56	0.83	1.12	1.53

2.3.3 Diver effects and between-diver variance in paua counts

The *paired dive* data is used to evaluate diver effects and within-site variability in paua density. Ten divers have participated in the paua research dive surveys but in general only three to five divers participate in a single year (Table 6).

Initial analysis of the *paired dive* observations was limited to the *10min_count* data. The rationale for this is that, while restricting the number of observations, these data should be the most consistent. That is, additional variance that would be introduced by estimating paua counts from patch categories and from variable swim durations will be avoided.

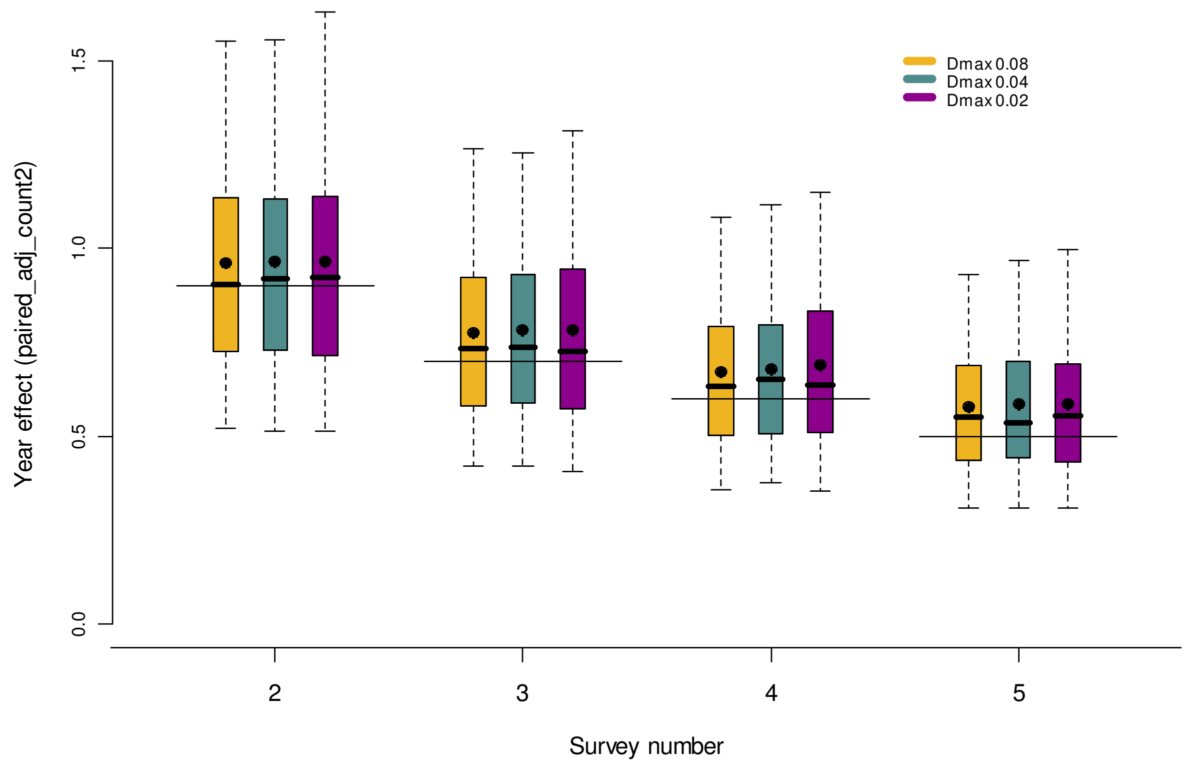

Figure 27: Estimated "year" effects from GLM fits to simulated *paried_adj_count2* data for a "less ideal" scenario with Dmax value of 0.02, 0.04, and 0.08. Results are from 1000 replicates and the box and whiskers show the 5th, 25th, 50th, 75th and 95th quantiles of the year effect distributions. Means of the "year" effect distributions are shown with black circles and the simulated "true" relative year effects are indicated with the broad horizontal lines.

7 DISCUSSION

Paua research dive surveys, based on a timed-swim method, have been conducted using consistent methods since 1993. Over that time, 2293 individual dives have been recorded across the five QMAs that support major commercial fisheries. The dive survey data, summarised as relative abundance indices through GLM analyses (RDSI), have been used routinely in stock assessments. These data represent a considerable investment and resource; understanding potential biases in the RDSI is crucial for their use in assessing stock status.

One of the primary objectives of this research project is to assess the extent to which the current or any revised RDSI are useful as indices of relative abundance for the current Bayesian stock assessment model. Given the available data, it is not possible to answer this question. A fundamental issue with the paua research dive survey is that it is based on a fixed search time rather than a fixed search area. Research divers are directed to maximise the number of paua they find during the fixed-time swims, so even if the area searched during a swim were known, there would almost certainly be some non-linearity between paua density and the diver paua counts.

The paua diver simulation model developed for these analyses was designed so that it could generate non-linear behaviour between q (the proportion of paua in the potential search area that are counted) and density. This was accomplished through clumped distributions of paua patches and simulated divers' tendency to maintain a direction of movement when patches were encountered. A more realistic simulation model would include aspects of diver knowledge about the terrain of the survey area and where paua are more likely to be encountered. However, even with a more complex model it would not be possible to validate that the simulation model adequately reflects reality. Results of the

Table 25: Summary of data simulated for the "less ideal" scenario, by simulation Dmax value and survey. Statistics include: the mean relative density (relative to the first survey); the mean relative paua count (*adj_count2*, relative to the first survey); the minimum and maximum mean paua count (*paired_10min_count*) across strata; and the minimum and maximum mean number of patches in paired survey observations across strata.

					Dmax and survey number										
	Dmax=0.08					Dmax=0.04					Dmax=0.02				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Rel. density	1.0	0.9	0.7	0.6	0.5	1.0	0.9	0.7	0.6	0.5	1.0	0.9	0.7	0.6	0.5
Rel. paua	1.000	0.904	0.734	0.648	0.561	1.000	0.913	0.738	0.651	0.566	1.000	0.911	0.733	0.655	0.566
Paua count															
- Min.	127.5	106.1	108.4	70.4	48.3	69.1	59.4	59.4	39.7	27.7	38.5	33.6	33.3	21.4	14.6
- Max.	221.0	193.4	144.7	134.7	150.1	118.7	103.9	78.5	73.4	80.3	65.7	56.9	43.9	42.1	44.4
Patches															
- Min.	22.7	21.0	21.2	16.2	13.1	16.2	14.6	14.8	10.9	8.3	10.7	9.6	9.7	6.7	4.9
- Max.	28.6	26.9	24.4	23.4	24.7	22.0	20.4	17.7	16.9	17.9	15.6	14.2	11.9	11.3	12.0

Table 26: Bias in the GLM estimates of "year" effects from fits to the *paired_adj_count2* and *paired_10min_count* data, by simulation model and survey. Bias is measured as the proportional error in the mean "year" effect relative to the simulated relative density. Results are from the "less ideal" scenario.

					Dmax and survey number							
	Dmax=0.08				Dmax=0.04				Dmax=0.02			
	2	3	4	5	2	3	4	5	2	3	4	5
Paired_adj_count2	0.065	0.107	0.115	0.156	0.071	0.118	0.129	0.167	0.072	0.114	0.146	0.171
Paired_10min_count	0.064	0.121	0.145	0.200	0.073	0.141	0.167	0.218	0.072	0.133	0.176	0.213

Table 27: The mean GLM estimates of "year" effect c.v.s. Results are from the "less ideal" scenario.

	Dmax value		
	0.08	0.04	0.02
Paired_adj_count2	0.238	0.245	0.255
Paired_10min_count	0.225	0.233	0.245

Table 28: The probability that the 95% confidence limits on "year" effects encompass the true values for GLM fits to *paired_adj_count2* and *paired_10min_count* data, by simulation model and survey. Results are from the "less ideal" scenario.

					Dmax and survey number							
	Dmax=0.08				Dmax=0.04				Dmax=0.02			
	2	3	4	5	2	3	4	5	2	3	4	5
Paired_adj_count2	0.834	0.816	0.807	0.814	0.832	0.824	0.834	0.804	0.838	0.830	0.805	0.823
Paired_10min_count	0.834	0.817	0.792	0.798	0.848	0.828	0.832	0.792	0.850	0.832	0.810	0.819

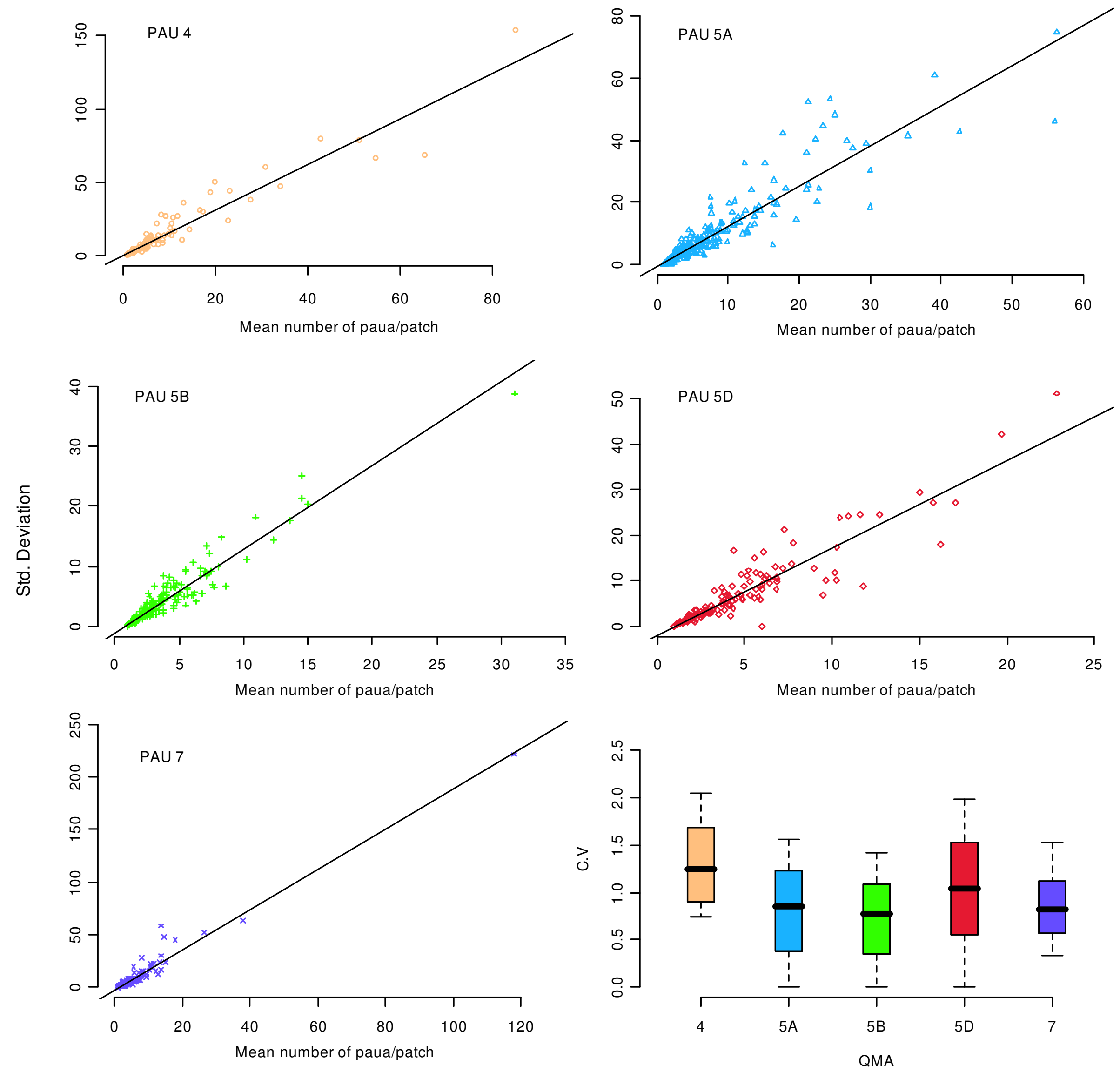

Figure 3: Mean number of paua per patch and the standard deviation of the number of paua per patch within individual dives, by QMA, and quantile plots (10th, 25th, 50th, 75th, and 90th quantiles) of the distribution of the c.v.s of the number of paua per patch by QMA.

Table 6: Number of paua research dive survey swims conducted by diver and year.

	Year																
Diver	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
A	51	35	54	13	40	31	65	26	102	67	32	29	41	35	23	10	27
B									11	41	46		18	11			
C										15							
D				15													
E	7	17			48		23		64	14	28	24		4		14	37
F		20	8	36	24	34	3										
G	56	24	50	35													
H	6	19			12	14	73	34	74	63	38	31	51	27	14	18	40
I	3								8								
J	15	25	65	43		17	24	24	33		8	22	28	35	21		

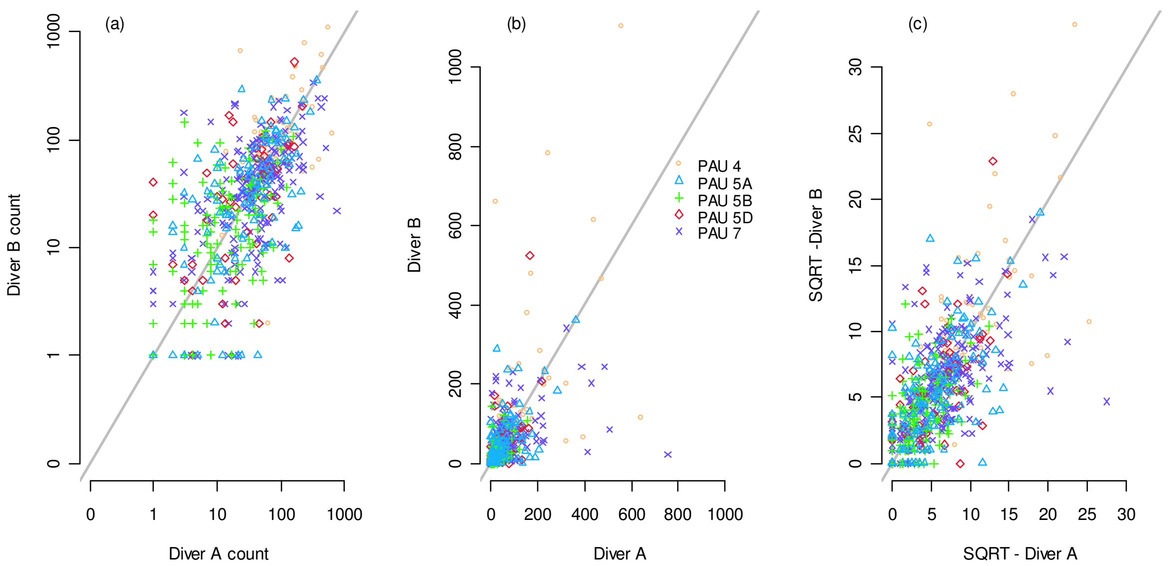

Figure 4: *Paired dive actual_10min_count* data plotted on different scales: (a) log-log scale; (b) arithmetic scale; (c) square root transformed. The diver labelled "A" was randomly selected.

An appropriate statistical model for analysing the paired dive counts is not immediately obvious as the variance of the paired observations changes with the mean count (Figure 4). Log-transformed data appear to have higher between-diver variance at low counts, opposite to the variance pattern on an arithmetic scale. Square-root transformation of the data may result in a reasonable residual distribution.

To estimate diver effects and the between-diver variance in observations, GLM models were fitted to the *paired dive* data. The *10min_count* observations were transformed (either log or square-root) and explanatory variables were diver and an identifier for each *paired dive*, both treated as categorical variables. Gaussian error distributions were assumed.

Summary statistics for the GLM fits are shown in Table 7. Diver effects were significant for both the log and square-root transformation of the count observations, based on the AIC criterion. The proportion of the total variance accounted for by the models is high for both transformations, though slightly higher for the log transformation (Table 7). Residual patterns are not ideal for either transformation, though slightly better for the log transformation (Appendix Figures 1 and 2).

To increase sample sizes and the number of divers in the analysis of diver effects, GLM models were also fitted to the *all_count* data. These data should have increased between-diver variance due to differences in the duration of the swims and error introduced from inferring counts from patch size categories.

For the GLM fits to the *all_count* data, only models with log transformed data are presented. The diver effects for the *all_count* GLM were significant based on the AIC criterion, and the r^2 value was only slightly lower than that of the *10min_count* model fit (Table 7). Residual patterns are shown in Appendix Figure 3. Given the decrease in model fit is minor when the *all_count* data are fitted rather than the *10min_counts* data, it is not unreasonable to use the fuller data set to characterise between-diver observations.

With the inclusion of the additional observations in the *all_count* data, the significance of many of the individual diver effects increases (Table 8). Some of the diver effects are quite large, ranging from

6.6 Simulations under a "less ideal" scenario

The final simulations are designed to investigate a less ideal scenario where density trends differ among the strata (see Figure 24, panel c). For this scenario the stock density decreases by 50%, with larger declines in the strata with the greatest initial abundance. Simulations are conducted for a range of maximum densities (*dmax* values of 0.08, 0.04, and 0.02) using model M2. Simulations are conducted with seven paired dives in each stratum and GLM models are fitted to the paired dive observations.

For this set of model runs, the bias in simulated diver paua counts (i.e., *adj_count2*) relative to the simulated mean density is higher than for the "relatively ideal" scenario: at a relative density of 0.5 the bias is about 4% for the "relatively ideal" scenario and 13% for the "less ideal" scenario (compare survey 3 in Table 21with survey 5 in Table 25). This is attributable to the larger decreases in density simulated for the strata with the greatest initial abundance. The bias in paua counts increases only slightly when lower average densities (lower *dmax*) are simulated. The range in mean paua counts (*paired_10min_counts*) across strata and surveys, from 15 to 221, encompasses the range seen in research paua dive surveys except for the higher values seen in PAU4 (compare Table 11 with Table 25). Likewise, the range in the mean number of patches per paired dive is similar to that in the research dive surveys.

Bias in estimated diver effects from the GLM fits to the *paired_adj_count2* data is slightly larger than the bias in the simulated paua counts, increasing from about 7% at a relative density of 0.9 to about 16% at a relative density of 0.5 (Table 26). The biases are slightly higher when the average simulated density is lower (lower *dmax*). Comparing the "less ideal" scenario with the "relatively ideal" scenario at the comparable relative densities of 0.5, the bias in GLM "year" effects increased to 16% from 10% (compare survey 3 in Table 22 with survey 5 in Table 26).

The variance of the GLM estimates of "year" effects" across replicates is relatively insensitive to the average density, increasing only slightly at the lower simulated densities (Figure 27).

The GLM estimates of the "year effect" c.v.s increase slightly at smaller average densities (i.e., *dmax*) and they also increase slightly for fits to the *paired_adj_count2* data relative to fits to the *paired_10min_count* data (Table 27). The mean c.v.s for the "less ideal" scenario are slightly lower than the comparable c.v.s for the "relatively ideal" scenario because the range in simulated survey densities is greater for the "relatively ideal" scenario.

The probabilities that the 95% confidence limits on estimated "year" effects encompass the true (simulated) value, are higher (and closer to 95%) for the GLM fits to the *paired_adj_count2* data than for the fits to the *paired_10min_counts* (Table 28), consistent with the lower bias in "year" effect parameters for the *paired_adj_count2* fits. The probability that the confidence limits encompass the true is only slightly lower for the "less ideal" scenario than for the comparable relative density for the "relatively ideal" scenario (compare survey 3 in Table 24 with survey 5 in Table 28).

For the "less ideal" scenario, the bias in simulated paua counts was intentionally higher than for the "relatively ideal" scenario which resulted in greater bias in the GLM estimates of "year" effects. However, confidence limits on the "year" effects were only slightly less reliable for the "less ideal" scenario compared with the "relatively ideal" scenario.

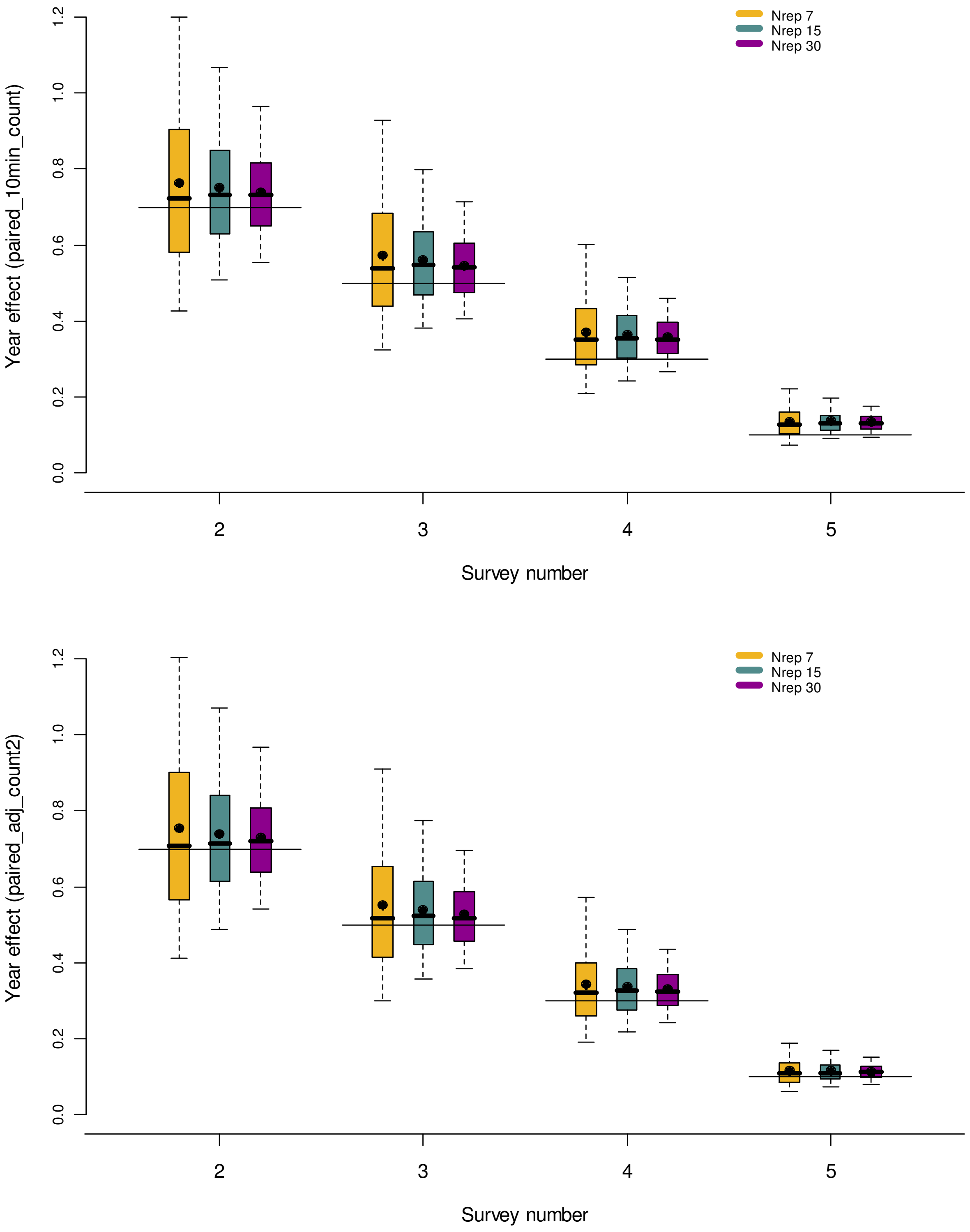

Figure 26: Estimated year effects from GLM fits to simulated *paried_10min_count* data (upper panel) and *paired_adj_count2* data (lower panel) for a "relatively ideal" scenario with 7, 15, and 30 paired dives (Nrep) per stratum. Results are from 1000 replicates and the box and whiskers show the 5th, 25th, 50th, 75th and 95th quantiles of the year effect distributions. Means of the year effect distributions are shown with black circles and the simulated "true" relative year effects are indicated with the narrow horizontal lines.

multipliers of 0.54 to 1.40 relative to the "base" diver (A), although the standard errors of the estimates are quite large (Table 8).

The distribution of residuals from the GLM fits to paua counts, accounting for diver and paired-swim effects (i.e., year and site), provides some information about the small-scale variability in paua distributions. The distribution of model residuals from the fit to the *all_count* data is summarised by QMA in Figure 5. The residuals are further summarised by strata within QMA in Table 9.

Table 7: Results of GLM fits to the *paired dive* observations. The model description includes: "C", *10min_count*; "A", *all_count*; ID, a unique identifier for each paired swim; and Diver, a unique identifier for each diver. GLM statistics include: MAR, the median absolute residual; and ResSD, the standard deviation of model residuals.

Model description	AIC	r^2	Null df	Res df	RSE	MAR	ResSD
Sqrt(C+1)~ID	6165.5	0.821	1237	618	2.502	0.809	1.309
Sqrt(C+1)~ID+Diver	6146.7	0.825	1237	612	2.483	0.839	1.281
Log(C+1)~ID	3539.7	0.830	1237	618	0.866	0.347	0.420
Log(C+1)~ID+Diver	3524.5	0.834	1237	612	0.861	0.316	0.415
Log(A+1)~ID	6532.2	0.821	2292	1146	0.862	0.306	0.430
Log(A+1)~ID+Diver	6445.7	0.829	2292	1137	0.846	0.298	0.415

Table 8: Estimated diver effects (Est.), their standard errors and p-values from GLM fits to the *10min_count* and *all_count* data.

	10min_count			*All_count*					
	Est.	Std. Error	Pvalue	Est.	Std.	Pvalue	exp(Est.)	95% CI	95% CI
A	0			0			1.00		
B	-0.18	0.12	0.12	-0.08	0.11	0.45	0.92	0.74	1.15
C				-0.54	0.31	0.08	0.58	0.31	1.08
D				-0.31	0.32	0.34	0.74	0.39	1.39
E	0.02	0.10	0.84	0.09	0.08	0.26	1.09	0.93	1.27
F	-1.38	0.71	0.05	-0.39	0.11	0.00	0.67	0.54	0.85
G				0.34	0.10	0.00	1.40	1.15	1.71
H	0.11	0.07	0.13	0.19	0.06	0.00	1.21	1.07	1.37
I	-0.64	0.43	0.14	-0.61	0.36	0.09	0.54	0.26	1.12
J	-0.01	0.10	0.95	0.12	0.07	0.10	1.12	0.97	1.30

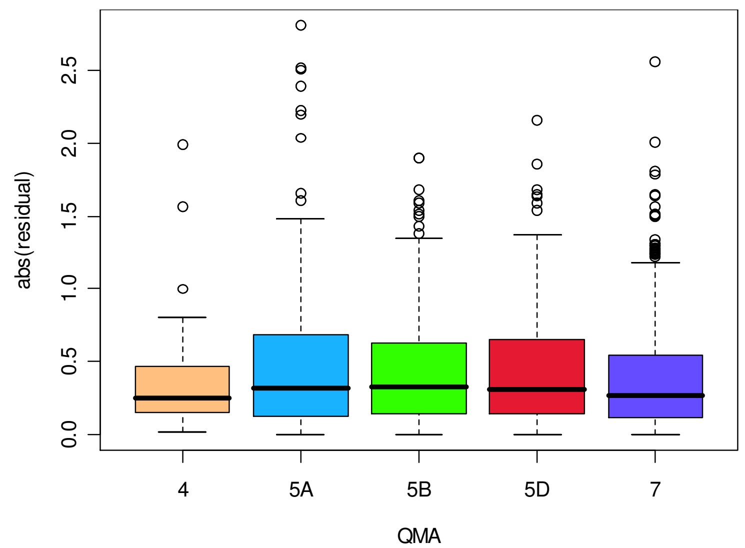

Figure 5: Boxplots of residuals (absolute value) for the GLM fit to *all_counts* observations, by QMA.

Table 9: Paua research survey summary statistics for *single dive* data, by QMA and strata. "Patches" is the number of patches per swim; "Prop. zero" is the proportion of dives with no paua found; "Time first" is the mean time to the first paua; "Residuals" are residuals from the GLM fits to the *all_count* data.

			Patches		*All_counts*		Residuals				
QMA	Stratum	N	Mean	SD	Mean	SD	Mean Absolute	SD	Median	Prop. zero	Time first
PAU 4		148	22.0	9.7	144.4	159.9	0.35	0.32	0.25	0.00	0.19
	1	52	17.1	9.0	131.9	193.5	0.32	0.21	0.22	0.00	0.28
	2	26	19.8	6.3	204.1	183.0	0.34	0.24	0.25	0.00	0.13
	3	40	26.9	8.0	122.4	78.3	0.27	0.18	0.22	0.00	0.17
	4	30	25.6	11.2	143.9	150.2	0.53	0.57	0.34	0.00	0.20
PAU 5A		378	9.3	7.6	53.6	67.6	0.49	0.53	0.32	0.15	2.01
	South	88	7.9	7.3	33.4	47.8	0.46	0.57	0.22	0.22	1.91
	Chalky	116	9.4	8.0	34.5	43.8	0.47	0.42	0.38	0.16	2.10
	Dusky	84	10.0	8.0	89.6	88.9	0.53	0.61	0.33	0.13	2.14
	Central	30	7.8	5.9	50.5	48.9	0.62	0.62	0.44	0.13	3.10
	George	58	11.0	7.1	72.6	80.4	0.46	0.49	0.32	0.03	1.41
	Milford	2	5.5	3.5	39.0	46.7	1.13	0.00	1.13	0.00	2.50
PAU 5B		693	8.0	6.6	25.1	32.1	0.44	0.38	0.33	0.11	2.09
	East Cape	138	6.4	5.6	26.4	36.1	0.43	0.39	0.31	0.13	2.83
	Ruggedy	138	12.4	7.7	31.1	26.2	0.36	0.36	0.24	0.05	1.74
	Waituna	98	7.6	6.3	24.8	39.7	0.43	0.33	0.37	0.10	2.52
	Codfish	79	7.7	6.3	28.0	38.9	0.42	0.34	0.34	0.13	0.96
	Pegasus	114	6.6	5.6	18.0	21.2	0.43	0.33	0.33	0.13	1.90
	Lords	126	6.5	5.4	21.8	29.1	0.56	0.44	0.47	0.11	2.22
PAU 5D		228	13.7	10.2	59.5	71.0	0.48	0.46	0.31	0.05	1.36
	Catlinse	98	11.1	8.0	58.0	70.8	0.49	0.49	0.31	0.08	1.73
	Catlinsw	130	15.6	11.2	60.7	71.5	0.47	0.44	0.32	0.02	1.10
PAU 7		846	18.7	12.8	58.0	77.5	0.39	0.38	0.27	0.03	0.84
	Campbell	36	2.4	2.5	5.4	6.7	0.70	0.40	0.72	0.28	2.85
	Staircase	52	22.9	11.6	61.5	41.9	0.30	0.28	0.20	0.00	0.66
	Rununder	204	12.9	9.4	40.4	67.9	0.44	0.34	0.37	0.02	1.24
	Perano	200	11.5	8.3	67.5	106.6	0.53	0.50	0.40	0.06	1.22
	NthnFaces	162	26.8	11.5	60.4	53.2	0.29	0.32	0.17	0.01	0.08
	DUrville	192	27.4	11.4	73.7	76.1	0.24	0.21	0.17	0.00	0.27

2.3.4 Variance of paua counts within strata and QMA

The paired dives at a single site are not independent, so analyses of the paua research diver data should be based on the combined data from the *paired dives*. The combined data (*paired_all_count*) are analysed here to estimate the variance among observations within strata and among strata within QMA to inform the structure of the simulation model.

The paired count observations were analysed with GLMs, using log transformed *paired_all_count* data and assuming a Gaussian error distribution. The explanatory variables evaluated were year, visibility code, and either QMA, stratum, or paua fine-scale statistical area. All variables were treated as categorical. Only second order interactions of year and the geographical variables were considered as the objective was to characterise the variability among count data at different geographical scales.

For the GLM including QMA as the geographical explanatory variable the standard deviation of model residuals was 0.804; this decreased to 0.735 with strata and 0.64 with paua fine-scale statistical area as the explanatory variable (Table 10). Including visibility code as an explanatory variable in the models resulted in trivial improvement to the fits.

Residual statistics from the GLM fit with year and stratum interactions are summarised by QMA and stratum in Table 11.

Table 21: Summary of data simulated for the "relatively ideal" scenario, by number of replications and survey. Statistics include: the mean relative density (relative to the first survey); the mean relative paua count (*adj_count2*, relative to the first survey); the minimum and maximum mean paua count (*paired_10min_count*) across strata; and the minimum and maximum mean number of patches in paired survey observations across strata.

	Number of replications (Nrep) and survey number														
	Nrep=7					Nrep=15					Nrep=30				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Rel. density	1.0	0.7	0.5	0.3	0.1	1.0	0.7	0.5	0.3	0.1	1.0	0.7	0.5	0.3	0.1
Rel. paua	1.0	0.714	0.517	0.322	0.107	1.0	0.722	0.525	0.325	0.109	1.0	0.719	0.517	0.323	0.109
Paua count															
- Min.	152.9	114.3	91.6	57.4	17.3	156.9	118.0	90.7	56.4	18.2	158.3	116.7	88.8	57.4	18.2
- Max.	257.8	192.5	137.4	91.9	40.7	250.8	184.8	140.9	93.8	41.1	251.1	189.7	137.5	92.9	41.5
Patches															
- Min.	24.9	21.8	19.3	14.2	5.8	25.1	22.0	18.9	14.2	5.8	25.2	22.0	19.1	14.4	5.8
- Max.	29.9	27.0	23.9	19.1	11.3	29.9	26.9	23.7	19.4	11.3	29.8	27.2	23.8	19.4	11.4

Table 22: Bias in the GLM estimates of "year" effects from fits to the *paired_adj_count2* and *paired_10min_count* data, by simulation model and survey. Bias is measured as the proportional error in the mean "year" effect relative to the simulated relative density. Results are from the "relatively ideal" scenario.

	Number of replications (Nrep) and survey number											
	Nrep=7				Nrep=15				Nrep=30			
	2	3	4	5	2	3	4	5	2	3	4	5
Paired_adj_count2	0.073	0.102	0.137	0.146	0.055	0.078	0.121	0.148	0.040	0.052	0.102	0.133
Paired_10min_count	0.089	0.143	0.230	0.351	0.072	0.121	0.212	0.354	0.055	0.090	0.188	0.333

Table 23: The mean GLM estimates of "year" effect c.v.s. Results are from the "relatively ideal" scenario.

	Number of replications		
	7	15	30
Paired_adj_count2	0.241	0.167	0.119
Paired_10min_count	0.230	0.159	0.113

Table 24: The probability that the 95% confidence limits on "year" effects encompass the true values for GLM fits to *paired_adj_count2* and *paired_10min_count* data, by simulation model and survey. Results are from the "relatively ideal" scenario.

	Number of replications (Nrep) and survey number											
	Nrep=7				Nrep=15				Nrep=30			
	2	3	4	5	2	3	4	5	2	3	4	5
Paired_adj_count2	0.827	0.822	0.833	0.816	0.823	0.822	0.782	0.785	0.817	0.781	0.750	0.711
Paired_10min_count	0.825	0.808	0.788	0.706	0.825	0.806	0.711	0.574	0.809	0.758	0.612	0.407

6.5 Simulations under a "relatively ideal" scenario

The next simulations are designed to evaluate the effect of increasing the number of dives per stratum on estimates of "year effects" in GLM analyses. The simulations are constructed with relatively ideal conditions: the stock density decreases by 90% over five surveys and density trends are similar among all strata (see Figure 24, panel b). Simulations are conducted with 7, 15, and 30 paired dives in each stratum. Model M2 with a maximum density of 0.08 paua/m^2 is used. GLM models are fitted only to the paired dive observations.

For this set of model runs, the bias in simulated paua counts (i.e., *adj_count2*) relative to the simulated mean density increases from about 2% at a relative density of 0.7 to 9% at a relative density of 0.1 (Table 21). The range in mean paua counts (*paired_10min_counts*) across strata and surveys encompasses the range seen in paua research dive surveys except for the higher values seen in PAU4 (compare Table 11with Table 21). Likewise, the range in the average number of patches per paired dive is similar to that in the research dive surveys.

Bias in estimated diver effects from the GLM fits to the *paired_adj_count2* data is slightly larger than the bias in the simulated paua counts, increasing from about 5% at a relative density of 0.7 to about 14% at a relative density of 0.1 (Table 22, Figure 26). The biases are reduced slightly with a larger number of replicate dives per stratum. Biases are higher for the GLM fits to the *paired_10min_count* data, in particular at lower paua densities (Table 22).

The GLM estimates of the "year" effect c.v.s decrease as the number of replicate dives per stratum increases, from about 0.24 with 7 replicate dives to 0.12 with 30 replicate dives (Table 23): c.v.s are slightly lower for the fits to the *paired_10min_counts* than for the fits to the *paired_adj_count2* data.

The probabilities that the 95% confidence limits on estimated "year" effects encompass the true (simulated) value, are higher (and closer to 95%) for the GLM fits to the *paired_adj_count2* data than for the fits to the *paired_10min_counts* (Table 24), consistent with the lower bias in "year" effect parameters for the *paired_adj_count2* fits. With a higher number of dive survey replicates, the probability that the 95% confidence limits encompass the simulated value decreases because the "year effect" c.v.s are smaller. This effect is larger at the lower simulated densities where the bias in estimates is larger (Table 24).

These results suggest that with even slight non-linearity in the relationship between paua density and survey paua counts, increasing sample sizes to increase the precision of GLM "year" effect estimates may be unwarranted as this would be more likely to lead to erroneous conclusions about relative stock status. That is, the tighter confidence limits on the "year" effect parameters are less likely to include the true value. Also, the bias in the GLM estimates of "year" effects is greater than the bias in the survey mean adjusted paua counts suggesting that using a standardisation procedure may be unwarranted. When a GLM standardization is applied, adjusting the paua count data for processing time results in less bias than not adjusting the count data.

Table 10: Results of GLM fits to the *paired_all_count* observations. Model descriptions include the variables: "P", the *paired_all_count*; "Strat", stratum; "Stat", paua fine-scale statistical area; "Vis", visibility code. GLM statistics include: MAR, the median absolute residual; and ResSD, the standard deviation of model residuals.

Model	AIC	r^2	Null df	Res df	RSE	MAR	ResSD
Log(P+1)~Year:QMA	3751.5	0.229	1145	1110	1.223	0.685	0.804
Log(P+1)~Year:Strat	3659.4	0.368	1145	1042	1.143	0.577	0.735
Log(P+1)~Year:Stat	3769.7	0.583	1145	749	1.095	0.414	0.642
Log(P+1)~Year:QMA+Vis	3757.5	0.231	1145	1106	1.224	0.677	0.802
Log(P+1)~Year:Strat+Vis	3665.5	0.369	1145	1038	1.144	0.586	0.734
Log(P+1)~Year:Stat+Vis	3776.2	0.583	1145	745	1.098	0.417	0.642

Table 11: Paua research dive survey summary statistics for *paired dive* data, by QMA and strata. "Patches" is the number of patches per paired dive; "all counts" is the *paired_all_count* observations; "Prop. Zero" is the proportion of *paired dives* with no paua found. The residual statistics come from the GLM fit that includes year and stratum interaction terms.

			Patches		All counts		Residuals			
QMA	Stratum	N	Mean	SD	Mean	SD	Mean absolute	SD	Med.	Prop. zero
PAU 4		74	43.9	17.4	288.9	275.7	0.58	0.52	0.44	0.00
	1	26	34.2	16.8	263.7	352.9	0.65	0.73	0.37	0.00
	2	13	39.6	9.4	408.2	322.6	0.58	0.45	0.47	0.00
	3	20	53.8	14.7	244.8	140.9	0.50	0.26	0.56	0.00
	4	15	51.2	17.9	287.9	201.8	0.55	0.43	0.32	0.00
PAU 5A		189	18.6	13.3	107.3	121.6	1.08	0.91	0.83	0.08
	South	44	15.8	13.2	66.7	79.2	1.35	0.97	1.13	0.14
	Chalky	58	18.7	13.3	69.1	81.3	1.14	0.85	1.03	0.10
	Dusky	42	20.1	14.8	179.2	158.0	0.99	0.93	0.53	0.07
	Central	15	15.6	10.7	101.1	77.4	1.10	0.99	0.87	0.07
	George	29	22.0	12.0	145.1	147.4	0.74	0.78	0.34	0.00
	Milford	1	11.0	-	78.0	-	-	-	-	0.00
PAU 5B		346	15.9	11.9	50.2	54.3	0.88	0.75	0.67	0.05
	East Cape	69	12.8	9.7	52.7	61.4	1.00	0.82	0.87	0.07
	Ruggedy	69	24.8	14.0	62.2	46.9	0.70	0.65	0.57	0.01
	Waituna	49	15.2	11.6	49.6	63.6	0.81	0.72	0.55	0.02
	Codfish	39	15.5	11.6	56.5	69.9	0.98	0.82	0.81	0.08
	Pegasus	57	13.2	9.1	36.1	36.4	0.94	0.80	0.77	0.09
	Lords	63	13.0	9.4	43.6	45.8	0.88	0.68	0.71	0.03
PAU 5D		114	27.4	18.7	119.1	119.9	0.86	0.71	0.68	0.01
	Catlinse	49	22.2	14.7	115.9	120.2	0.93	0.81	0.71	0.02
	Catlinsw	65	31.3	20.5	121.5	120.5	0.81	0.62	0.65	0.00
PAU 7		423	37.4	23.8	116.0	126.9	0.64	0.62	0.47	0.00
	Campbell	18	4.8	4.0	10.8	8.9	0.60	0.41	0.58	0.00
	Staircase	26	45.7	21.4	122.9	69.5	0.44	0.41	0.35	0.00
	Rununder	102	25.7	16.2	80.8	105.9	0.70	0.63	0.50	0.00
	Perano	100	23.1	14.5	134.9	170.9	1.01	0.82	0.77	0.02
	NthnFaces	81	53.7	20.9	120.8	97.1	0.41	0.34	0.32	0.00
	DUrville	96	54.9	20.3	147.4	122.7	0.46	0.40	0.36	0.00

2.3.5 Time to first and proportion zeros

Divers began recording the time that the first paua was encountered during each swim in 1999 (see Table 2). This information is truncated to the nearest minute such that if the time taken to find the first paua is less than 1 minute the *time to first* is recorded as 0.

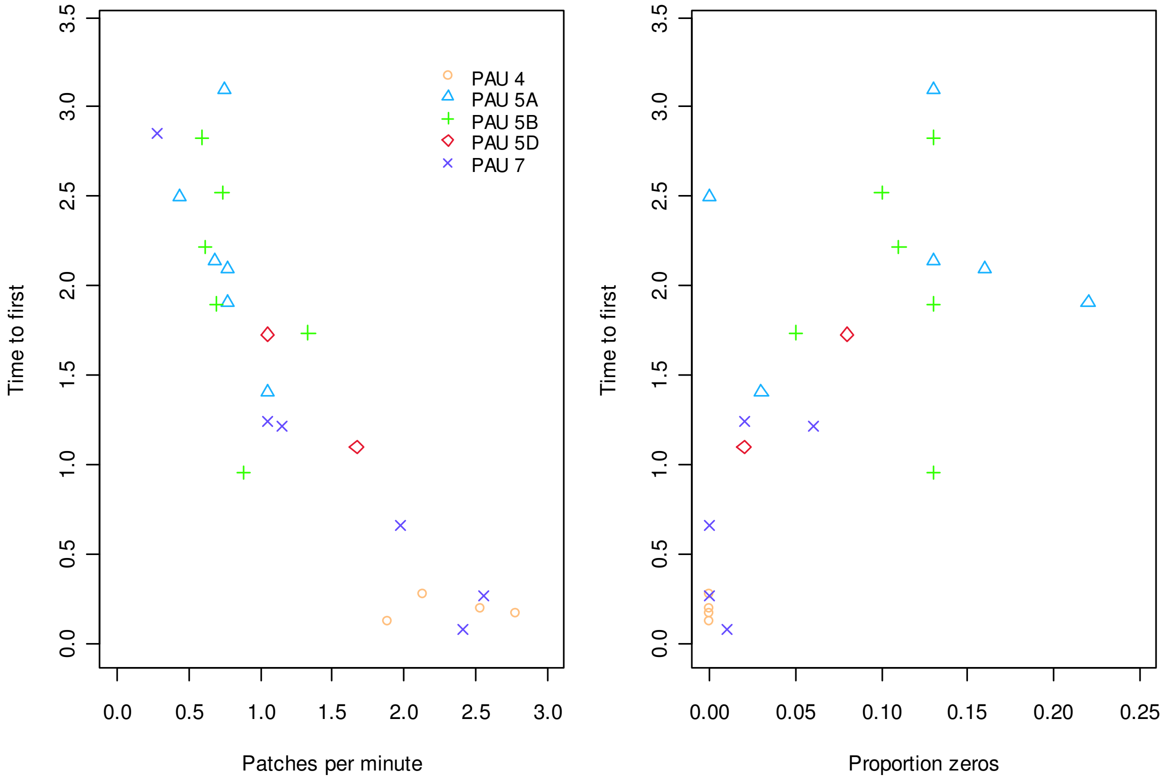

Figure 6: Mean patches per minute (left panel) and proportion of zeros (right panel) versus mean time to first for *single dives*, by stratum and QMA.

Time to first is variable among the QMA and among the strata within each QMA (Table 9). All strata within PAU 4 have consistently low *time to first*, while strata within PAU 5A and PAU 5B have generally high average *time to first.* Within PAU 7 *time to first* is quite variable among the strata. Not surprisingly, there is a fairly strong relationship between the mean number of patches found per minute of swim and the mean *time to first* (Figure 6). The relationship between the proportion of dives that found no paua and the time to first is not quite as strong (Figure 6).

3 SIMULATING PAUA DISTRIBUTIONS AND DIVER SWIMS

Constructing a simulation model to emulate the paua research diver surveys comprises two main components: modelling the distribution of paua on reefs, and modelling the behaviour of divers as they conduct a survey swim.

The simulated reef is set up as a rectangular grid comprised of 1 m^2 squares. These squares can be thought of as having coordinates in an *x* and *y* direction. For the simulations discussed here, each grid is 160 m in the *y* direction (*Y*=160) and 120 m in the *x* direction (X=120). Each diver swims in only half of the full grid (i.e., 80 m in the *y* direction), so potentially has an area of 9600 square meters to survey. This is considerably less than the area a real diver could potentially survey (15 709 square metres based on the air hose restriction), but given that a diver is unlikely to survey more than 2400 square metres during a single swim (see discussion below) this is unlikely to limit the utility of these results.

3.1 Model of patch size distribution

Simulating paua distributions on each grid has two components – a model for the distribution of patch sizes and a model for the spatial distribution of patches.

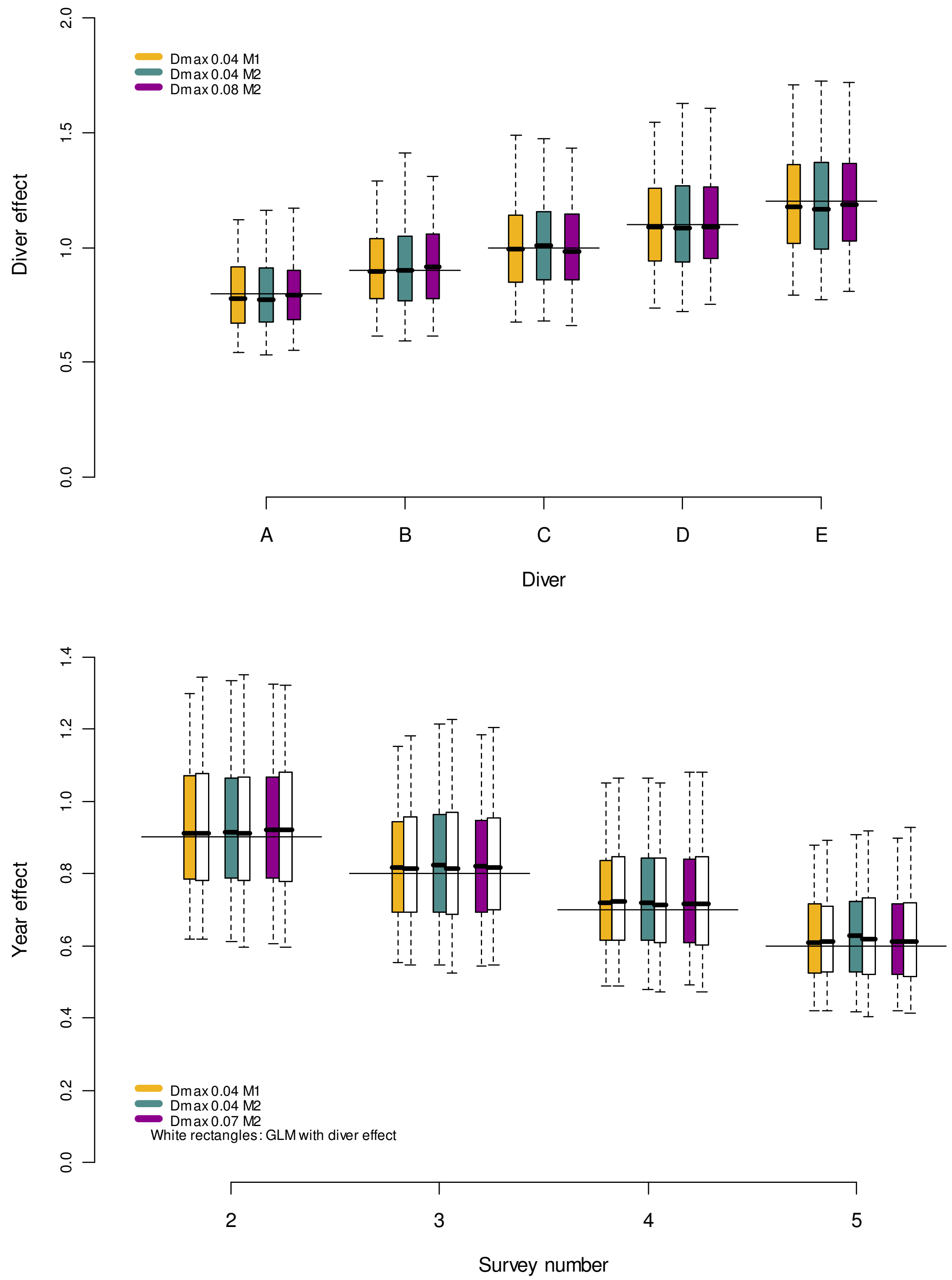

Figure 25: GLM estimates of diver effects (for 5 divers relative to the 6th diver) for the three simulation model formulations (top panel), and estimated "year" effects (relative to the first survey) for the GLM models fit to individual *adj_count2* data with and without inclusion of diver effects (lower panel). The "box and whiskers" indicate the 5th, 25th, 50th, 75th, and 95th quantile of the distributions and the narrow horizontal lines indicate the simulated values.

Table 17: Summary of simulated data for the "diver" analyses, by simulation model and survey. Statistics include: the mean relative density (relative to the first survey); the mean relative paua count (*adj_count2*, relative to the first survey); the minimum and maximum mean paua count (*paired_10min_count*) across strata; and the minimum and maximum mean number of patches in paired survey observations across strata.

	Model and survey number														
	M1-04					M2-04					M2-08				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Rel. density	1.0	0.9	0.8	0.7	0.6	1.0	0.9	0.8	0.7	0.6	1.0	0.9	0.8	0.7	0.6
Rel. paua	1.0	0.919	0.811	0.720	0.612	1.0	0.918	0.817	0.720	0.621	1.0	0.923	0.813	0.722	0.616
Paua count															
- Min.	86.1	76.0	75.0	65.0	53.7	86.8	75.3	73.8	62.8	52.7	156.9	136.7	136.1	115.5	94.3
- Max.	131.7	121.7	114.0	102.3	87.7	131.8	121.4	112.9	102.5	88.8	250.8	234.0	212.3	193.5	162.1
Patches															
- Min.	31.6	29.5	29.1	26.6	23.3	18.4	17.0	16.8	15.3	13.4	25.1	23.7	23.4	21.8	19.6
- Max.	39.5	38.3	36.5	34.8	32.3	23.3	22.5	21.5	20.4	18.8	29.9	29.1	28.1	27.2	25.5

Table 18: Probability of selecting GLM model including diver effects based on AIC criterion.

	M1-04	M2-04	M2-08
adj_count2	0.725	0.713	0.714
10min_count	0.563	0.628	0.624

Table 19: The mean GLM estimates of "year" effect c.v.s.

	M1-04	M2-04	M2-08
Adj_count2	0.128	0.131	0.128
Adj_count2 with diver effects	0.152	0.156	0.152
Paired_adj_count2	0.155	0.165	0.160
10min_count	0.111	0.125	0.122
10min_count with diver effects	0.132	0.148	0.145
Paired_10min_count	0.133	0.156	0.153

Table 20: The probability that the 95% confidence limits on "year" effects encompass the true values for GLM fits to alternative simulated count data, by simulation model and survey. The highlighted values show the GLM model that performed best in the sense that the probability is closest to 0.95.

	Model and survey number											
	M1-04				M2-04				M2-08			
	2	3	4	5	2	3	4	5	2	3	4	5
Adj_count2	0.720	0.721	0.715	0.744	0.739	0.702	0.713	0.704	0.726	0.693	0.706	0.710
Adj_count2 + diver	0.771	0.774	0.785	0.809	0.794	0.743	0.772	0.770	0.779	0.778	0.764	0.775
Paired_adj_count2	0.820	0.803	0.792	0.819	0.825	0.798	0.821	0.807	0.823	0.801	0.806	0.828
10min_count	0.747	0.751	0.720	0.694	0.752	0.721	0.736	0.713	0.724	0.707	0.703	0.710
10min_count + diver	0.805	0.793	0.785	0.782	0.800	0.771	0.779	0.759	0.761	0.771	0.764	0.772
Paired_10min_count	0.837	0.823	0.804	0.793	0.846	0.825	0.817	0.816	0.816	0.799	0.798	0.817

The function selected to simulate the distribution of patch sizes is relatively simple in its parameterisation but allows a broad range of patch size distributions. Parameters of the function can be readily changed to simulate the effects of fishing on paua distribution. The patch size function is a compound distribution, combining a geometric and a lognormal distribution.

The single parameter discrete geometric distribution has the characteristic that the mode is always at 1, which is consistent with the research dive survey data which has a modal patch size of 1. This component of the distribution captures the size distribution of small patches, generally comprising 20 or fewer paua. The geometric function has a single parameter (g), and the mean patch size for this component of the patch size function is $1/g$. The lognormal distribution, which captures the distribution of larger patches, has two parameters – the mean $(\overline{x})$ and standard deviation (std), (expressed on the log-scale) of the distribution.

The final parameter of the compound patch size function is the proportion of patches which are large, that is coming from the lognormal distribution (p). The mean patch size is then given by:

$$\frac{(1-p)}{g}+p\overline{x}\ .$$

Given randomly selected parameters ε_i, γ_i, and K, the size of each patch i (S_i) is simulated by:

$$S_i=\begin{cases} round\left(\exp\left(\ln(\overline{x})+\gamma_i(sd)-0.5(sd)^2\right)\right) & \varepsilon_i \le p \\ K & \varepsilon_i > p \end{cases}$$

where $\varepsilon_i \sim U[0,1]$, $\gamma_i \sim N[0,1]$, and $K \sim Geometric[g]$.

3.2 Model of patch distribution

Paua patches are placed into the grid based on a parameter that controls how clumped the patches are (c). This can range from a highly clumped patch distribution to a random patch distribution. For a random patch distribution, the placement of each patch is governed by random variables that control the *x* and *y* location:

$$x_i = round(\varsigma_i) \qquad \varsigma_i \sim U(1,X)$$
$$y_i = round(\upsilon_i) \qquad \upsilon_i \sim U(1,Y)$$

Note that more than one patch can be placed in a grid square.

For a clumped distribution, the location of the first patch, and potentially some other patches, are selected as for a random distribution while the subsequent patch locations are determined by:

$$x_i' = x_{i-1} + \mathrm{round}\left(0.8(\omega_i cX)\right) \qquad \omega_i \sim N(0,1)$$
$$y_i' = y_{i-1} + \mathrm{round}(\psi_i cY) \qquad \psi_i \sim N(0,1)$$

$$x_i=\begin{cases} x_i' & 1 \ge x' \le X_i \\ X + x_i' & x_i' < \mathrm{X} \\ x_i' - X & x_i' > \mathrm{X} \end{cases} \qquad y_i=\begin{cases} y_i' & 1 \ge y' \le Y_i \\ Y + y_i' & y_i' < Y \\ y_i' - X & y_i' > Y \end{cases}$$

Thus, when the initially selected location (x_i', y_i') is outside the grid area the location is moved to the other end of the grid axis as if the axis folded over and was continuous.

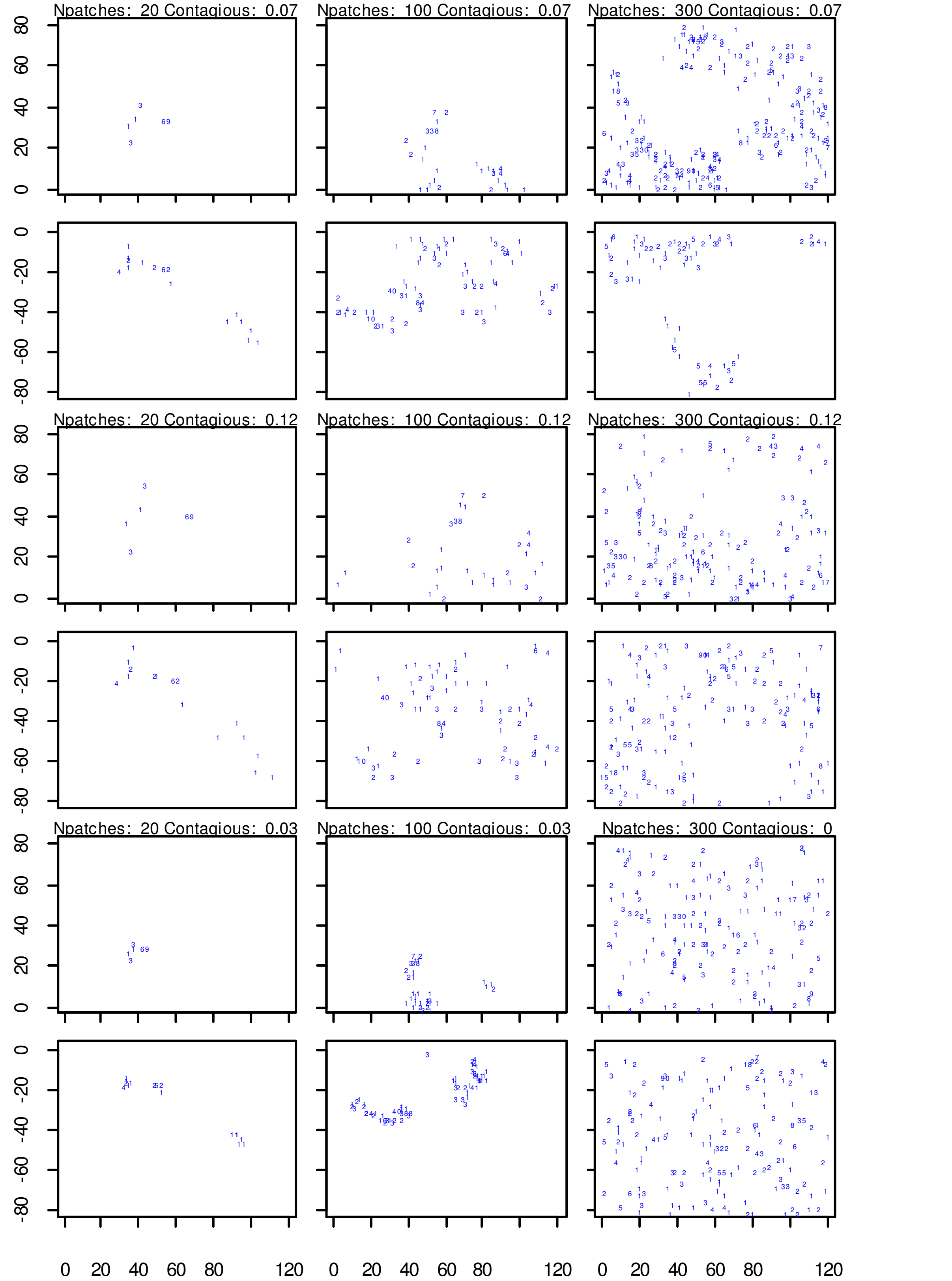

Figure 7: Example patterns of paua patch distributions, with number of patches (Npatches) of 20, 100, and 300 and clumped distributions with the *c* equal to 0 (random), 0.03 0.07, and 0.12. The distributions were simulated with $\bar{x} = 50$; $g = 0.55$; and $p = 0.05$. **The number of paua in each grid square is shown in blue.**

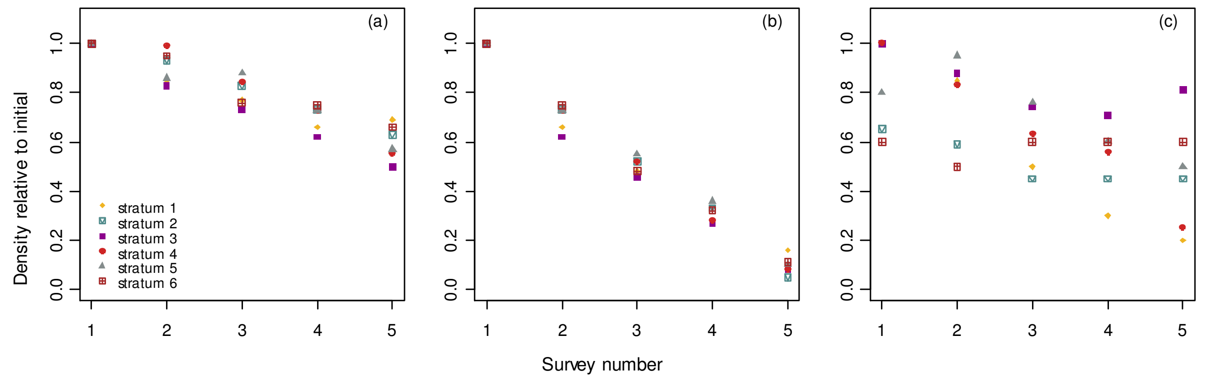

Figure 24: Relative density trends in the six simulated strata for: (a) the diver effect scenarios, (b) the "relatively ideal" scenario, and (c) the "less ideal" scenario.

Bias in estimated diver effects from the GLM fits to the *adj_count2* data are relatively small and variance in the diver effect estimates are similar across the three formulations of the simulation model (Figure 25). The probability that the GLM model with diver effects is selected over that without the diver effects, based on the AIC criterion, is higher for fits to the adjusted count data (*adj_count2*) than for the *10min_count* data (Table 18). Across the three simulation model formulations, the probability of selecting the GLM with diver effects ranges from 0.713 to 0.725 for the fits to the *adj_count2* observations. For fits to the *10min_count* data, the probability of selecting the model with diver effects ranges from 0.563 to 0.628.

For GLM models fitted to the individual diver observations, the variances of the estimated "year" effects are marginally larger for the models that include diver effects, while biases in the "year" effects are similar for models with and without inclusion of diver effects (Figure 25).

The GLM model estimates of "year" effect c.v.s are lowest for models fitted to the individual diver observations without diver effects, intermediate for fits to individual diver observations with diver effects, and highest for fits to the paired diver observations (Table 19). Mean c.v.s are higher for the paua counts adjusted for processing time (*adj_count2*) than for unadjusted counts (*10min_count*). Mean c.v.s are similar among the three simulations model formulations.

The probabilities that the 95% confidence limits on "year" effect estimates encompass the true (simulated) value are shown in (Table 20) for the three GLM models fitted to the simulated paua count data. All probabilities are much lower than 0.95, the value that would be expected if the estimated confidence limits were consistent with the simulated scenarios. GLM models that include diver effects perform better than those without diver effects for fits to individual diver counts, but models fitted to the paired diver observations perform better than both in terms of greater consistency in the confidence limit estimates (Table 20). Confidence limits from fits to the *paired_adj_count2* performed better than those from the *paired_10min_count* data for the M2-08 model, in terms of their probability of encompassing the simulated value. The M2-08 model spans a greater density range.

These results suggest that little is gained by estimating diver effects, and GLM fits to the paired diver observations are likely to produce more consistent confidence limit estimates.

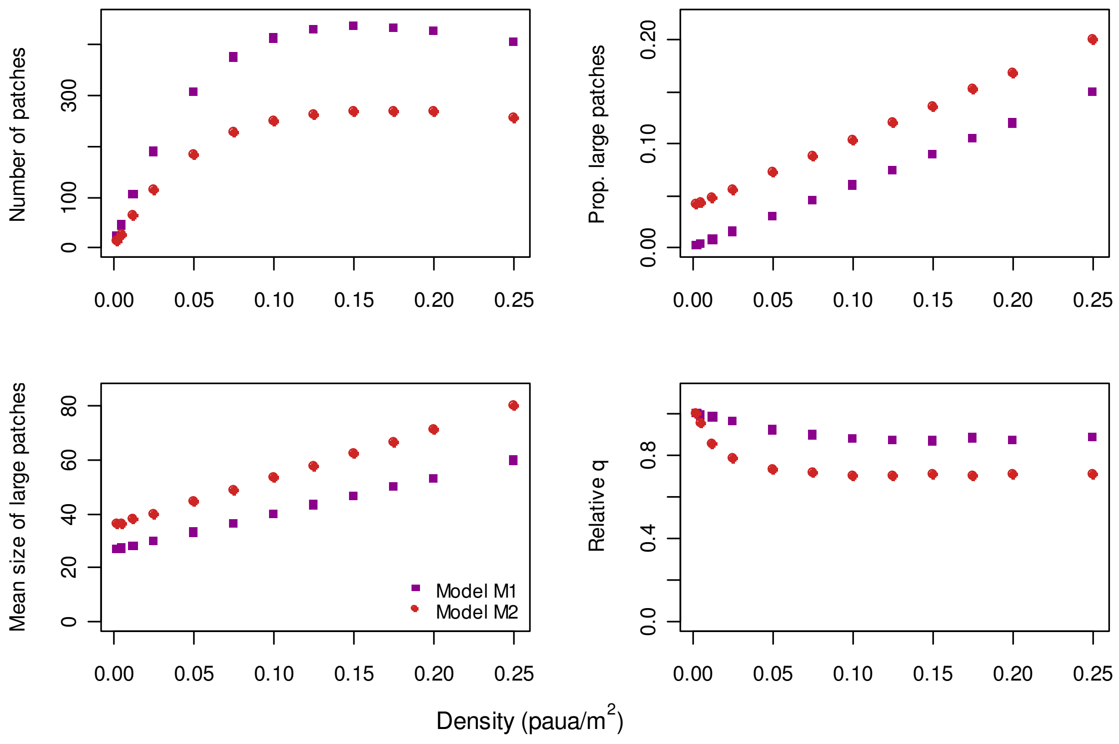

Figure 22: The relationships between paua density and the simulated number of patches, the proportion of patches that are large (*p*), the mean size of large patches (*x*), and the 10-minute paua count adjusted for processing time (*adj_count2*) relative to the maximum (relative *q*), for models M1 and M2.

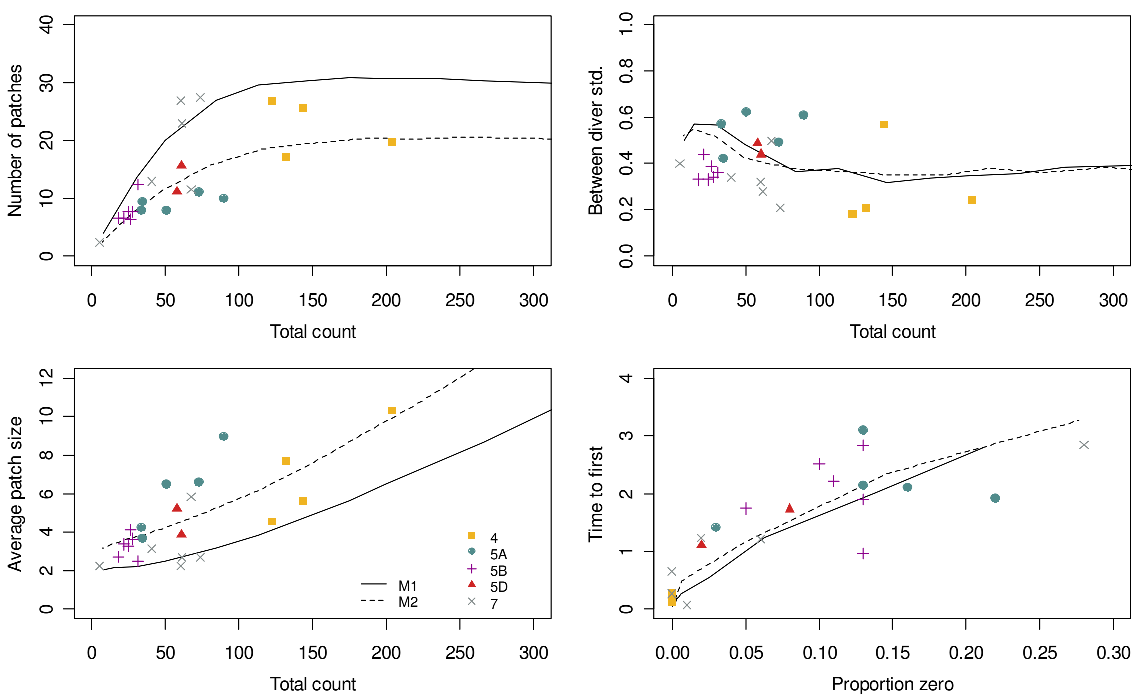

Figure 23: Comparison of simulated model summary statistics from model M1 and M2 and actual observations from paua dive surveys by stratum and QMA. Statistics include: the total paua count, the average number of patches per dive, the average patch size, the between-diver standard deviation in paua counts, the time to first paua, and the proportion of dives with no paua observed.

This formulation results in a higher degree of clumping in the *x* direction than in the *y* direction resulting in a tendency for patches to occur on a diagonal. For the clumped distributions there are two additional specifications for patch placement that increase the probability that the simulated diver will find more patches than in a random patch distribution pattern. First, randomly selected positions must be within the inner 20th to 80th percentiles of grid squares in both the *x* and *y* directions. Second, random positions are selected for a randomly selected (uniform between 2 and 8) number of patches in addition to the placement of the first patch. Following these random positions the pattern is clumped.

Figure 7 (opposite) shows some example patch distributions for a range of the clumped *c* parameters and a range in the number of patches in the grid area.

3.3 Model of diver behaviour

The simulated diver generally moves one grid square at a time, maintaining a direction of movement unless a paua patch is seen or 40 seconds have elapsed in the current direction without seeing a patch. When a patch is observed the diver moves directly to it. If more than one patch is in the divers *field of vision* (the area he has seen), the diver moves to the closest patch.

The distance that a diver can see is controlled by a *distance_of_vision* parameter. The field of vision is encompassed by a 90^0 area in the direction of movement (Figure 8). Both the position of the diver and the position of the paua patches are treated as if they were at the centre of the grid squares. Thus the *distance_of_vision* parameter does not operate as a continuous variable but as a step function. For the simulations described here the *distance_of_vision* parameter has been fixed at 4.2 m, resulting in a maximum range of 4 m vision on the perpendicular axis of movement.

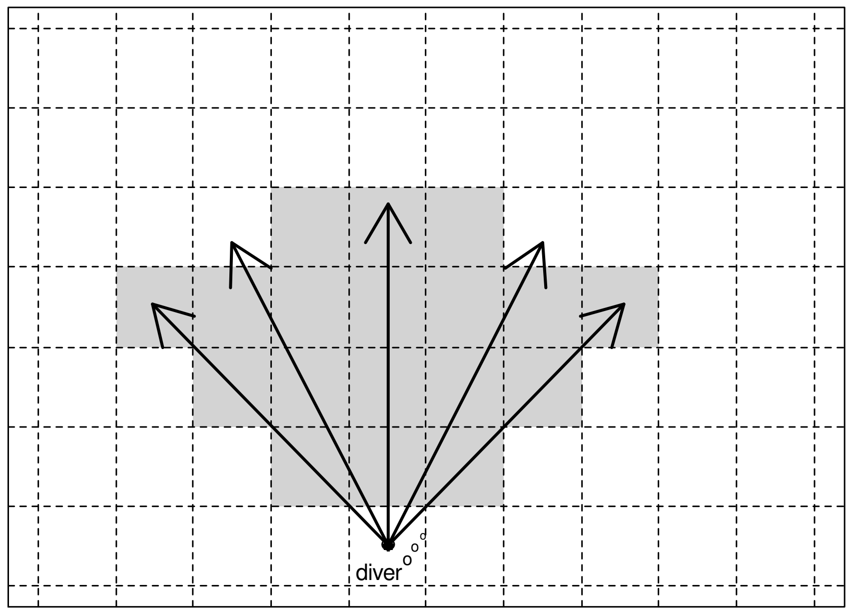

Figure 8: Schematic of a diver's field of vision. The length of the arrows is the *distance_of_vision,* and the grey shaded area shows the grid squares the diver "sees" when moving to the position labelled "diver".

When a diver enters the grid area, the *distance_of_vision* is higher than for the remainder of the swim (2.5 times higher, for simulations described here). This reflects a diver dropping from the surface onto the reef and being able to observe a greater area at that time. The initial field of vision for simulated divers is always the same, reflecting a diver observing the reef from a position of x=20 and y=0. If paua patches are seen in the initial field of vision, the diver begins the swim at the largest of the patches. If no patches are observed the diver enters the grid at the extreme end of the y axis that has been observed.

The simulated divers swim at a continuous speed, controlled by a *diver_speed* parameter. For the simulations described here, *diver_speed* is generally fixed at 0.5 m per second, a value suggested by Reyn Naylor (NIWA, pers. comm.). Some simulations are conducted that include diver effects. For these simulations, individual divers who differ in their average speed are simulated (described below).

Each dive begins with 10 minutes (600 seconds) on the clock. Time is decremented due to swimming and to processing paua patches (described below). When the first paua patch is encountered, a second 10 minute clock begins and the swim continues until this clock runs down to zero.

Although the diver movement is generally one grid square at a time, this changes when the diver sees a paua patch or moves into an area he has been in before. When a patch is seen the diver moves directly to that patch. When the diver moves into an area he has been in before, he takes a large (8 grid squares) step away from that area.

Examples of diver movement patterns relative to paua patches are shown in Figure 9.

3.4 Time to record and process samples

The average time to record and process paua patches during the research dive survey was estimated at 7.8 seconds (McShane et al. 1996). This processing time estimate is for patches containing 20 or fewer paua; for larger patches the swim clock is stopped. While data on processing time for patches of different sizes is not available, it is clear that processing a patch of 20 paua will take significantly longer than processing a patch with a single paua. For the purpose of these simulations, variable processing times were assumed for different patch sizes.

The assumed processing time for patches of various sizes comprises two components – the time to collect paua and the time to count and record the size of the paua patch. It is assumed that collecting each paua takes 2.3 seconds; with a maximum of four paua collected during each swim, the maximum time to collect paua is 9.2 seconds (Table 12). The time to count and record patch size is assumed to increase with the number of paua in each patch (Table 12).

Given the total time assumed for processing paua patches of different sizes and the proportion of patches of size 20 or fewer in each patch size category (Table 12), the simulated mean time to process a paua patch of 7.7 seconds is in close agreement with the estimate from the McShane (1996) study.

Variability in processing time is included in the simulations, at the *paired dive* level. Processing time is assumed to be normally distributed with a c.v. of 0.1. That is, for each paired dive the total time required to process paua, based on the values in Table 12, is randomly adjusted with a c.v. of 0.1.

6.2 Diver effects

On the basis of the number of dives involved in recent paua research dive surveys, six divers are simulated with three randomly selected divers participating in each survey. The simulated divers differ in their average swimming speed: swimming speeds range from 80% to 120% of the overall average speed (0.5 m/second). At the site level, random error, normally distributed with a c.v. of 0.15, is added to the individual divers' speed. That is, the random component of the diver's speed is the same for the pair of divers at each site.

6.3 Simulation model parameters

For this set of analyses, two models that differ in the relationships between density and average patch size are simulated, models M1 and M2. With the exception of the simulation parameters *std* and *c*, all parameters that control the size and distribution of patches vary with density (Figure 22). The parameter *std* is fixed at 1.0 for both M1 and M2, and the "clumped" parameter *c* is 0.07 for model M1 and 0.14 for model M2. The resultant non-linearity between *q* and stock abundance is relatively minor (Figure 22).

Simulations were run for both models M1 and M2 across a range of densities to assess how similar model output statistics are to observations from the actual paua research dive survey. The simulations result in observations that are generally consistent with the actual dive surveys (Figure 23).

The between-diver variance in paired-swim paua counts generated from models M1 and M2 are similar to those of the actual research diver paua surveys (Figure 23). Additional variance in simulated diver paua counts is generated by adding lognormal error to the density simulated for each grid (i.e., at the site level). The magnitude of the lognormal error is set so that the variance of the paired paua counts generates the same variance as estimated from the research diver survey data at the stratum level (ResSD=0.735, Table 10).

6.4 Estimating diver effects

The first set of simulations is constructed to evaluate how well diver effects are estimated, and whether including diver effects improves the ability to accurately estimate "year effects" in GLM analyses. For these simulations, the stock density decreases by 40% over five surveys, with similar density trends among all strata (Figure 24, panel a). Three scenarios are simulated: model M1 with maximum density (*dmax*) of 0.04 paua/m^2 (M1-04), model M2 with maximum densities of 0.04 (M2-04), and model M2 with 0.08 paua/m^2 (M2-08). For each survey, 15 paired dives are conducted per stratum. That is, 15 random sites are selected for each stratum. Negative binomial GLMs with year and stratum effects, and with and without diver effects, are fitted to the simulated data. One thousand replicates are run and summary statistics compiled for GLM models fitted to the *10min_count* and *adj_count2* estimates from individual and paired dives.

For this set of simulations the diver paua counts (i.e., *adj_count2*) are only slightly biased relative to the simulated densities. The mean paua counts, relative to those of the first survey, are about 2% higher than the simulated relative densities (Table 17). The biases are fairly consistent across the three formulations of the simulation model. The range in average diver paua counts (*10min_counts*) across strata and surveys encompasses much of the range seen in actual research paua dive surveys (compare Table 11 with Table 17). Likewise, the range in the average number of paua patches per paired dive is similar to that in the research dive surveys.

6 SIMULATIONS WITH VARIABLE PATCH SIZE AND VARIABLE NUMBER OF PATCHES

The scenarios with constant number of patches and constant patch size are extreme, and the paua research dive survey data do not tend to support such extreme assumptions. A further set of simulations are conducted where the average patch size and the number of patches simulated both vary with paua density. This set of simulations attempts to emulate the actual paua dive surveys: multiple strata are simulated; diver effects are included; and GLM analyses are used to estimate "year" effects. Moderate values are used for the "clumped" parameter so that non-linearity between q and stock abundance is small.

The GLMs fitted to the simulated data assume a negative binomial distribution with a log-link function, consistent with the procedure used in recent stock assessments (e.g., Breen & Smith 2008b). The explanatory variables are: survey number (i.e., "year" effects), stratum, and diver. All explanatory variables are treated as categorical.

6.1 Population structure

A paua population is simulated at the QMA level with six strata that differ in their area and paua density. Initial densities in the strata are scaled relative to a parameter *dmax,* so that a range of densities can be investigated. The length, mean width, relative initial density, and relative number of paua for each stratum are shown in Table 16.

Table 16: Characteristics of the six strata in the simulated population.

	Stratum					
	1	2	3	4	5	6
Length (km)	40	20	30	50	40	30
Mean width (m)	90	80	100	60	80	70
Initial density relative to *dmax*	0.80	1.00	0.85	0.90	0.75	0.80
Initial relative number of paua	2880	1600	2550	2700	2400	1680

Information on paua densities in the QMA is not available. At best, estimates can be made based on assumptions about the search area during the 10 minute timed surveys. The assumed average swimming speed of research divers (0.5 m/second) is probably a fairly reasonable estimate. The effective area searched depends on the divers' field of vision and their ability to search areas of the site where paua are more likely to occur. It is this latter component that is most difficult to quantify.

The highest average research dive survey paua count is 204 paua per swim in stratum 2 of PAU 4 (see Table 9). For this stratum, the average number of patches per swim is 19.8, with 89.8% of the patches having 20 or fewer paua. Assuming an average processing time of 7.8 seconds per patch, 77% of the survey time is spent searching for paua. Given an average swimming speed (0.5 m/second) and an assumed field of vision of 4 m results in a paua density of 0.22 paua/m^2. If the average field of vision were actually 2 m, the paua density would be 0.44 paua/m^2. These estimates will tend to be biased high given divers will tend to focus effort in the parts of the site that have the highest density.

Ultimately, any paua density estimates are speculative and it is not possible to determine actual paua densities in the QMA without further information. Therefore, for the following simulations the *dmax* parameter is scaled so that the simulated diver paua counts are consistent with the range of observations in the paua diver surveys.

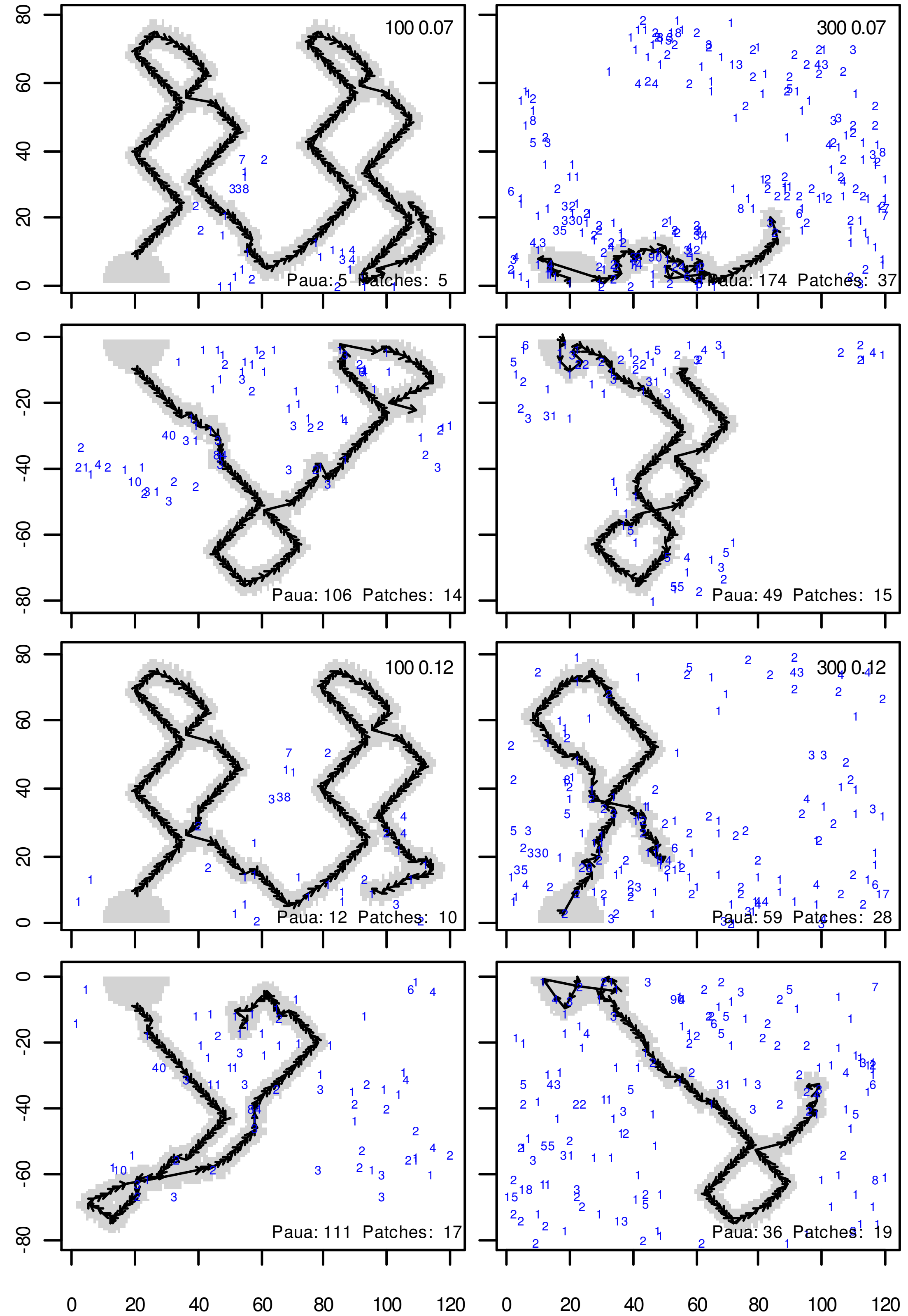

Figure 9: Examples of simulated dive surveys for 100 and 300 patches per grid and clumped distribution parameter value of 0.07 and 0.012. Paua patches are shown in blue (number in the patch), the track and direction of the diver is shown with black arrows, and the area the diver has seen is shown in gray. "Paua" and "Patches" show the number of paua and paua patches encountered during the dive.

Table 12: The proportion of observations (across all QMAs) at each patch size for patch sizes less than or equal to 20, and the simulated time to process each of those patch sizes.

		Time (seconds)		
Patch size	Proportion	Count /write	Collect paua	Total process
1	0.5837	3	2.3	5.3
2	0.1500	3	4.6	7.6
3	0.0720	3	6.9	9.9
4	0.0477	4	9.2	13.2
5	0.0306	4	9.2	13.2
6	0.0220	4	9.2	13.2
7	0.0188	5	9.2	14.2
8	0.0153	5	9.2	14.2
9	0.0100	5	9.2	14.2
10	0.0085	6	9.2	15.2
11	0.0070	6	9.2	15.2
12	0.0078	6	9.2	15.2
13	0.0033	7	9.2	16.2
14	0.0048	7	9.2	16.2
15	0.0039	7	9.2	16.2
16	0.0048	8	9.2	17.2
17	0.0024	8	9.2	17.2
18	0.0031	8	9.2	17.2
19	0.0022	9	9.2	18.2
20	0.0022	9	9.2	18.2

4 SIMULATION MODEL CHARACTERISTICS

The paua diver simulation model was run over a broad range of parameter values to determine a reasonable range for each parameter, where "reasonable" was determined by results that were consistent with dive survey observation for the paua QMA. Table 13 shows the values for the various parameters that control the behaviour of the simulator. For each combination of parameter values, 1000 paired swims were simulated (i.e., 2000 individual swims). The statistics summarised from these simulations are presented in Table 14. For this set of simulations, diver effects (i.e., variable diver speed) were not simulated. Summary statistics are reported for *single dive* events.

Table 13: Parameter description and range of parameter values assessed in the paua diver simulation model.

Description	Symbol	Range of values
Diver_speed		0.5 m/second
Distance_of_vision		4.2 m
Geometric distribution parameter	*g*	0.45, 0.65
Proportion of patches that are large	*p*	0.01, 0.05, 0.1
Mean size of large patches	*x*	20, 50, 80
Standard deviation of the log of *x*	*std*	0.7, 1.0
Clumped distribution parameter	*c*	0.03, 0.07, 0.12, 0.18, 0 (random)
Number of patches simulated	*Nsim_patch*	20, 60, 100, 200, 300, 400, 500

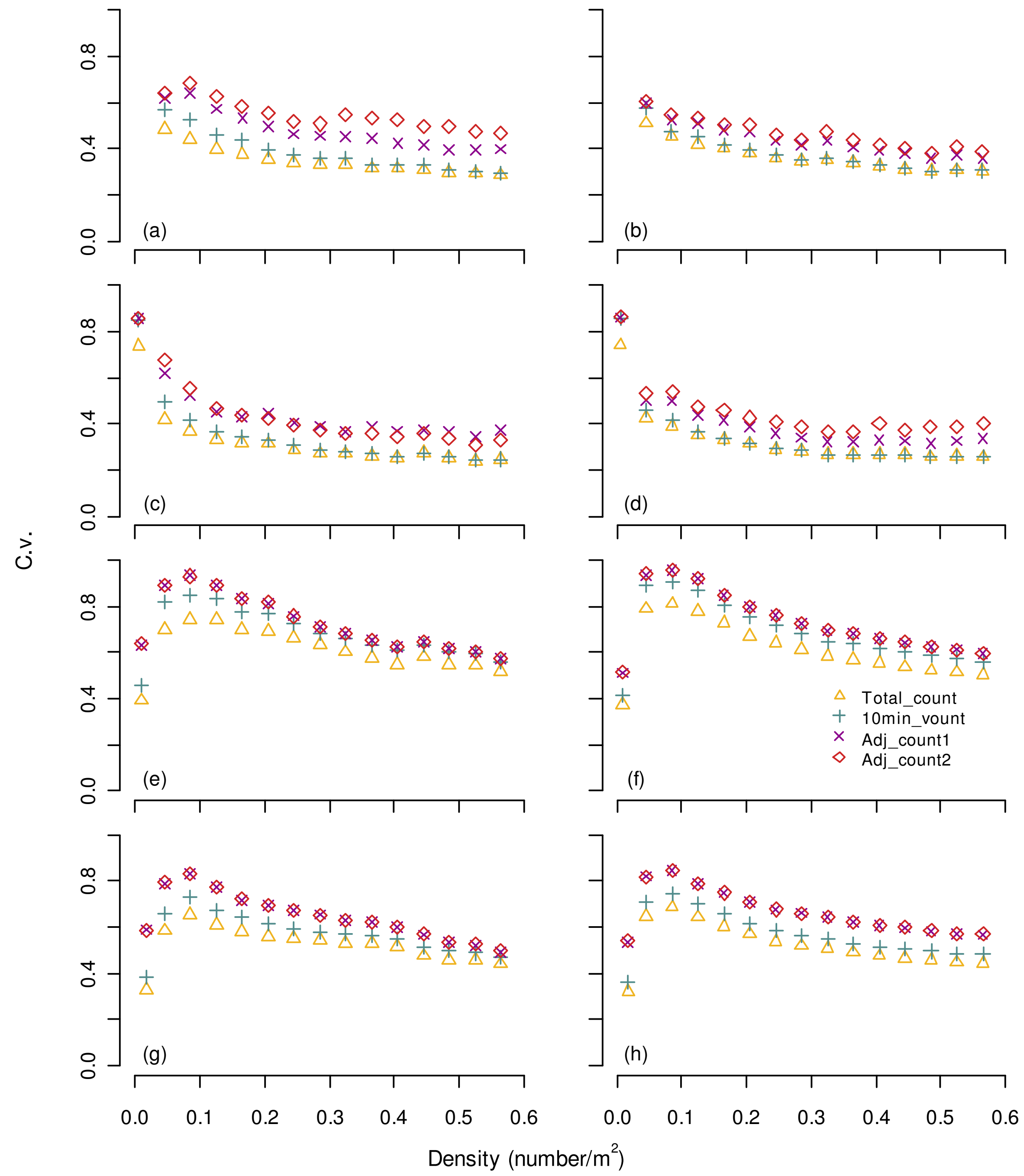

Figure 21: C.v. of the distribution of paua counts for alternative simulation scenarios (a - h, described in Table 15) and alternative paua count estimators.

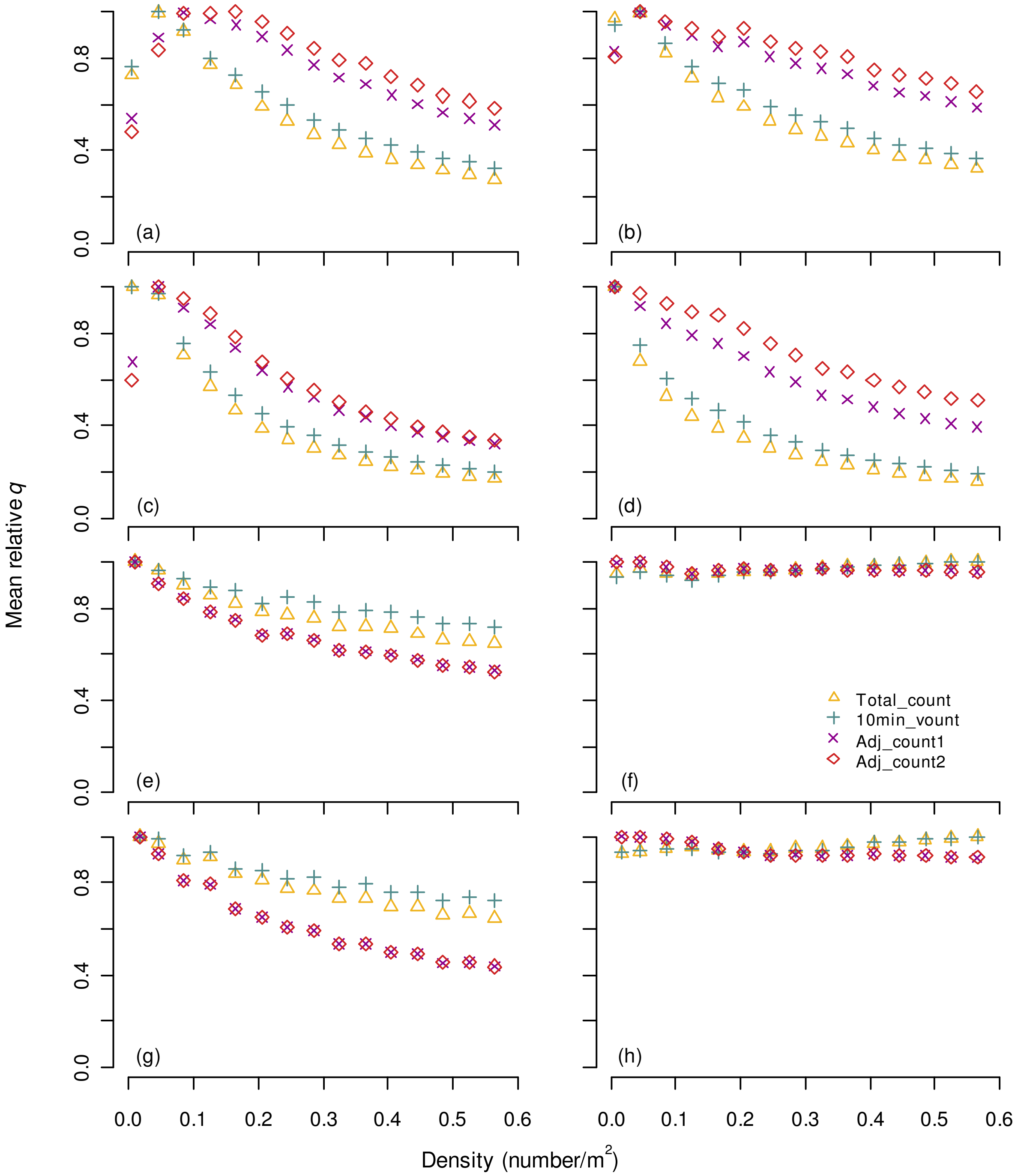

Figure 20: Relative *q* (mean proportion estimated relative to the maximum mean proportion estimated) for alternative simulation scenarios (a - h, described in Table 15) and alternative paua count estimators.

Table 14: Summary statistics for the paua diver simulation model trials.

	Name:
For individual swims:	
Number of patches enumerated	*Npatch*
Total number of paua counted	*Npaua*
Ratio of standard deviation of patch size to mean patch size	*CVPsize*
Time to first paua	*Tfirst*
Proportion of dives with zero paua counted	*Pzero*
For paired swims:	
Std. Dev. of the paired swim paua counts (log(number counted+1))	*SDdiver*

4.1 Influence of model parameter values on summary statistics

The influence of the diver simulation model parameter values on simulated diver survey data is assessed through the mean of some key summary statistics.

The geometric distribution parameter that controls the size distribution of small paua patches (*g*) has in general little influence on summary statistics (Figure 10). The average number of patches observed per dive increases slightly and the number of paua observed per dive decreases slightly with higher values of the *g* parameter. This results because less time is required to process the smaller patch sizes generated by a higher *g* value. The *CVPsize* statistic also increases with higher values of the *g* parameter.

The simulation model parameter *std*, which controls the variance of the size of large paua patches, has little effect on summary statistics with only a minor effect on the *CVPsize* statistic (Figure 11).

The most influential simulation model parameter, other than the number of patches simulated in the grid, is the parameter that controls the degree of clumping of the paua patches (parameter *c*, Figure 12). With patch distributions more clumped, the number of patches (*Npatch*) and the number of paua observed (*Npaua*) increases, as does the between-diver standard deviation of patch size in paired dives (*SDdiver*).

The mean size of large patches (*x*) and the proportion of patches that are large (*p*) affects the number of paua observed, but has little influence on the number of patches observed (Figure 12).

The mean time to first (*Tfirst*) and the proportion of dives that encounter no paua (*Pzero*) are essentially unaffected by simulation model parameter values, other than the clumped *c* parameter and the number of patches simulated (Figures 10, 11, & 12).

The ratio of the fraction of paua observed to the fraction of the grid area surveyed in each dive is an indication of how efficient the simulated divers are at finding paua patches. As expected, given a random paua distribution, the ratio is essentially 1 (Figure 13). Actually, the ratio falls below 1 when the number of patches in the grid is high because the swim clock runs down before all observed patches can be processed. At the extreme clumped distribution (*c*=0.03), the "efficiency" ratio ranges from 1.6 to 2.3 indicating divers find significantly more paua than would be expected if there were a random search pattern and random paua distribution.

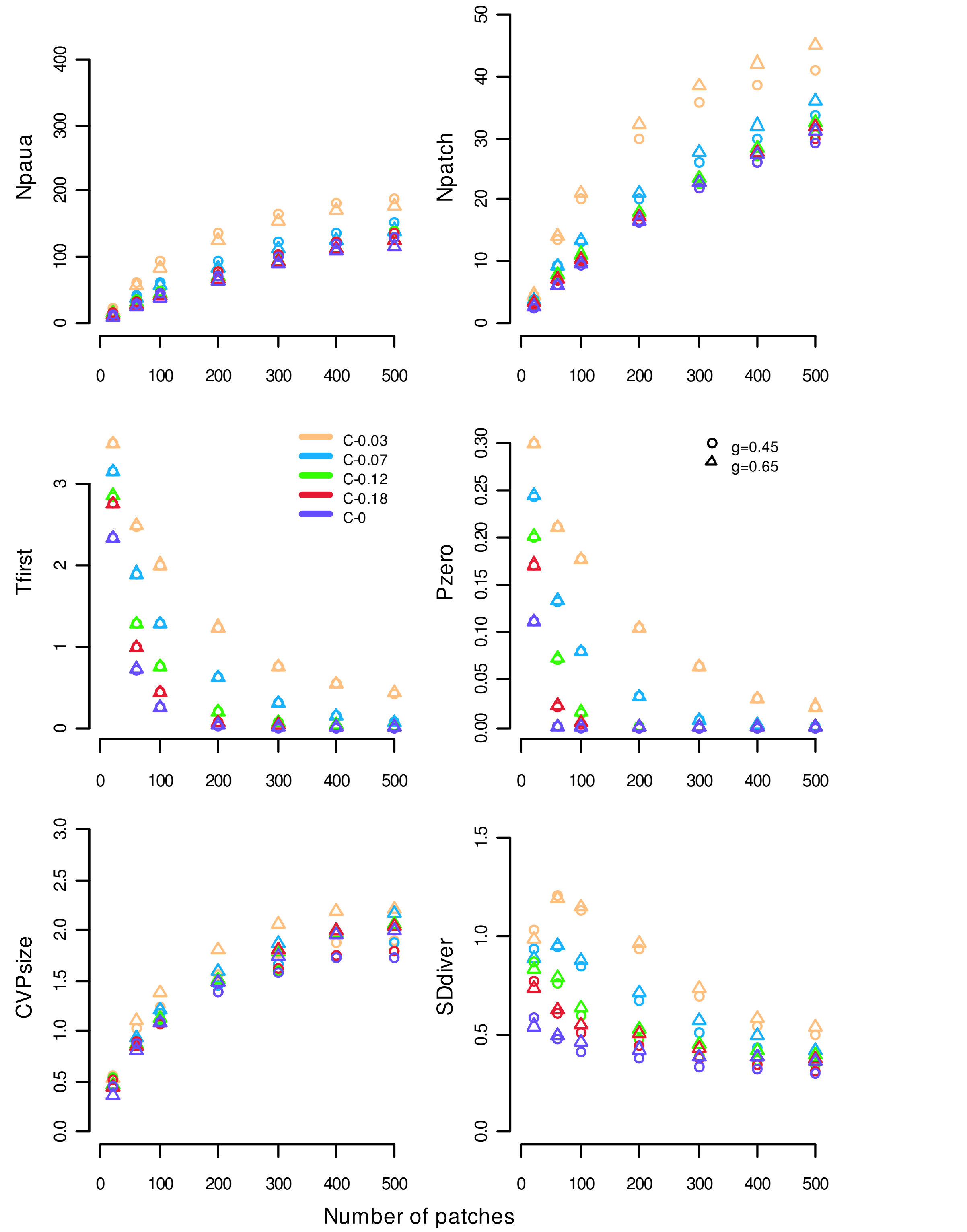

Figure 10: Mean of simulation summary statistics (*Npaua, Npatch, Tfirst, Pzero, CVPsize, and SDdiver*) versus number of patches simulated for two levels of the model *g* values. Model parameters *x, std,* and *p* are fixed at 50, 1.0, and 0.05, respectively.

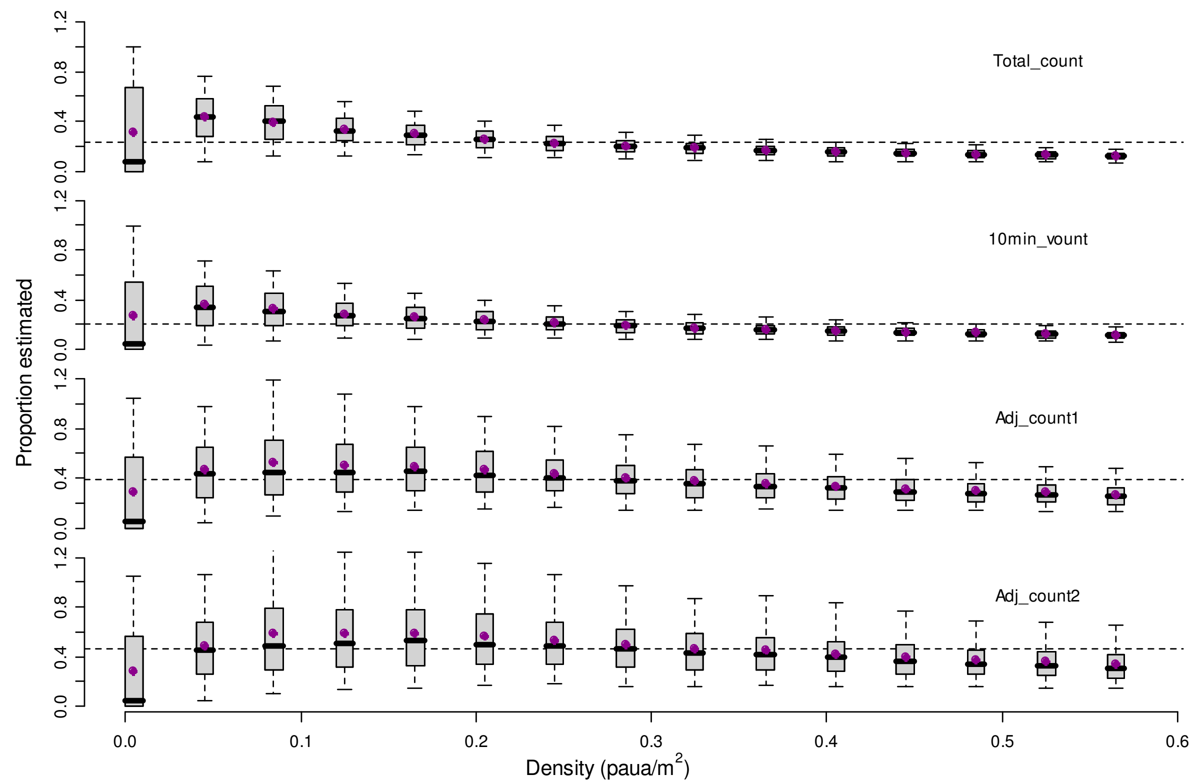

Figure 18: Distribution of the proportion of paua estimated for *total_count*, *10min_ count*, *adj_count1* and *adj_count2* estimators at alternative paua densities. Results are from the fixed patch size simulation "c". The box and whiskers indicate the 5th, 25th, 50th, 75th, and 95th quantiles. Means are shown with filled circles. The horizontal dashed lines show the mean proportion estimated across densities.

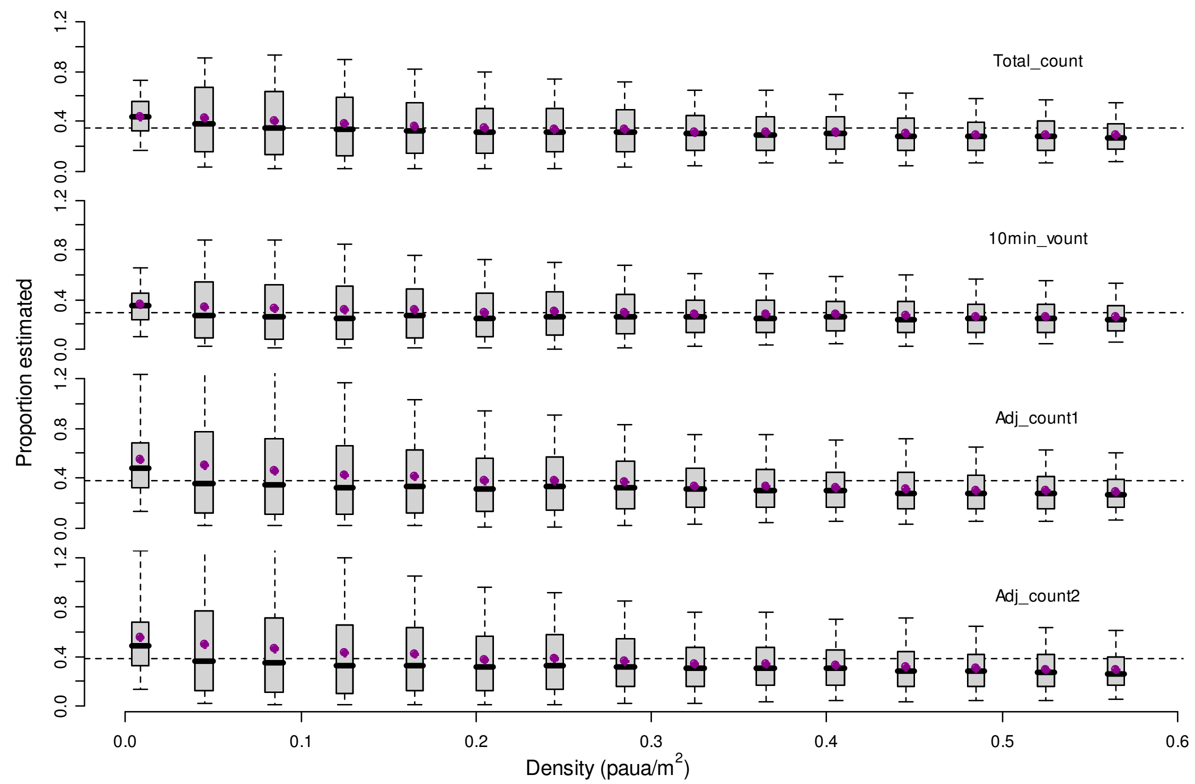

Figure 19: Distribution of the proportion of paua estimated for *total_count*, *10min_ count*, *adj_count1* and *adj_count2* estimators at alternative paua densities. Results are from the fixed number of patches simulation "e". The box and whiskers indicate the 5th, 25th, 50th, 75th, and 95th quantiles. Means are shown with filled circles. The horizontal dashed lines show the mean proportion estimated across densities.

For each of the two scenarios, four sets of simulations were conducted at paua densities (*d*) ranging from 0.005 to 0.565 paua/m^2. The *fixed patch size* scenario was run with patch sizes of 7 and 13 and with model parameter *c* values of 0.03 and 0.07. All other model parameters were fixed (Table 15). The *fixed number of patches* scenario was run with 75 and 150 patches simulated in the grid and model parameter *c* either fixed at 0.05 or varying as a function of density (Table 15). The relationship between model parameter *c* and density was such that paua were more clumped as density decreased. For the *fixed number of patches* scenarios the proportion of patches that was large also increased as a function of density (Table 15).

For the paua diver simulation model, the mean patch size ($\bar{s}$) is a function of model parameters *p*, *g*, and *x*:

$$\bar{s} = \frac{(1-p)}{g} + px \qquad p \le 1 .$$

For the *fixed number of patches* scenarios, the mean patch size is controlled by varying the mean size of large patches (*x*):

$$x = \frac{\bar{s}}{p} - \frac{(1-p)}{pg} .$$

For each *fixed patch size* and *fixed number of patches* scenario, 1000 simulations are conducted at each of the 15 density levels. Four indices of paua counts are summarised from the *paired dive* observations: two that reflect actual counts (*total_count* and *10min_count*) and two that adjust the 10 minute counts for processing time (*adj_count1* and *adj_count2*). *Adj_count1* assumes 7.8 seconds to process patches with 20 or fewer paua and *adj_count2* assumes the processing times shown in Table 12, although actual processing times are variable among the simulation trials.

Table 15: Simulation model parameter values for fixed patch size (models a to d) and fixed number of patches (models e to h) scenarios.

	Fixed patch size				*Fixed number of patches*			
Parameter	a	b	c	d	e	f	g	h
G	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
P	0.3	0.3	0.3	0.3	0.6*d*	0.6*d*	0.6*d*	0.6*d*
Std	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	0.03	0.07	0.03	0.07	0.03+0.1*d*	0.05	0.03+0.1*d*	0.05
Nsim_patch	variable	variable	variable	variable	75	75	150	150
$\bar{s}$	7	7	13	13	variable	variable	variable	variable

The distribution of paua counts from model runs *c* and *e* are shown in Figures 18 and 19, respectively. Results are presented as the proportion of the total paua in the grid that is estimated. For model runs *c* and *e* the relationship between proportion estimated and paua density is non-linear for all the paua enumeration methods. The variance of the estimates is higher for the two “adjusted” counts.

Results from all simulations are shown in Figure 20, plotted as the relative *q*’s (ratio of the mean proportion estimated to the maximum of the mean proportion estimated). For all simulated scenarios the relative *q*’s are non-linear with simulated density. The degree of non-linearity tends to be higher for the *fixed patch size* scenarios (a – d), than for the *fixed number of patches* scenarios (e – f). None of the estimation methods is clearly superior, although the *10min_count* performs better than the *total_count* and the *adj_count2* performs better than the *adj_count1* in terms of less non-linearity in relative *q* (Figure 20).

The c.v.s of the relative *q* estimates are shown in Figure 21 and are higher for the adjusted counts than for the unadjusted counts, and also tend to be higher for the *10min_count* than for the *total_count*.

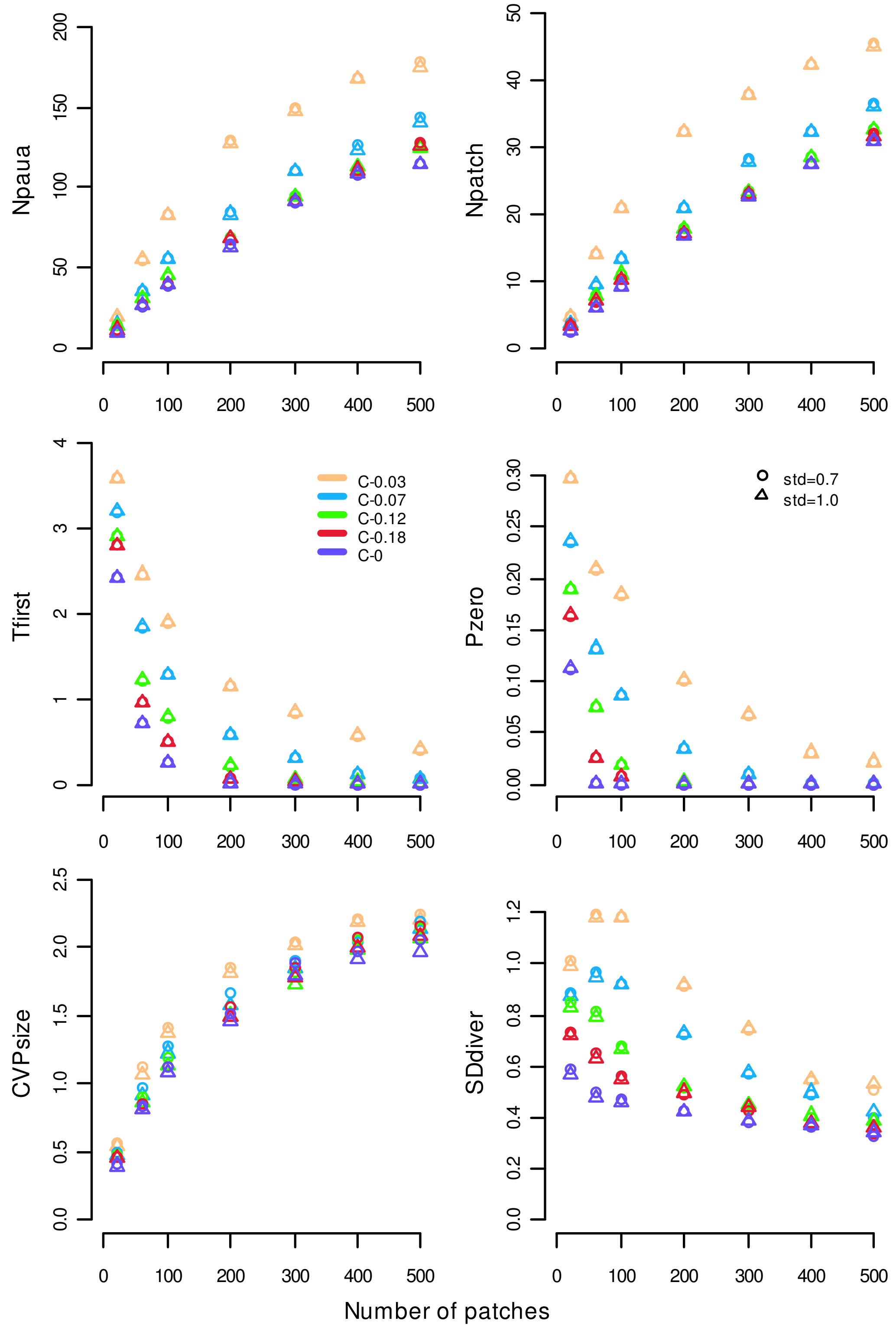

Figure 11: Mean of simulation summary statistics (*Npaua, Npatch, Tfirst, Pzero, CVPsize, and SDdiver*) versus number of patches simulated for two levels of the model *std* values. Model parameters *g, x,* and *p* are fixed at 0.65, 50 and 0.05, respectively.

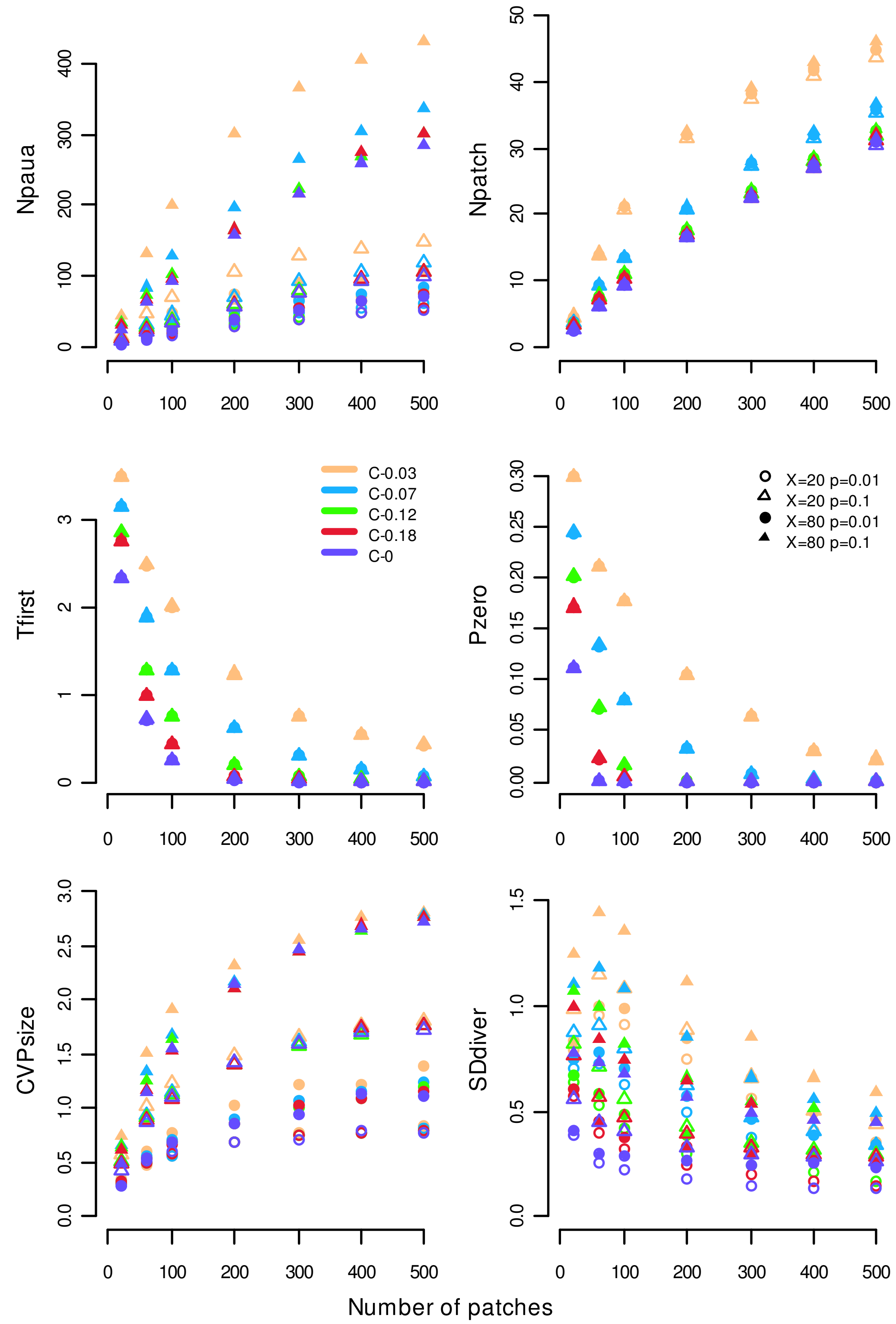

Figure 12: Mean of simulation summary statistics (*Npaua, Npatch, Tfirst, Pzero, CVPsize, and SDdiver*) versus number of patches simulated for two levels of the model *x* and *p* parameter values. Model parameters *g* and *std* are fixed at 0.65 and 1.0, respectively.

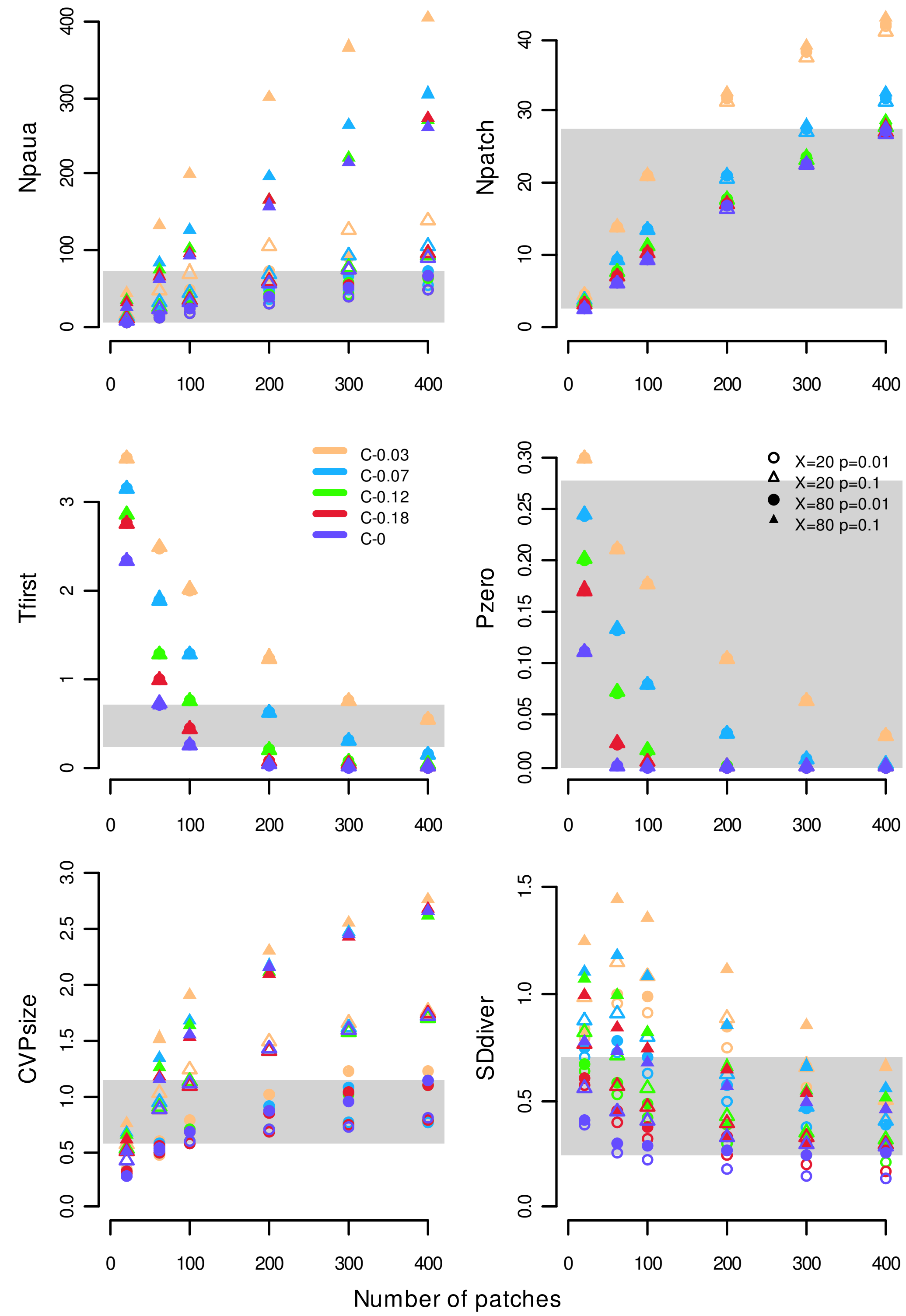

Figure 17: Mean of simulation summary statistics (*Npaua*, *Npatch*, *Tfirst, CVPsize*, *and SDdiver*) versus number of patches simulated for two levels of the model *x* and *p* parameter values. Model parameters *g* and *std* are set at 0.65 and 1.0, respectively. The grey shaded areas show the range of values observed among strata in PAU 7 for each summary statistic.

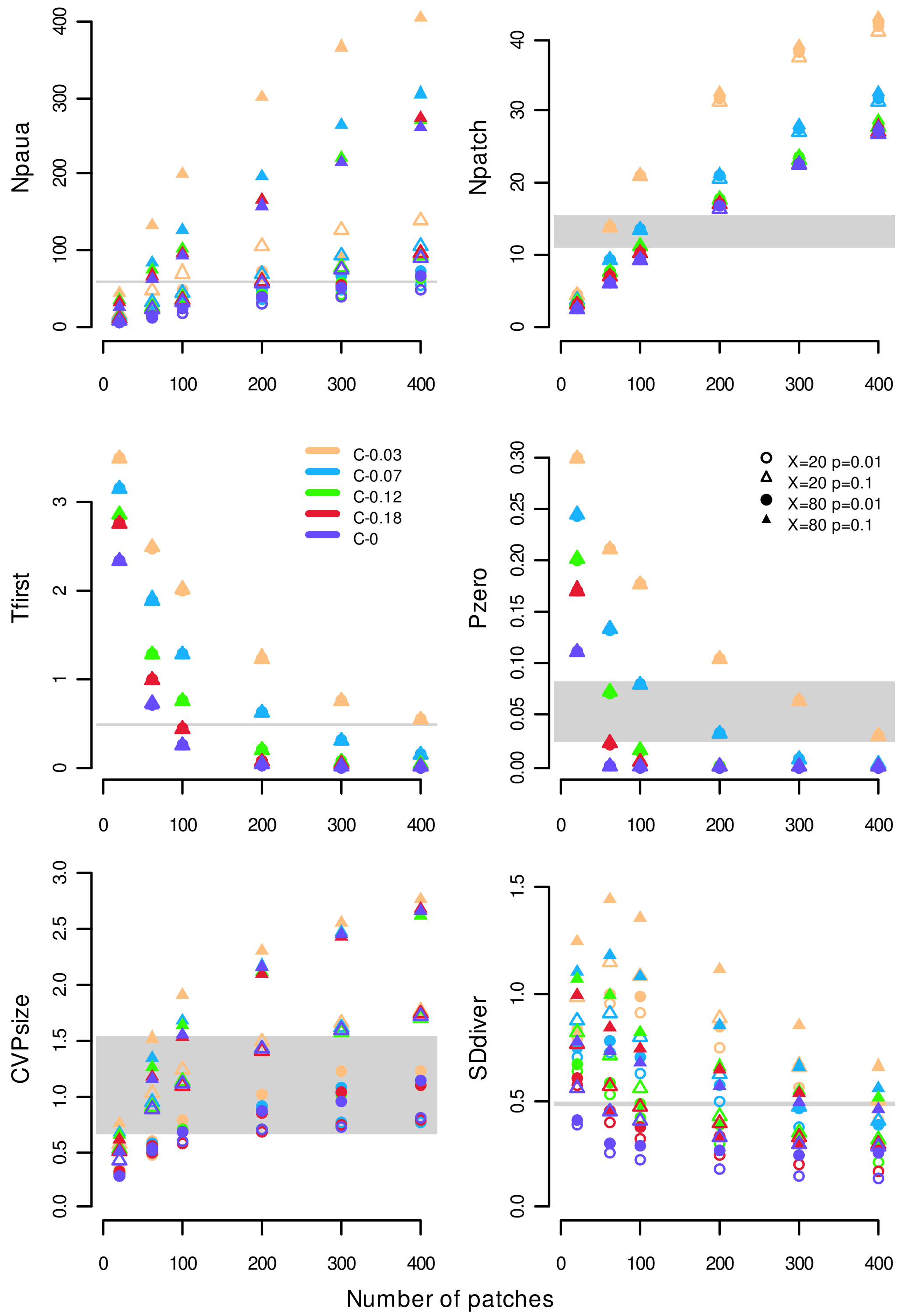

Figure 16: Mean of simulation summary statistics (*Npaua*, *Npatch*, *Tfirst, CVPsize, and SDdiver*) versus number of patches simulated for two levels of the model *x* and *p* parameter values. Model parameters *g* and *std* are set at 0.65 and 1.0, respectively. The grey shaded areas show the range of values observed among strata in PAU 5D for each summary statistic.

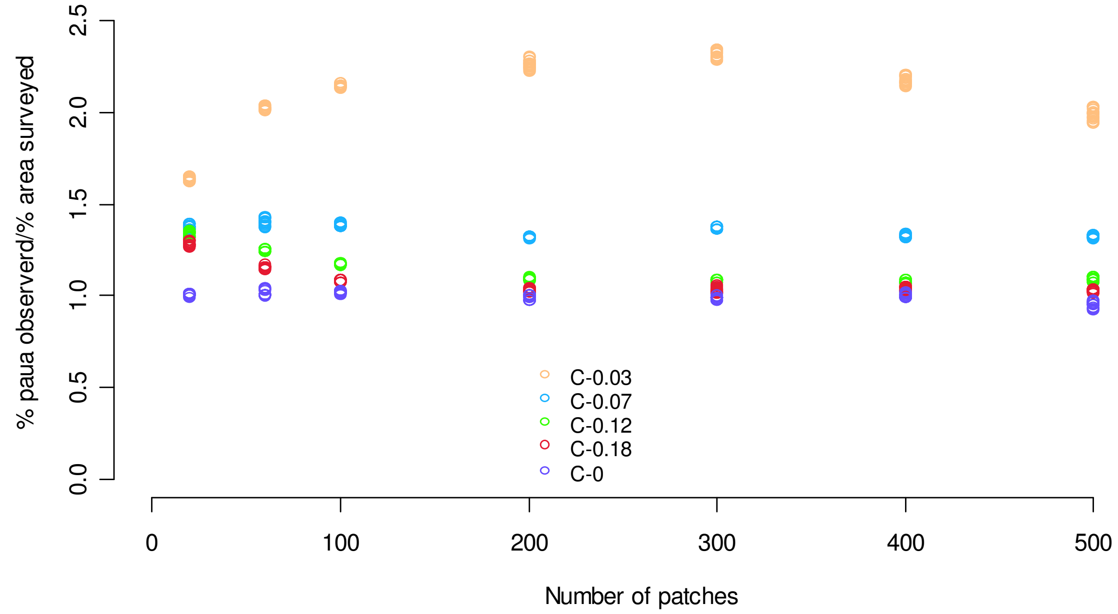

Figure 13: The ratio of the proportion of the paua observed to the proportion of the area surveyed versus the number of patches simulated in the grid for alternative values of the clumped parameter *c*.

4.2 Model parameter values consistent with dive survey data

The research paua survey data, summarised by stratum, can be used to define a range of simulation model parameters that are consistent with the QMA observations.

For example, the average number of patches in research surveys of PAU 4 ranges from 17.1 to 26.9. These values are consistent with a total number of patches per grid of about 100 to 400 (Figure 13). However, grid patch numbers of 100 require a high degree of clumping in the patch distribution to generate the observed number of patches per swim, and that combination is inconsistent with the observed *Tfirst* and *Pzero* observations. The *Tfirst* and *Pzero* values from the research dive surveys are in fact inconsistent with either a random paua distribution and with a highly clumped paua distribution (Figure 13).

For all of the QMA, the summary statistics *Npatch*, *Pzero*, and *SDdiver* in combination suggest that a random distribution of paua patches and a highly clumped distribution of paua patches are inconsistent with the research diver data (Figures 14 to 17). Clumped distributions with parameter values of 0.07 to 0.12 appear to be most consistent with the dive survey observations.

5 SIMULATIONS WITH FIXED PATCH SIZE AND FIXED NUMBER OF PATCHES

The paua dive survey simulations conducted by Cordue (2009) were based on theoretical considerations about how paua research diver behaviour interacts with paua density. That approach differs from the mechanistic approach adopted here, but similar scenarios can be investigated with the paua diver simulator described in this report. Cordue (2009) simulated two scenarios; 1) a constant number of patches as density changes (*fixed patch size*), and 2) a constant number of paua per patch as density changes (*fixed number of patches*). Both of these scenarios are simulated here.

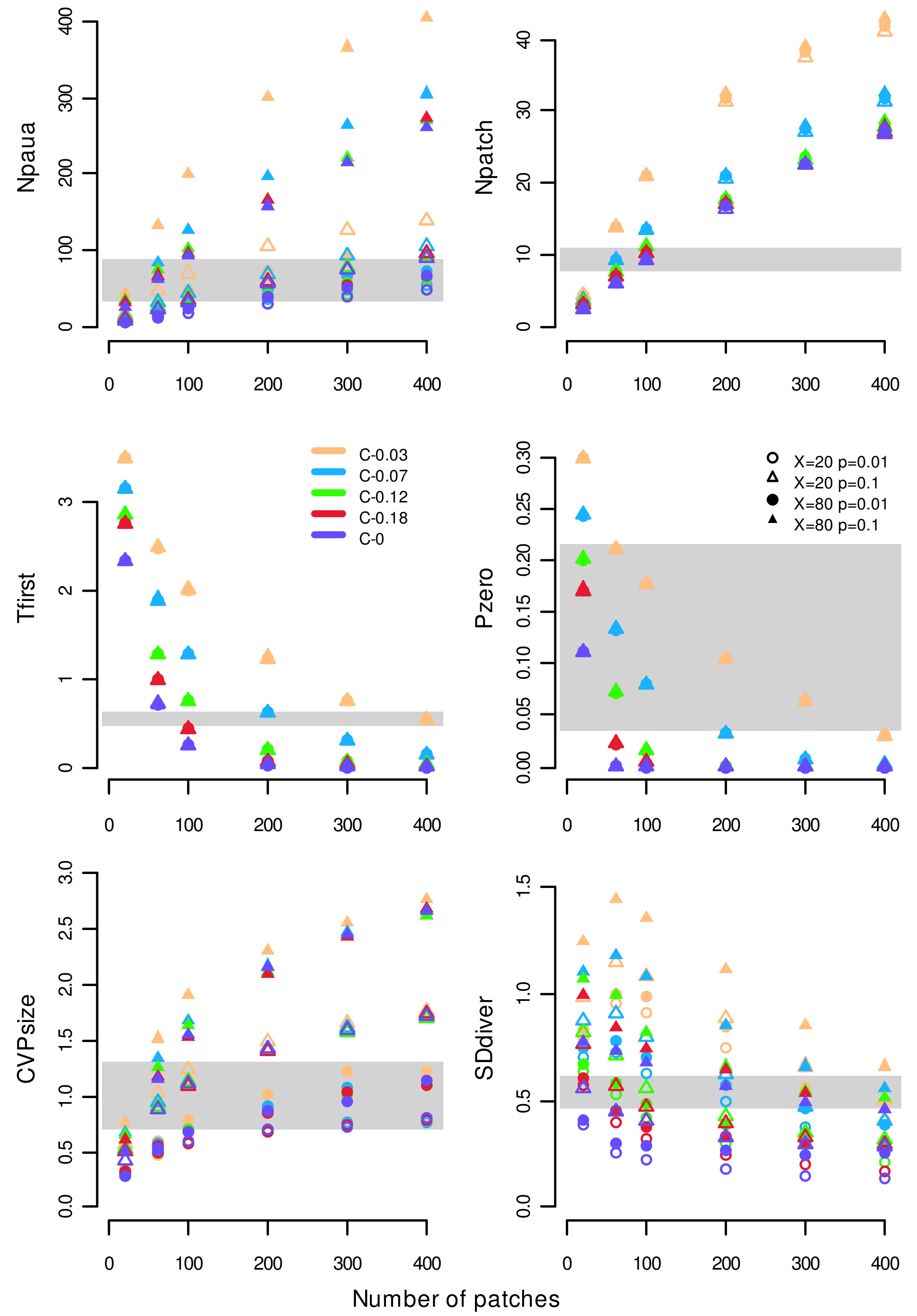

Figure 14: Mean of simulation summary statistics (*Npaua*, *Npatch*, *Tfirst*, *CVPsize*, *and SDdiver*) versus number of patches simulated for two levels of the model *x* and *p* parameter values. Model parameters *g* and *std* are set at 0.65 and 1.0, respectively. The grey shaded areas show the range of values observed among strata in PAU 5A for each summary statistic.

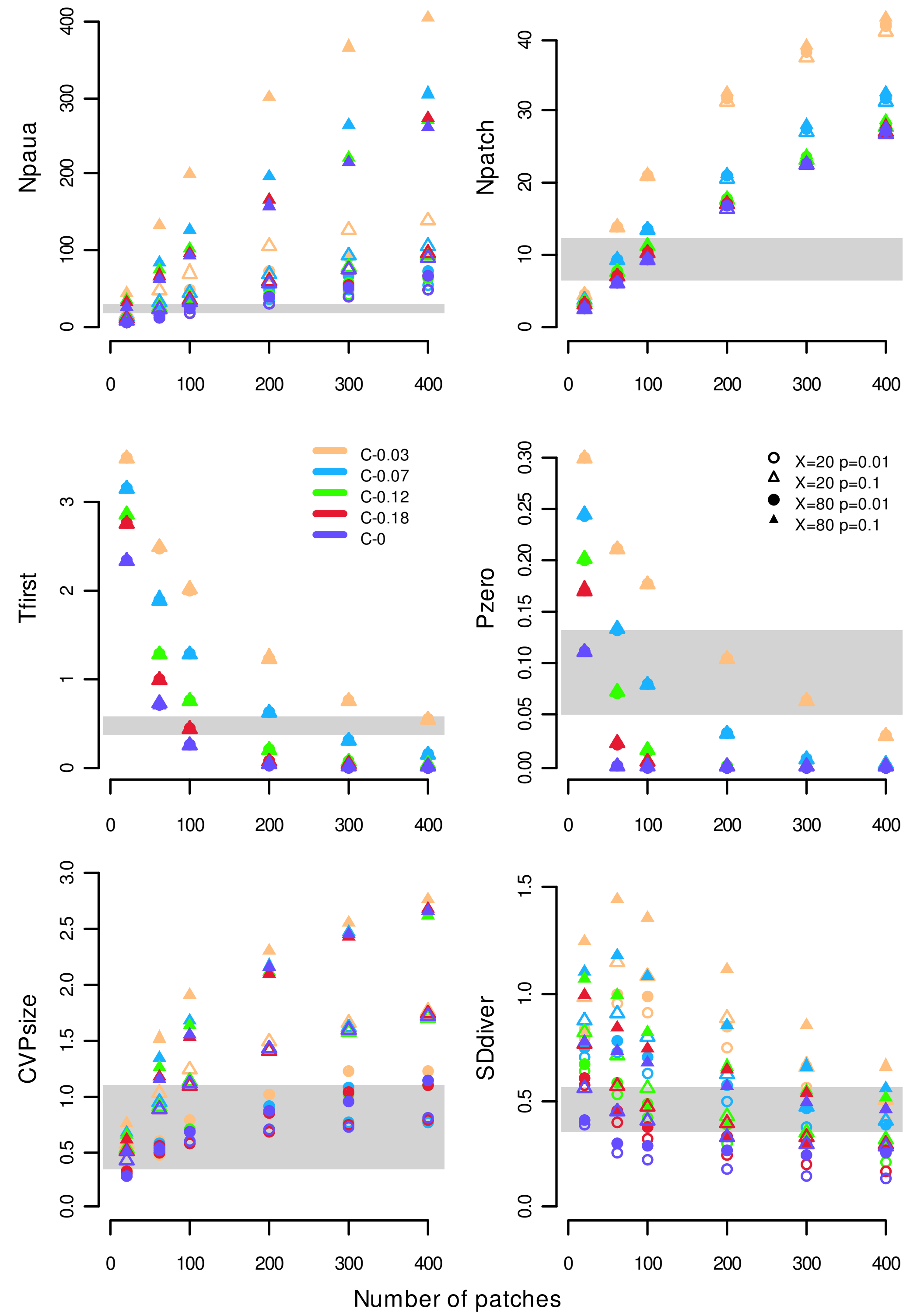

Figure 15: Mean of simulation summary statistics (*Npaua*, *Npatch*, *Tfirst*, *CVPsize*, *and SDdiver*) versus number of patches simulated for two levels of the model *x* and *p* parameter values. Model parameters *g* and *std* are set at 0.65 and 1.0, respectively. The grey shaded areas show the range of values observed among strata in PAU 5B for each summary statistic.