CEBRA Report Cover Page			
Project Title, ID & Output #	CEBRA Project 1301C - Improving the methods used for constructing ballast water risk tables		
Project Type	Final Report		
DAFF Project Sponsor	Andrew Cupit	**DAFF Project Leader/s**	Peter Stoutjesdijk
CEBRA Project Leader	Andrew Robinson	**NZ MPI Collaborator**	N/A
Project Objectives	The research of this project supports implementation of the Biosecurity Bill 2014 (currently under consideration at Federal Parliament) and Australia's international obligations as a signatory to the International Convention for the Control and Management of Ships' Ballast Water and Sediments. The project aimed to deliver effective biosecurity controls through the provision of up-to-date and valid risk based decision making to identify and effectively target those vessels posing the highest risk of translocating marine pests between Australian ports. This information is used to differentiate between those ships that are posing a higher biosecurity risk and those that are low risk, essentially allowing the department to direct high risk ships to manage their ballast water, whilst exempting ships with low risk ballast water from unnecessary management processes to reduce the costs of regulation and avoid the inherent risks of managing ballast water on rough seas.		
Outputs	**(1) Report No. 1301C. (2) Ballast water risk tables for seven species.** This research underpins risk based decision making, informing ships to mange high risk ballast water or allow for the provision of exemptions from managing ballast water when the ship's ballast water is low risk.		
CEBRA Workplan Budget	**Year 2013-14**	**Year 2014-15**	**Year 2015-16**	**Year 2016-17**

	TBA $90,000			
Project Changes	*NA*			
Research Outcomes	***Generating synthetic air and sea temperature data*** The original version of the BWRA generated sea temperature data in such a way that substantially different estimates of lifecycle completion could occur on 31 December vs. 1 January for the same species. The original methodology also demonstrated limitations when considering year-to-year variation. These issues were addressed using a block bootstrap technique which has been shown to be a more appropriate methodology for estimating lifecycle completion. ***Estimating likelihood from lifecycle models*** The original version of the BWRA estimated high risk based on the likelihood of a species completing on average ≥80% of its lifecycle. This project proposed a different methodology for estimating high risk by estimating risk based on the proportion of simulations in which a species completed 100% of its lifecycle. An arbitrary cutoff of 5% of simulations was identified as the most appropriate cutoff (as there is a paucity of empirical data to identify a more appropriate cutoff).			
Recommendations	That the Department of Agriculture: • Notes that the MPSC has endorsed the new method for generating sea surface temperatures. • Notes that the MPSC has endorsed defining the monthly yes/no decision point for acceptable risk of introduction to: full lifecycle being completed in 5% of simulations on any day in a month. • Considers developing a method based on satellite-derived sea surface temperature data to generate data for simulation modelling at every port. • Considers developing a method for determining a risk cutoff that incorporates the number of transits between ports.			
Related Documents	Zhao, S., Caley, P., Arthur, T., Robinson, A., and Gregg, M. 2013. Ballast Water Risk Table Reconstruction. ACERA Project 1104E Report 1 / ABARES Report 43325.			
Report Complete	Date: *06/05/15*			

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	Received by:	Date:
	CEBRA / SRC Approval	Date:
	DAFF Endorsement ( ) Yes ( ) No	Date:
	Report published	Date:

Report on CEBRA project 1301C

Updating the Methods for Ballast Water Risk Table Construction

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June, 2015

Ackowledgements

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Executive Summary

To estimate and manage the likelihood of transferring marine pests within Australia, CSIRO and the Department of Agriculture (formerly the Department of Agriculture, Fisheries and Forestry) developed the Australian ballast water risk assessment (hereafter called the BWRA). The original system was endorsed by the National Introduced Marine Pests Coordination Group. Current decisions on the system are now made by the Marine Pest Sectoral Committee (MPSC).

The BWRA is a modular, species-specific system that estimates the likelihood that a species could be taken up from one Australian port, transported to another Australian port and successfully complete its lifecycle there, for any given month in the year. The intent of the system is that when likelihood of a successful transfer is high, the vessel needs to exchange its ballast water before arriving in the recipient port. Currently 129 ports and seven species (*Asterias amurensis* - Northern Pacific Seastar, *Carcinus maenas* - European Green Crab, *Varicorbula gibba* - European Clam, *Musculista senhousia* - Asian Date or Bag Mussel, *Sabella spallanzani* - European Featherduster Worm, *Undaria pinnatifida* - Japanese Seaweed or Wakame, and *Crassostrea gigas* - Pacific Oyster) are considered in the system.

The original version of the BWRA was constructed using a combination of code written for the open-source statistical environment R and Visual Basic in Microsoft Excel. The process was unnecessarily complicated by the need to move repeatedly between these two programs, and made code maintenance potentially difficult or expensive. In addition, the temperature tolerances for the species life-stages were embedded within the R code, which made updating difficult.

In a recent ACERA project (1004E), the table construction process was updated to allow the entire analytical process to occur within R. Microsoft Excel is now used only for the storage of input data and results. The code was modified to allow temperature tolerance data for the species of concern to be stored in an Excel worksheet, instead of being 'hard-wired' within the R code, and hence relatively inaccessible. The table generation process was further modularised for ease of use, and to allow risk tables to be updated without necessarily running full code within each module. During that project some problems with the underlying methodology for module D were identified, which have implications for estimating likelihood. In this project we explore these problems and identify solutions.

A critical component of the risk assessment is estimating whether species are likely to be able to complete their lifecycle if introduced to a port by (1) simulating progression through lifecycles for select ports in response to sea (and in some cases air) temperatures, where SeaFRAME (Sea level Fine Resolution Acoustic Measuring Equipment) temperature data are available; and (2) using the results from the simulation models to develop statistical models that relate lifecycle completion to latitude, and then using the statistical models to predict lifecycle completion for the other ports. In the recent project problems were identified with the generation of synthetic air and sea temperature data (derived from SeaFRAME data), and with the interpretation of risk from the species lifecycle simulations.

Generating synthetic air and sea temperature data

In the original version of the BWRA, sea temperature simulations were generated in such a way that substantially different estimates of lifecycle completion for species introduced on 31 December vs. 1 January could occur, which is clearly unreasonable. The original

approach also had limitations when considering between-year variation in sea temperatures. To address this we used a technique known as a *block bootstrap*, with time series constructed by randomly selecting from the yearly blocks with replacement. We modelled the minimum daily temperature and the difference between the minimum and maximum daily temperature, with the maximum daily temperature simulated based on the simulated minimums plus the simulated differences. This ensures that maximum daily temperature is always greater than the minimum daily temperature. This approach ensures that year to year variation in temperatures is included in the simulations and that lifecycle simulation outcomes are similar for introductions on 31 December vs. 1 January.

Estimating likelihood from lifecycle models

In the original version of the BWRA, likelihood of survival was based on a species completing on average 80% of its lifecycle, given introduction in a particular month. It was argued that this cutoff reflected a good tradeoff between the "comfort and environmental protection provided by a low level, against the benefits and better risk resolution provided by a high level." Put another way, the argument was that if a species completes on average less than 80% of its lifecycle, then the likelihood of survival is low because it's not getting close to the end of its lifecycle. However, there is more that one way this average can result from simulations. From 1000 simulations an 80% average could be obtained because all the simulations give a percentage lifecycle completed of around 80%, or it could be obtained because in 800 simulations the species completes all of its lifecycle and in 200 simulations it completes none of its lifecycle. This type of result was common for many of the species' lifecycle simulations. The interpretation of likelihood from these two different scenarios is completely different, despite the fact the mean proportion of lifecycle completed is the same. In the latter case, using the mean, we would be concluding that a species that completed all of its lifecycle in 800 of 1000 simulations was on the border of being considered low likelihood; this is clearly not the case.

To address this, the MPSC has agreed to use as a criterion the proportion of simulations for which 100% of the lifecycle is completed. This still requires a cutoff above which survival is considered 'likely'. In the absence of detailed empirical information on what this cutoff should be, the decision at present is to use a 0.05 cutoff and to covert the metric to a monthly value by assuming that if the proportion of simulations on any day within a month exceeds 0.05, then that month will be considered risky for survival of the pest should it arrive. While other processes contribute to the probability of establishment, lifecycle completion is taken as a risk-averse proxy for establishment in the absence of any good quantitative evidence for the magnitude of effect of these other processes. For many species/port combinations, the new method increases the number of months in which lifecycle completion is considered likely. In this report we show the implications of choosing this cutoff for each simulated port and compare this with the old rule.

Future developments

It can be questioned whether it is appropriate to generalise lifecycle completion results to ports where sea surface temperature data are not available based on results at the 13 ports with SeaFRAME data. Generalising against latitude has obvious problems because it can only reliably describe very broad patterns in sea surface temperature; it does not take into account local conditions or ocean currents, which differ for example between the east and west coasts. One approach to address these problems would be to use satellite-derived sea surface temperature data as the raw data for simulation modelling at every port, removing the need to generalise using just latitude. These data would also provide more insights

into the spatial variation in temperature throughout a port.

Any cutoff based solely on the lifecycle simulations would be arbitrary, but fits with the decision being made because decisions apply to the arrival of individual vessels. However, the probability a pest will establish in a port over a given time period is actually determined by probability of establishment given arrival (from one vessel), in combination with the number of journeys carrying the pest arriving over that time period. Cutoffs could be developed that take account of the number of transits between ports.

Recommendations

We recommend that the Department of Agriculture:

- Notes that the MPSC has endorsed the new method for generating sea surface temperatures.

- Notes that the MPSC has endorsed defining the monthly yes/no decision point for acceptable risk of introduction to: full lifecycle being completed in 5% of simulations on any day in a month.

- Considers developing a method based on satellite-derived sea surface temperature data to generate data for simulation modelling at every port.

- Considers developing a method for determine a risk cutoff that incorporates the number of transits between ports.

1

Introduction

Exotic species carried by ballast water could potentially threaten the marine environment of recipient ports. To estimate and manage the risks of these species within Australia, CSIRO and the department developed the Australian ballast water risk assessment (hereafter called the BWRA)[1, 2, 3, 4]. The BWRA is a modular, species-specific system that estimates the likelihood that a species could be taken up from one Australian port (a donor port), transported to another Australian port (a recipient port) and successfully complete a simulated lifecycle there, for any given month in the year. The likelihood is expressed in binary form as either a '1' for high likelihood or a '0' for low likelihood. If the overall likelihood is '1', then the vessel would be considered 'risky' and must manage its ballast water before arriving in the recipient port. Currently 129 ports are considered.

The original version of the BWRA was constructed using a combination of code written for the open-source statistical environment R[5] and Visual Basic in Microsoft Excel. The process was unnecessarily complicated by the need to move backwards and forwards between these two programs, and the lack of in-house skills in Visual Basic programming made code maintenance potentially difficult or expensive. In addition, the temperature tolerances for the species life-stages were embedded within the R code, making updating difficult.

In a recent project[8], the construction process was updated to allow the entire construction process to occur within R. Microsoft Excel is now used only for the storage of input data and outputted results. The code was modified to allow temperature tolerance data for the species of concern to be entered into an Excel worksheet, instead of being 'hard-wired' within the R code, and hence relatively inaccessible. The risk table generation process was further modularised for ease of use, and to allow risk tables to be updated without necessarily running full code within each module.

A key outcome of that project was that ABARES now has a good understanding of the risk table methodology and the code used to generate the risk tables. This has led to the identification of problems with how sea surface temperature simulations were generated and how the cutoff for risk was defined. In this project we explore these problems and identify solutions.

2

Calculation of species lifecycle completion

2.1 Background

Marine pest species require appropriate conditions at every stage of their lifecycle to progress to the next stage and eventually establish a new population. A critical component of the BWRA is the calculation of how much of the lifecycle is likely to be completed given propagules are delivered via ballast water into a new port in a particular month. To complete a lifecycle a species arrives as larvae and proceeds through to successful reproduction, producing a new generation of larvae. The BWRA calculates the proportion of the lifecycle completed in two different ways. (1) For a subset of ports at which there are data available from Bureau of Meteorology's (BOM) SeaFRAME (Sea level Fine Resolution Acoustic Measuring Equipment) tidal gauges (n=15, excluding Cocos Island), the lifecycle is simulated directly based on life history parameters of the species and daily maximum and minimum sea surface temperatures. (2) The results from these simulations are then used to develop statistical models that relate the percentage of the lifecycle completed to latitude (a proxy for sea surface temperatures) for each month of the year. Generalised linear models (GLMs) are used if the relationship between survival and latitude is monotonic (e.g. either increasing or decreasing), or generalised additive models (GAMs) are used where the relationship is non-monotonic (e.g. low survival in low and high latitudes with high survival in middle latitudes). These models are then used to predict the percentage of the lifecycle completed for the remaining ports (n=114) for each month based on their latitude.

For direct lifecycle simulation, for each species there is a stochastic model written in R that progresses the species through its lifecycle stages based on the daily synthetic sea water temperature data, which is stochastically generated from time series models of sea surface temperature that have been developed for that port (see below). For intertidal species (e.g. *Crassostrea gigas*), air temperate is also incorporated. The models account for the fact that there are critical temperature thresholds outside which lifecycle stages cannot survive. For some species temperature also influences how quickly the species progresses through a lifecycle stage.

Problems exist with (1) how the synthetic temperature data are generated; and (2) how the likelihood of lifecycle completion (and hence likelihood of successful introduction) are calculated. These are described in detail in the following sections.
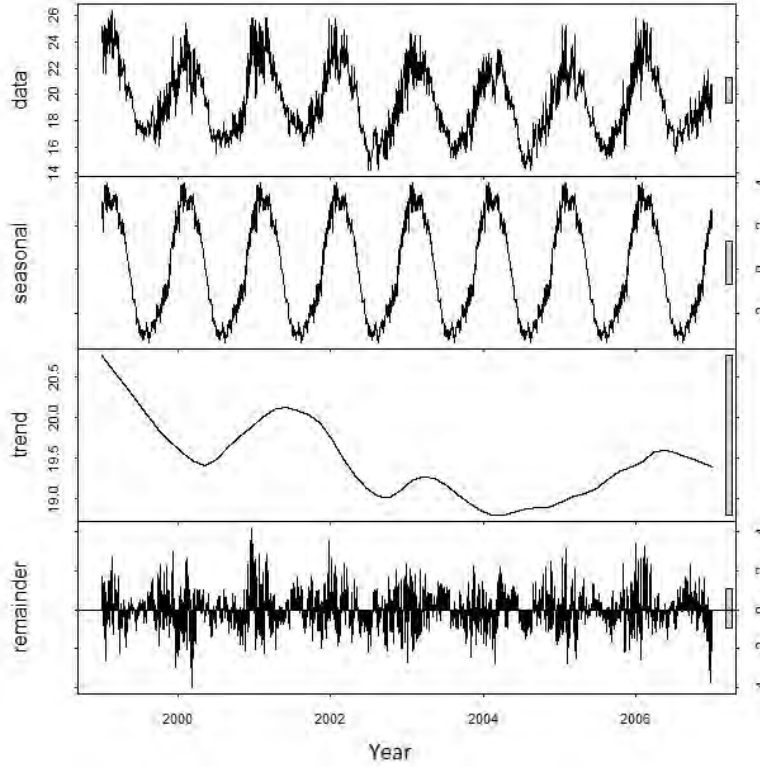
Figure 2.1: Decomposition of maximum daily sea surface temperature time series for Port Kembla

2.2 Generating synthetic sea and air temperature data

2.2.1 Previous approach and problem

The sea temperature simulations were generated by first decomposing the observed time series into a seasonal component, a trend and the residuals, by using the stl function in program R [2]. ARIMA models were then applied to the residuals to account for autocorrelation of daily temperatures. When the 1000 sea temperature simulations were generated the first 3 years of the stl-fitted seasonal and trend components were used, combined with 1000 randomly generated values from the best fitting ARIMA model. In cases where there was a significant trend in the sea temperature data over these first 3 years (e.g. Fig. 2.1), this resulted in substantially different estimates of the proportion of lifecycle completed for species introduced on 31 December as opposed to January 1 (Fig. 2.2). This should not be the case. A similar problem would occur when using the air temperature data, although in the case of air temperature the previous methodology used raw air temperature data rather than fitting any statistical models. In addition to the problem introduced by the trend, using the first three years of the stl trend and seasonal prediction meant that simulated temperature data ignored between-year variation in temperatures.
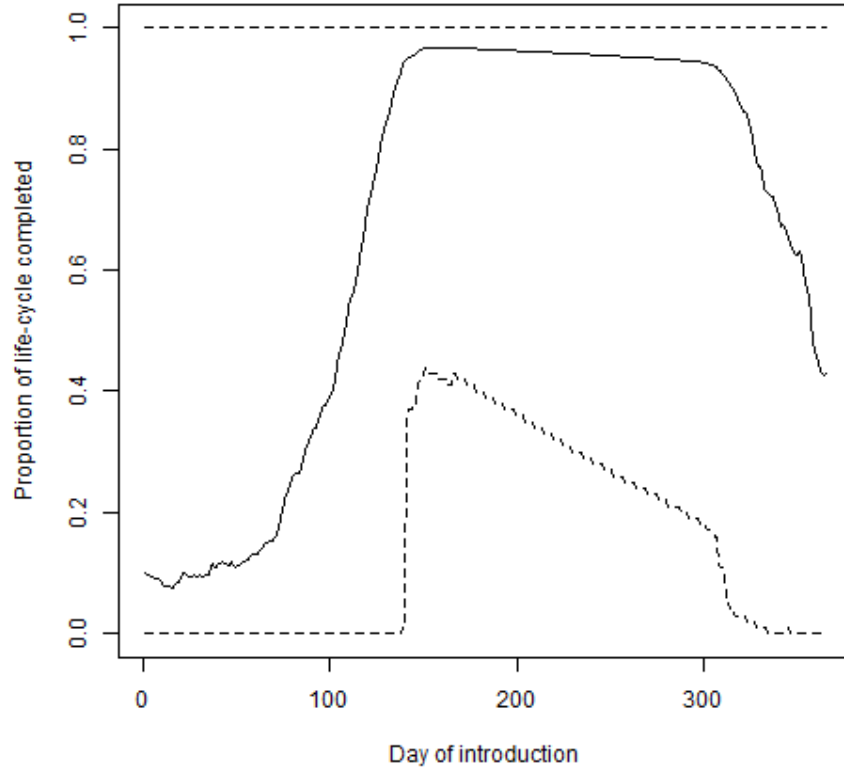
Figure 2.2: Average proportion of lifecycle completed for *A. amurensis* in Port Kembla (solid line) using the old temperature simulation method [2]. The dashed lines show the 2.5% and 97.5% quantiles.

2.2.2 Solution to problem

To fix the problem described in the previous section we used the following approach. For each port, ten or more years of recent temperature data were obtained and divided into yearly blocks (1 January — 31 December). We suggest using only the most recent 15 years to avoid the effect of any long-term trend on the underlying data. Years with at least 30 consecutive days of missing data were excluded from the analysis. For each of the 1000 simulations, a 10 year time series was generated by randomly selecting from the yearly blocks with replacement. Each of the 1000 time series was subjected to the stl and ARIMA fitting process. From each of these fits, we simulate one temperature time series, to produce our total number of 1000 simulated temperature time series. These simulations are then used to simulate species lifecycles. The lifecycle models are driven by daily maximum and minimum temperatures, so we model the minimum daily temperature and the difference between the minimum and maximum daily temperature, with the maximum daily temperature simulated based on the simulated minimums plus the simulated differences. This ensures that maximum daily temperature is always greater than the minimum daily temperature.

To test this approach, we used data from 1999 — 2009 to generate the simulated data, and then plotted this against observed temperature data from 2010 — 2012. The result for Port Kembla is shown in Fig. 2.3, with results for all other ports shown in Figs. A.1 — A.11 in Appendix A. In general, the observed data lie within the quantiles, with maxima and minima from the simulations capturing extremes. We also plotted the residuals from the minimum temperature modelling and the difference in temperature modelling, and

found no significant correlations, indicating that it was reasonable to derive maximum temperatures by adding simulated minimum temperatures to simulated differences.

When temperature simulations are generated in this way, in general the problem of species having a different proportion of lifecycle completed when introduced on 1 January vs. 31 December is removed. We show the new results for *A. amurensis* in Port Kembla in Figure 2.4. Unlike in Fig. 2.2, with the new approach the species completes on average about 50% of its lifecycle whether it is introduced on 1 January or 31 December. Results for all species can be seen in Appendix B.
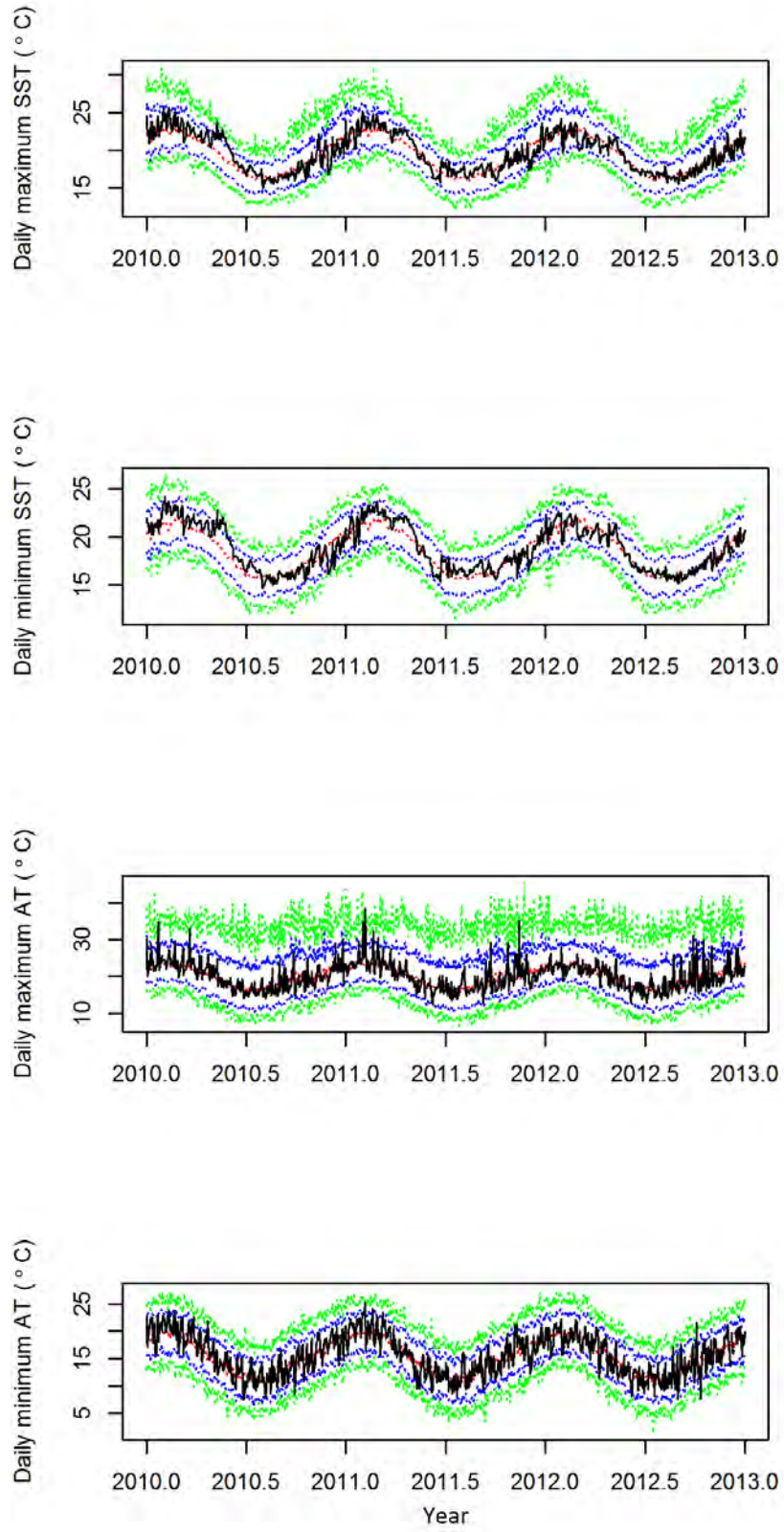
Figure 2.3: Simulated and actual temperatures in Port Kembla. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green. SST = Sea Surface Temperature. AT = air temperature.
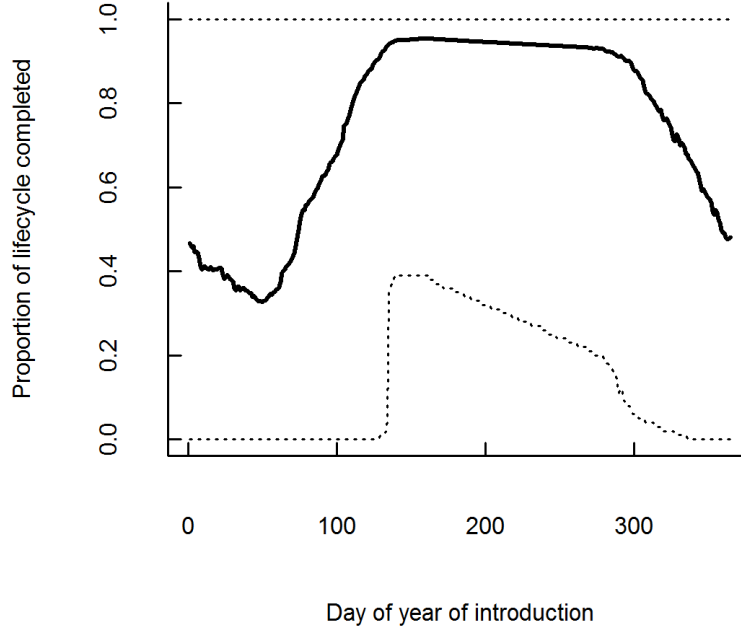
Figure 2.4: Average proportion of lifecycle completed for *A. amurensis* in Port Kembla (solid line) using the new temperature simulation method. The dashed lines show the 2.5% and 97.5% quantiles.

2.3 Estimating likelihood from lifecycle models

2.3.1 Previous approach and problem

The temperature simulations were used to drive lifecycle models for each species that estimate what proportion of the lifecycle is completed given introduction on a particular day of the year. The full lifecycle from arrival as larvae to successful production of new larvae is determined to take some number of days, which may or may not depend on temperature (this is species dependent), and is the sum of all the days spent in different parts of the lifecycle. In the model, species are introduced as larvae and begin to progress through their lifecycle. If the temperature moves outside a critical range (dependent on lifecycle stage), then the species dies and hence does not progress any further. Whether the species spawns or not in the new location is also temperature dependent. The proportion of the lifecycle completed was then calculated as the number of days the species progressed through its lifecycle, divided by the number of days in the full lifecycle. For example, if a full species lifecycle went for 300 days, and the larvae hit a critical temperature threshold at day 25 and died, then the proportion of lifecycle completed would be $25/300 = 0.08$. For each day of the year these simulations were repeated 1000 times (based on the 1000 temperature simulations).

In the original approach, these simulations were then used to calculate the **mean** proportion
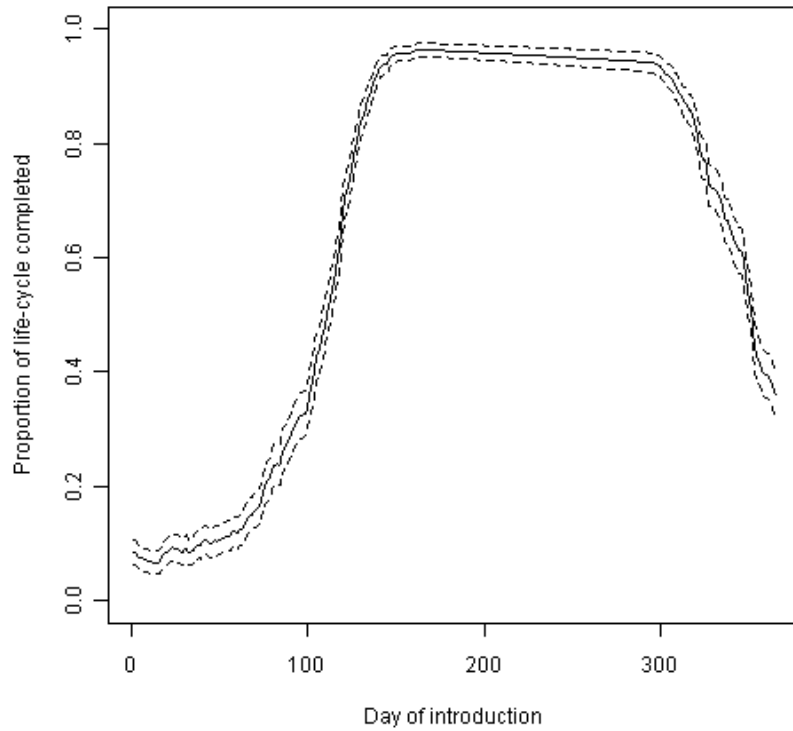
Figure 2.5: Proportion of lifecycle completed for *A. amurensis* in Port Kembla with 95% confidence interval for the estimate of the mean. Note: This figure was obtained using the previous method and hence uses the previous method's temperature simulations.

of lifecycle completed, which was then used to determine likelihood. Using the mean was justified by the tight confidence limits around it (Fig. 2.5)[3]. However, these confidence intervals are for the estimate of the mean; how tight they are depends on the number of simulations run as well as the inherent variability of the simulations. We see this by plotting the simulation quantiles, which show large spread in the simulation results (Fig. 2.2).

Hayes et al. [3] argued that a high likelihood of lifecycle completion should be assumed if the mean proportion of the lifecycle completed exceeded 0.8. They suggested that this cutoff reflected a good tradeoff between the "comfort and environmental protection provided by a low level, against the benefits and better risk resolution provided by a high level." Put another way, the argument is that if a species completes on average less than 80% of its lifecycle, then the likelihood of survival is low. However, there is more that one way this average can result from simulations. From 1000 simulations an 80% average could be obtained because all the simulations give a percentage lifecycle completed of around 80%, or it could be obtained because in 800 simulations the species completes all of its lifecycle and in 200 simulations it completes none of its lifecycle. The interpretation of likelihood from these two different scenarios is completely different, despite the fact the mean proportion of lifecycle completed is the same. In the latter case, using the mean, we would be concluding that a species that completed its lifecycle in 800 of 1000 simulations was on the border of being considered low likelihood; this clearly seems unreasonable if the lifecycle simulations provide a reasonable representation of whether the port environment is likely to be suitable for a particular species, at least in terms of its temperature profile.

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2.3.2 Solution to problem

If lifecycle simulations are to form the basis for estimating likelihood of lifecycle completion, then likelihood should be based on the proportion of simulations where a certain percentage of the lifecycle is completed, rather than the mean percentage of lifecycle completed. This requires two decisions: (1) what percentage of the lifecycle completed should be used?, and (2) what proportion of simulations exceeding this percentage should be considered as indicating high likelihood? While other processes contribute to the probability of establishment, which is ultimately what determines risk, lifecycle completion is taken as a risk-averse proxy for establishment in the absence of any good quantitative evidence for the magnitude of effect of these other processes.

What percentage of lifecycle completed should be chosen?

For the first question, in consultation with the Marine Pest Sectoral Committee (MPSC), we have adopted a strict interpretation that for an individual simulation a species needs to complete 100% of its lifecycle. This fits best with how the lifecycle models are currently structured, because if a species hits a critical threshold at some stage of its lifecycle it is then deemed to die and that simulation stops. When we hit a threshold we don't consider whether the environment after that time would have been suitable to complete a lifecycle. It therefore does not make sense to use the lifecycle modelling as it is currently structured and choose a percentage completed that is less than 100%. Changing the model to permit different usage would be a substantial undertaking.

Choosing a value of 100% of lifecycle completion means that the outcome is determined by the way the threshold is implemented in the model. With the original method, once a threshold is exceeded on one day, the lifecycle terminates. Variation in the outcome arises because the threshold value for each simulation is drawn from a distribution (uncertainty in each temperature threshold value is represented by a distribution rather than a single value), combined with the variable temperature simulations.

An alternative approach would be to increase the number of consecutive days that the threshold had to be exceeded. This approach may increase the number of simulations in which 100% of the lifecycle could be completed. However, without testing, it is not clear how large an effect this would have on the results. Given the uncertainties already incorporated into the model, including uncertainty about what the temperature thresholds should be, using a 1 day cut-off is the simplest approach, and was the one adopted in consultation with the MPSC.

What proportion of simulations with lifecycle completion should we consider as indicating high likelihood of lifecycle completion?

For the second question, one approach is to base the cut-off solely on some proportion of simulations with lifecycle completed. The main issue with this approach is that any cut-off is arbitrary in the absence of empirical evidence that relates likelihood of establishment to results from the lifecycle simulation models. However, the lifecycle simulation models have been designed to model habitat suitability (in terms of temperature) and hence a cut-off closer to zero than one is more appropriate.

For example, if we choose a 0.05 cutoff, then it means we will not consider species survival likely if the species completes its <u>entire</u> lifecycle in less than 5% of simulations. For a species that completes all of its lifecycle in 50 simulations and none of it for 950 simulations, this would also give a mean percentage of lifecycle completed of just 5%, but we see again that the interpretation of likelihood is completely different. Only completing an average of 5% of your lifecycle doesn't sound like a high likelihood, but completing all of your lifecycle in 5% of simulations may put the species on the edge of having a likelihood of survival that presents unacceptable risk.

Fig. 2.6 illustrates this for *C. gigas* in Portland. Under the previous rule, we wouldn't consider there is a high likelihood of introducing *C. gigas* if it arrived between about day 150 and day 280. However, at day 200, when on average the species completes about 70% of its lifecycle, it does this because in about 70% of simulations it completes <u>all</u> of its lifecycle and in about 30% of simulations it completes almost none of its lifecycle (Fig. 2.6c). Under the new interpretation, for this particular port and species, there would be a high likelihood of introduction over the entire year. The histograms also show that for this species when it doesn't complete its lifecycle it tends to die at an early stage of its lifecycle. In Appendix B we show these results for all species in all ports.
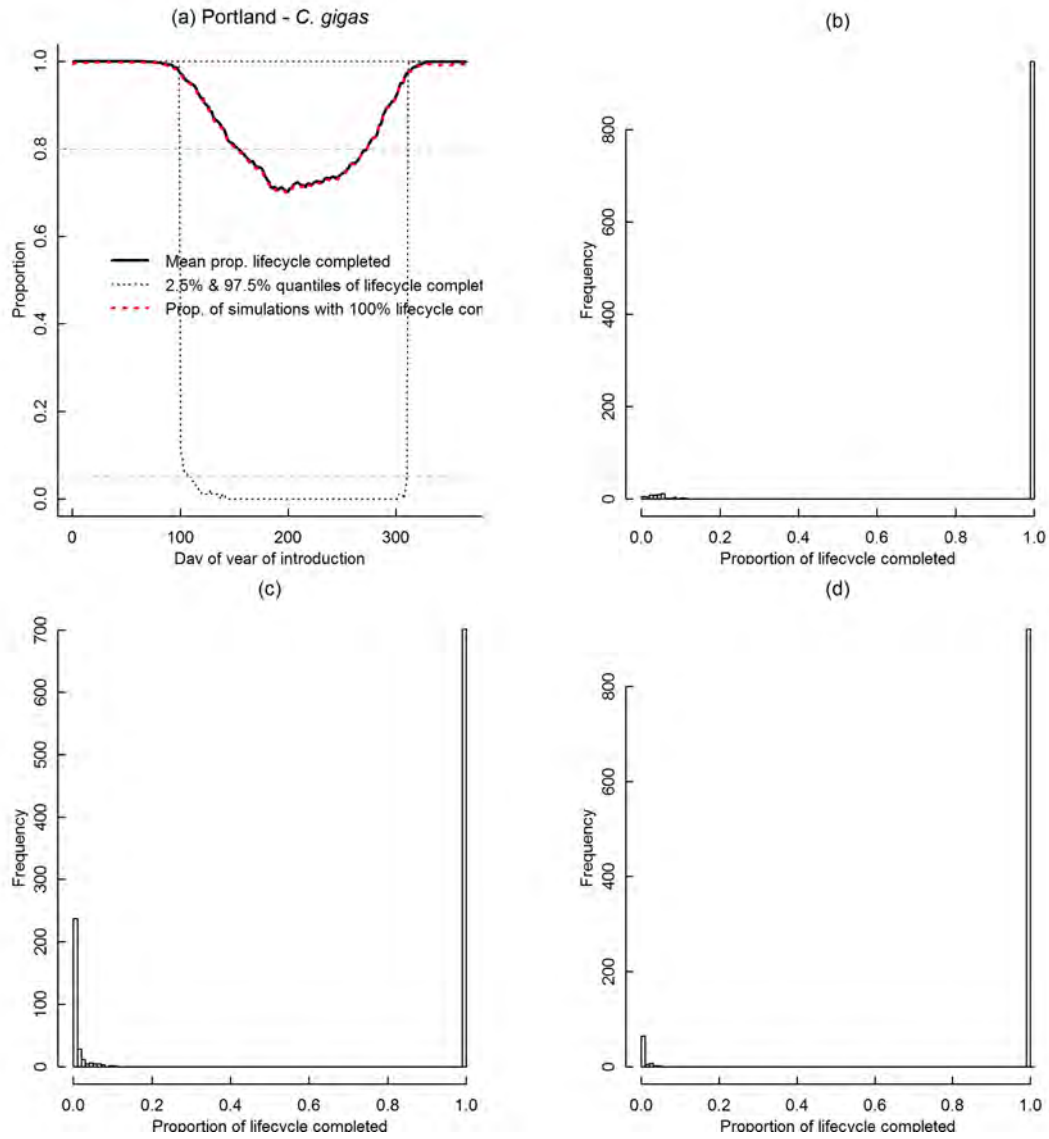
Figure 2.6: (a) Simulation results for lifecycle completion of *C. gigas* in Portland. Horizontal dashed lines show a 0.05 and a 0.8 cutoff. Histograms of proportion of lifecycle completed: (b) day 110; (c) day 200; (d) day 300.

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Monthly values

In the BWRA, the likelihood of 'survival' cut-off is actually based on monthly values (the system runs on monthly values). Under the previous method the average percentage of lifecycle completed in a month was calculated based on the monthly values for that month, with averages above 0.8 defined as months with unacceptable 'risk'. Two options for the cut-off were considered for the new method: (1) basing it on the proportion of simulations in the month in which the full lifecycle is completed e.g. 1,500 in 30,000. However, combining across the entire month has potential problems if the model suggests a significant transition in whether a lifecycle is completed or not part way through a month. This could result in lifecycle completion over an entire month appearing unlikely even though, based on daily values, trips within the month were actually associated with a high likelihood of lifecycle completion; or (2) basing the monthly value on a maximum daily value for the entire month, that is, if on at least one of the days in the month the lifecycle was completed on $> 5\%$ of simulations (50 in 1000), then lifecycle completion on any day in that month would be considered likely. In consultation with the MPSC, the second option was adopted, with a 5% cut-off.

Fig 2.7 shows examples for *C. gigas* in Portland and *U. pinnatifida* in Broome with these three different selection criteria. For *C. gigas* in Portland, we see that under the previous criterion of 80%, successful introduction given arrival would be considered unlikely for the months of June, July, August and September (Fig 2.7a). Under the new criterion, successful introduction given arrival would be considered likely for every month of the year (Fig 2.7c). In this particular case option 1 gives the same result (Fig 2.7b). For *U. pinnatifida* in Broome, we see that under the previous criterion introduction given arrival would be considered unlikely for all months (Fig 2.7d). In contrast to the Portland example, likelihood of lifecycle completion for *U. pinnatifida* in Broome is different depending on which new criterion is considered. Under the adopted criterion, months May, June and July would be associated with likely successful lifecycle completion (Fig 2.7f), while if the decision was based on the proportion of simulations across the entire month, months June and July would be associated with likely successful lifecycle completion (Fig 2.7e).

Results for all species can be seen in Appendix B.

Other approaches

Any cutoff based solely on the lifecycle simulations would be arbitrary, but fits with the decision being made because decisions apply to arrival of individual vessel. However, the probability a pest will establish in a port over a given time period is actually determined by the probability of establishment given arrival (from one vessel), in combination with the number of journeys carrying the pest arriving over that time period. Assuming the probability of completing the lifecycle given by the simulation model is equivalent to the probability of establishment given one arrival $Pr(e|a)$, and arrivals are independent of each other (that is, there is no interaction between arrivals that alter the probability a pest will establish), then a simple estimate of the overall probability of establishment ($Pr(E)$) over a time period changes with the number of transits over that period according to the formula:

$$Pr(E) = 1 - [1 - Pr(presence) \times Pr(e|a)]^{N_a} \tag{2.1}$$

From this we can calculate the expected number of successful incursions over a given time period T as $Pr(E) \times T$, or the expected time to a successful incursion in that month (or on that day), $1/Pr(E)$. These could be alternative metrics on which to base a cutoff, which could be explored in future work. Key questions/considerations would include: do values derived from the lifecycle models represent the probability of establishment given arrival (see earlier comments), or is some further modification of the value was required?; are transits independent of each other in terms of determining overall probability (formula above), or is there some interaction, for example Allee effects?; identify sources of transit data, the quality of these data and how best to use them; explore whether to use probability of presence in donor ports in calculations and if so how to estimate it; explore what an acceptable cut-off would be (e.g. 1 in x years, where x could be port specific, species specific, or one global value applied to all combination); and consider how this approach could be implemented (e.g. all transits between ports with a non-zero probability are required to do ballast exchange, or whether only the riskiest combinations are required to do exchange, until pairs that have a cumulative probability less than the cut-off remain (these would be allocated a '0' in the risk table).
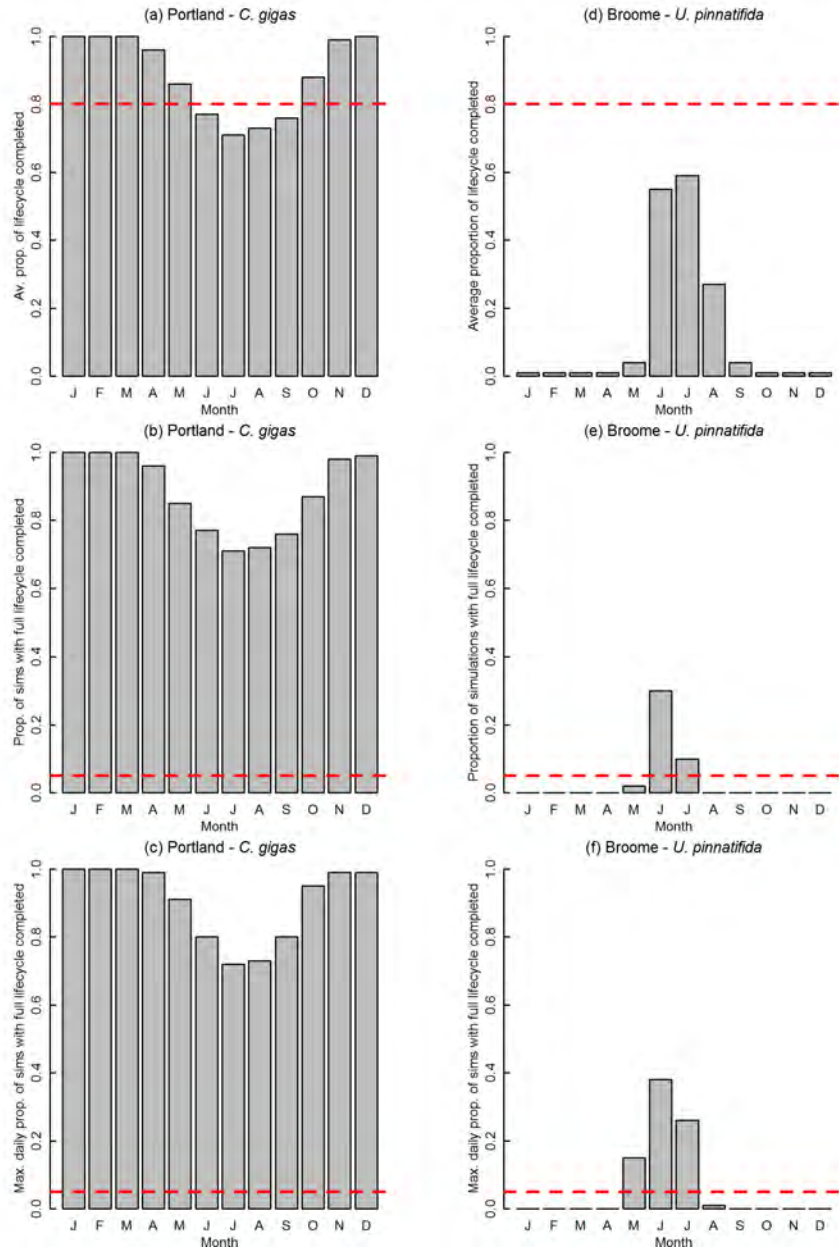
Figure 2.7: Simulation results for lifecycle completion by month. (a), (b) and (c) *C. gigas* in Portland; (d), (e) and (f) *U. pinnatifida* in Broome.

Statistical models for the other ports

Statistical models are still developed for lifecycle completion against latitude to allow predictions for the 114 ports that do not have SeaFRAME sea temperature data. The difference now is that the statistical model is based on the maximum daily proportion of simulations with full lifecycle completed (e.g. Fig 2.7c), rather than the average proportion of lifecycle completed. In many cases the resultant statistical models are similar to those developed previously, because these two metrics are often similar (for example, compare Fig 2.7a with Fig 2.7c). Statistical model fits for all species are shown in Appendix C. From the glm statistical models we can calculate the latitude that will apply to the 5% cutoff for lifecycle completion that has been adopted. These values are shown in Table 2.1, along with the latitudes based on the original method (an average of 80% of the lifecycle completed and old method of temperature simulations) to give an indication of the magnitude of the changes.

Table 2.1: Latitude cut-offs for likelihood of lifecycle completion from glm statistical models. ↓ = suitability to the south of the cut-off and ↑ = suitability to the north of the cut-off. all = all of Australia suitable. All latitudes are south of the equator.

Month	U. pinnatifida	A. amurensis	C. meanas	S. spallanzani	V. gibba	P. viridis	M. sallei
Jan	30.0 (37.4)↓	30.0 (37.0)↓	27.7 (36.5)↓	19.4 (27.4)↓	24.9 (28.9)↓	34.8 (30.9)↑	14.1 ↓(all)
Feb	27.6 (37.1)↓	28.9 (37.0)↓	26.8 (36.2)↓	18.4 (26.7)↓	22.8 (28.7)↓	32.6 (28.4)↑	12.9 ↓(all)
Mar	24.7 (33.8)↓	27.9 (35.2)↓	26.0 (34.3)↓	16.0 (25.2)↓	18.8 (26.9)↓	29.2 (25.8)↑	all (all)
Apr	22.0 (30.7)↓	28.1 (32.7)↓	26.3 (31.6)↓	15.0 (21.6)↓	16.9 (22.4)↓	25.4 (22.9)↑	all (all)
May	17.0 (25.4)↓	29.0 (30.4)↓	27.1 (29.3)↓	12.9 (17.9)↓	16.1 (21.1)↓	22.6 (18.4)↑	all (all)
Jun	15.4 (20.3)↓	29.0 (29.4)↓	27.8 (28.7)↓	12.3 (15.6)↓	18.5 (21.2)↓	20.5 (14.1)↑	all (all)
Jul	16.3 (21.2)↓	29.1 (29.8)↓	27.9 (30.3)↓	12.4 (16.4)↓	21.6 (23.3)↓	21.9 (13.6)↑	all (all)
Aug	22.0 (25.3)↓	29.1 (30.5)↓	27.8 (32.1)↓	12.7 (17.6)↓	23.6 (25.0)↓	26.6 (15.4)↑	all (all)
Sep	24.4 (29.2)↓	29.1 (31.6)↓	28.8 (33.7)↓	14.0 (19.9)↓	24.1 (26.2)↓	29.8 (20.5)↑	all (all)
Oct	26.2 (32.0)↓	29.3 (32.6)↓	29.5 (34.6)↓	15.8 (22.5)↓	25.0 (27.1)↓	31.8 (24.7)↑	11.2 ↓(all)
Nov	29.4 (33.9)↓	29.8 (33.3)↓	29.3 (35.4)↓	17.9 (24.1)↓	23.2 (27.8)↓	35.0 (27.1)↑	13.8 ↓(all)
Dec	31.1 (35.3)↓	30.2 (34.7)↓	28.5 (35.7)↓	19.9 (25.6)↓	23.2 (28.4)↓	35.2 (29.4)↑	13.8 ↓(all)

For example, for *U. pinnatifida* in January, latitudes between 37.4°S and 30.0°S are now also considered 'risky' (rather than just latitudes south of 37.4°S), meaning that voyages arriving in (say) Port Botany (34°S) that might be carrying *U. pinnatifida* (e.g. journeys from Melbourne) would not have been considered risky with the original method, but would now be considered risky. Similarly, for *A. amurensis* in January, latitudes between 37°S and 30°S are now also considered 'risky' for lifecycle completion. In contrast, the new methods had a very small effect on the estimate of risky latitudes for *A. amurensis* in June, only extending the latitude from 29.4°S to 29.0°S. On average, the new method increased the latitude regarded as 'risky' by about 5°(range 0.4°– 11.2°). The exception was *M. sallei*, where the suitable range decreased slightly in some months.

It can be questioned whether it is appropriate to generalise lifecycle completion results to ports where sea surface temperature data are not available based on results at the 13 ports with SeaFRAME data. Generalising against latitude has obvious problems, because it can only reliably describe very broad patterns in sea surface temperature; it does not take into account local conditions or ocean currents, which differ for example between the east and west coasts. One approach to address these problems would be to use satellite-derived sea

surface temperature data as the raw data for simulation modelling at every port, removing the need to generalise using just latitude. These data may also provide more insights into the spatial variation in temperature throughout a port if data of appropriate resolution could be obtained. Satellite derived data has been used to develop species range maps for marine pests in Australia [6, 7], using a different approach to lifecycle simulation modelling employed by the ballast water risk tables, but one also based on temperature tolerances. Potential distribution maps from that approach showed variation for a given latitude, indicating that differences would also likely arise from the lifecycle simulation approach if satellite data were used. For example, the range map for *C. meanas* [7] (p19) suggested potential suitability to about 23°S on the west coast and 20°S on the east coast. The use of satellite derived data in lifecycle simulation modelling could be the topic of a future project.

Comparison of number of 'risky' routes with original and new methods

There are 16,512 different transit routes covered under the risk tables. With both methods a high proportion of the routes are classed as 'risky', with the proportion increasing under the new method compared with the original method (Table 2.2). Note that many of these routes will be classed as 'risky' because, (i) the survey status of most ports is unknown (port surveys have not been conducted for many years and the original data is no longer accepted), and (ii) there is lifecycle completion compatibility between the donor and recipient port for at least one of the pest species. This last point is important, because should *M. sallei* become established in Australia, then with the current system, almost all routes will be classed as 'risky' in the absence of port surveys demonstrating likely absence of that pest (Table 2.1).

Table 2.2: Number of transit routes classed as 'risky' (of 16,512 possible routes) with the original and new methods. Analyses carried out using the April 2013 port survey status.

Month	Original method	New Method
January	7,243	13,167
February	7,754	12,707
March	8,056	13,536
April	9,906	13,555
May	11,969	13,548
June	11,626	12,534
July	11,569	12,474
August	11,507	12,363
September	10,692	13,159
October	10,019	12,818
November	9,080	12,537
December	7,023	13,028

Note that although a high proportion of routes are classed as 'risky', this does not necessarily mean a high proportion of transits will be classed as 'risky', because there are different transit frequencies on the different routes. An analysis based on the different transit frequencies was beyond the scope of this project.

Appendix A

Temperature time series plots

Here we show figures for observed and simulated temperature time series as described in Section 2.2. In general observed data from 2010 — 2013 lie within the quantiles, with maximums and minimums capturing extremes.
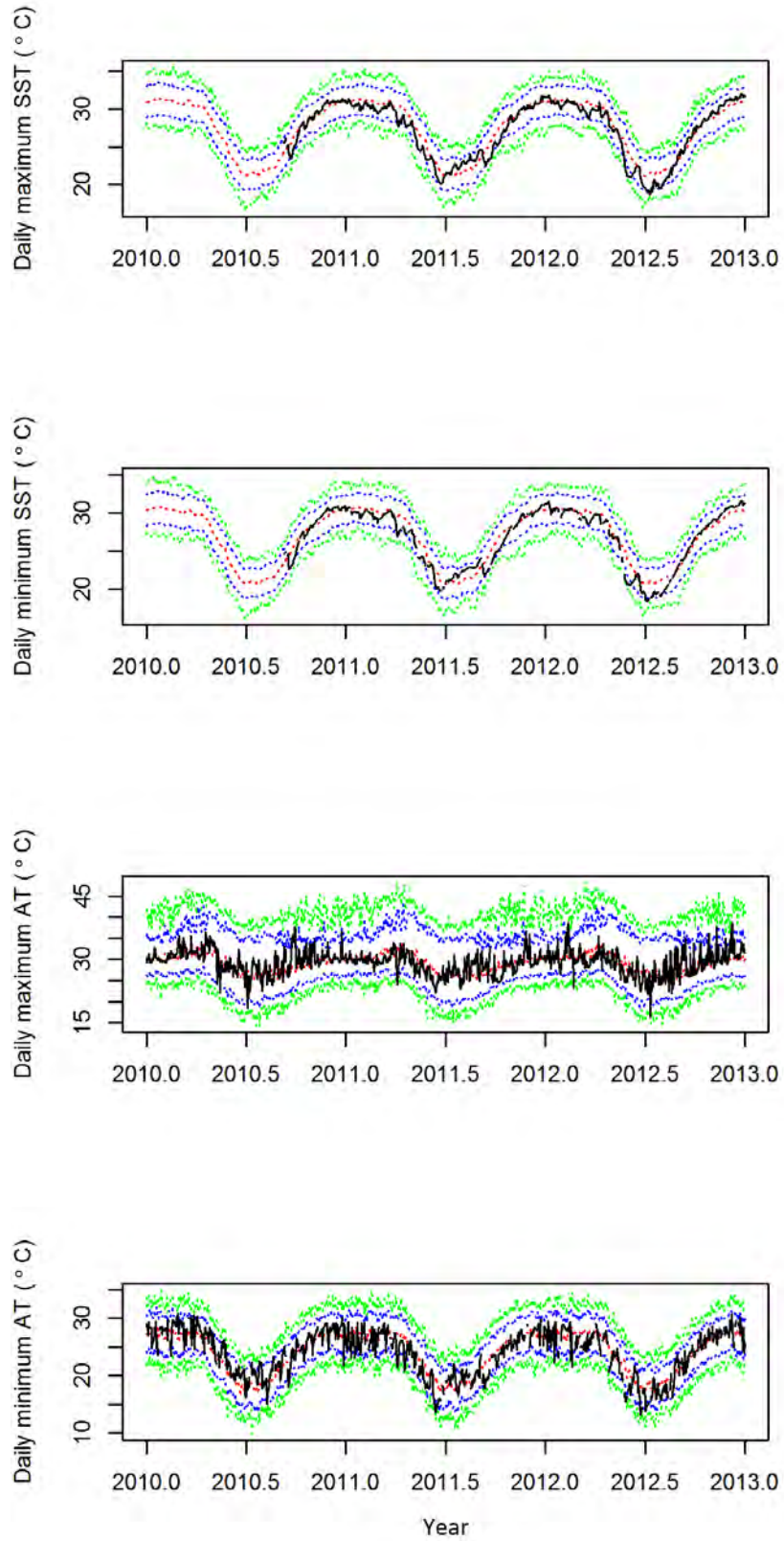
Figure A.1: Simulated and actual temperatures in Broome. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
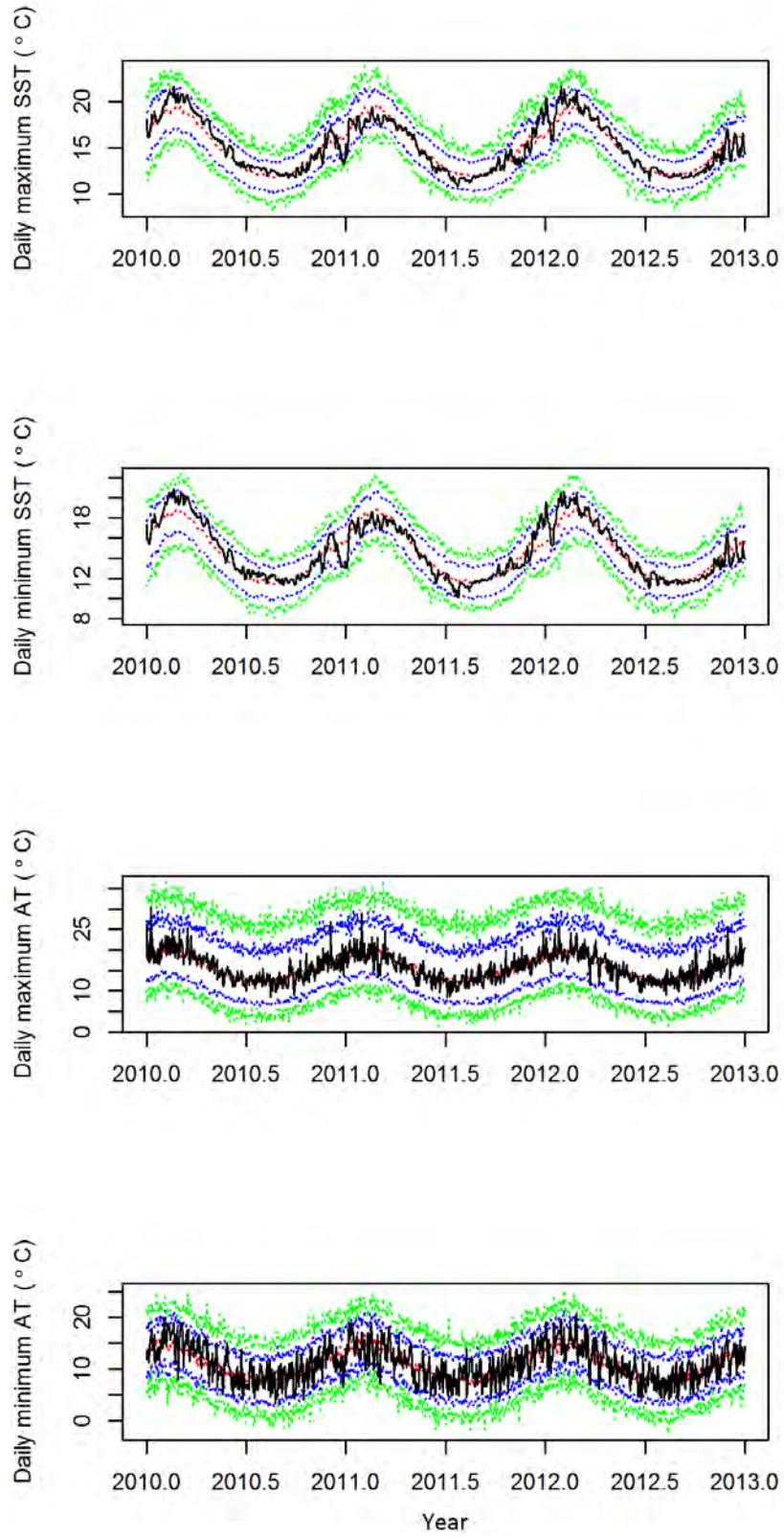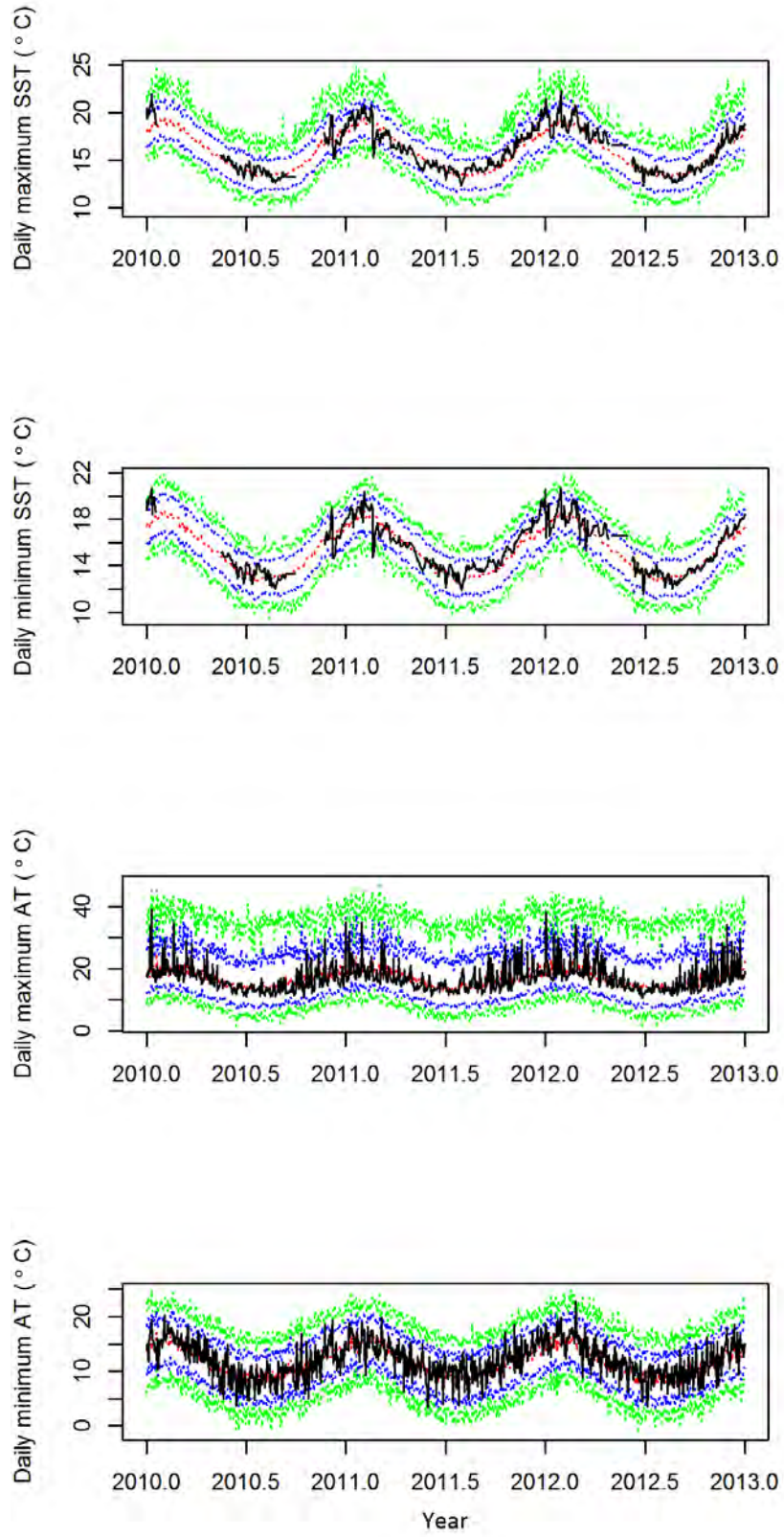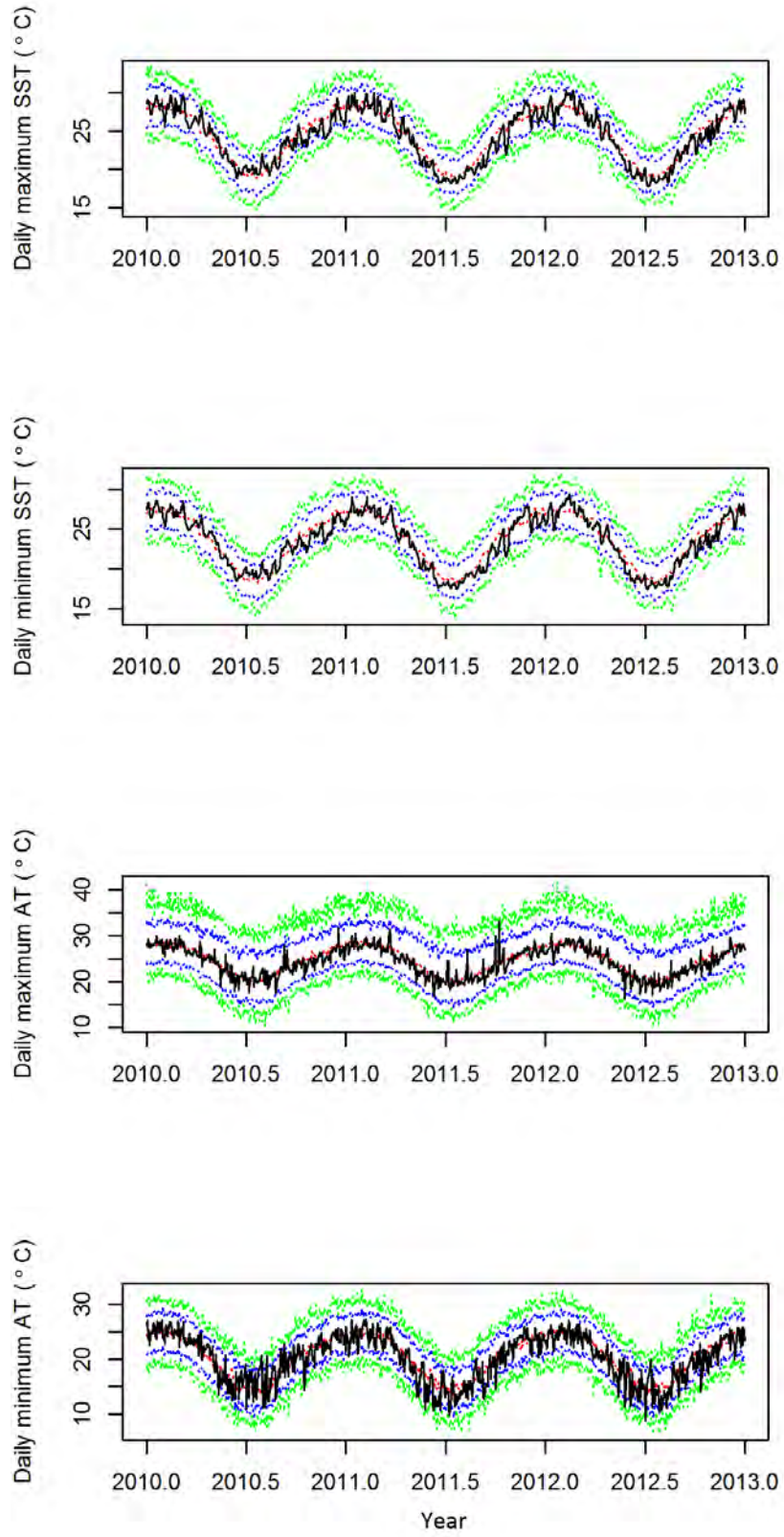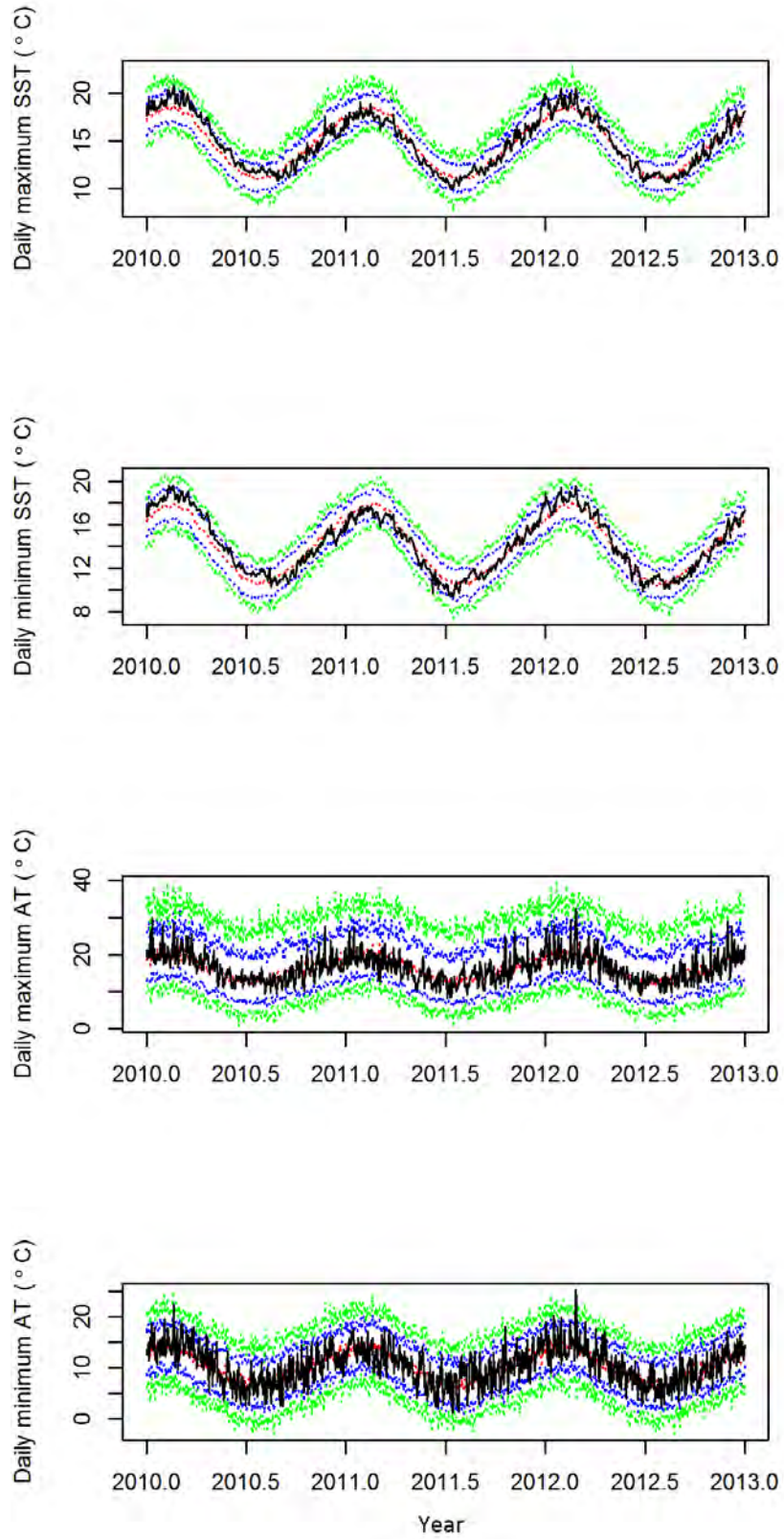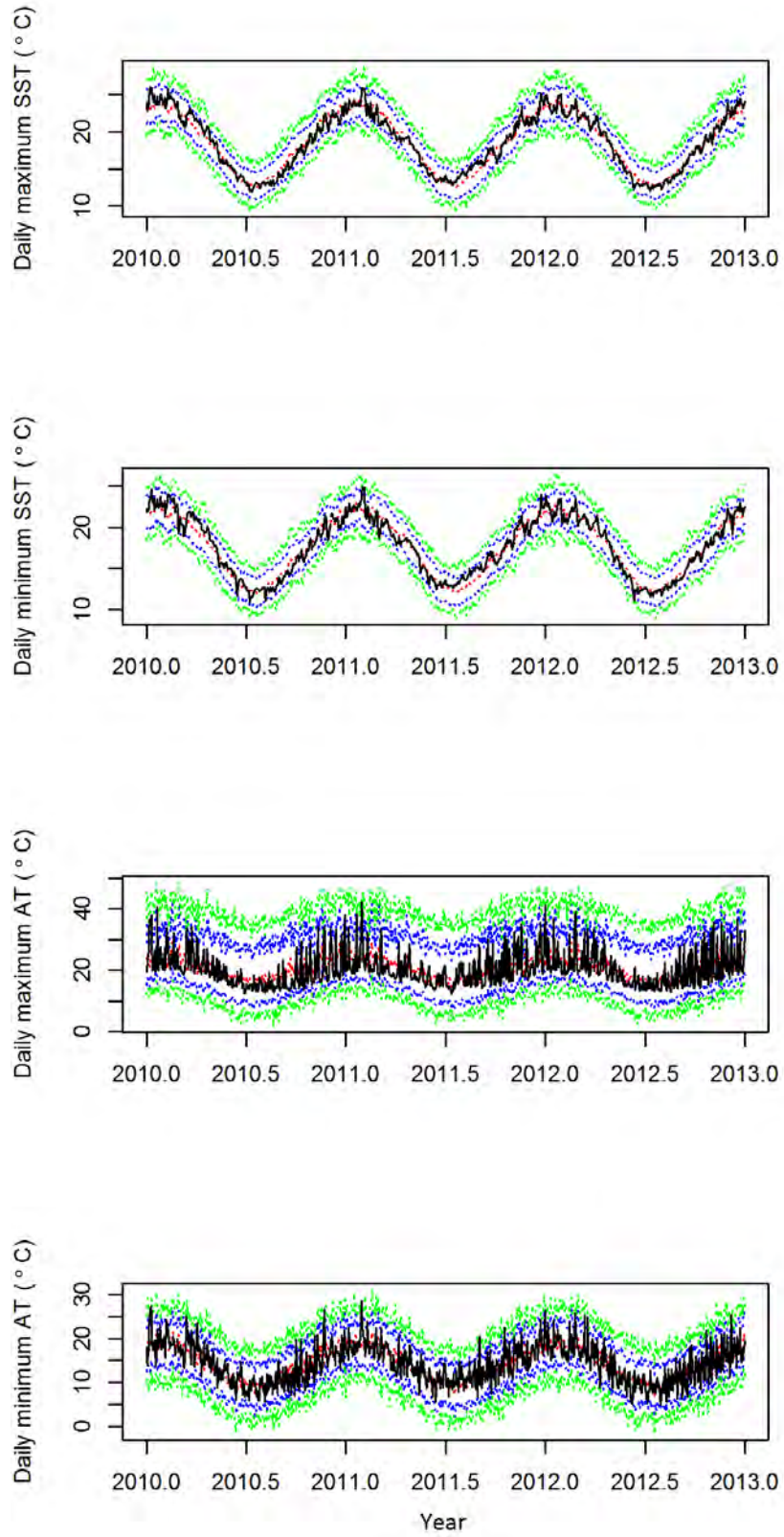
Figure A.2: Simulated and actual temperatures in Burnie. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
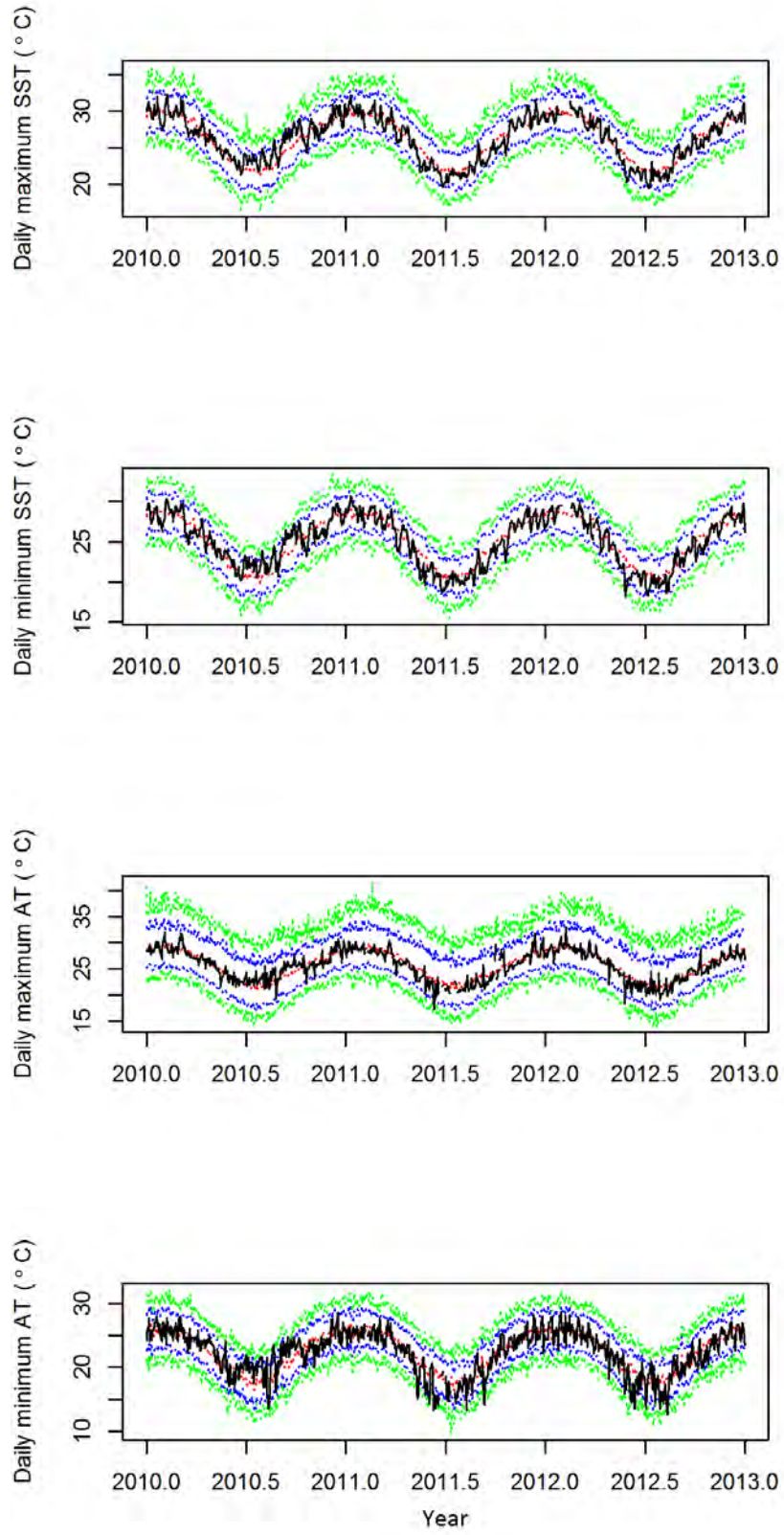
Figure A.3: Simulated and actual temperatures in Cape Ferguson. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
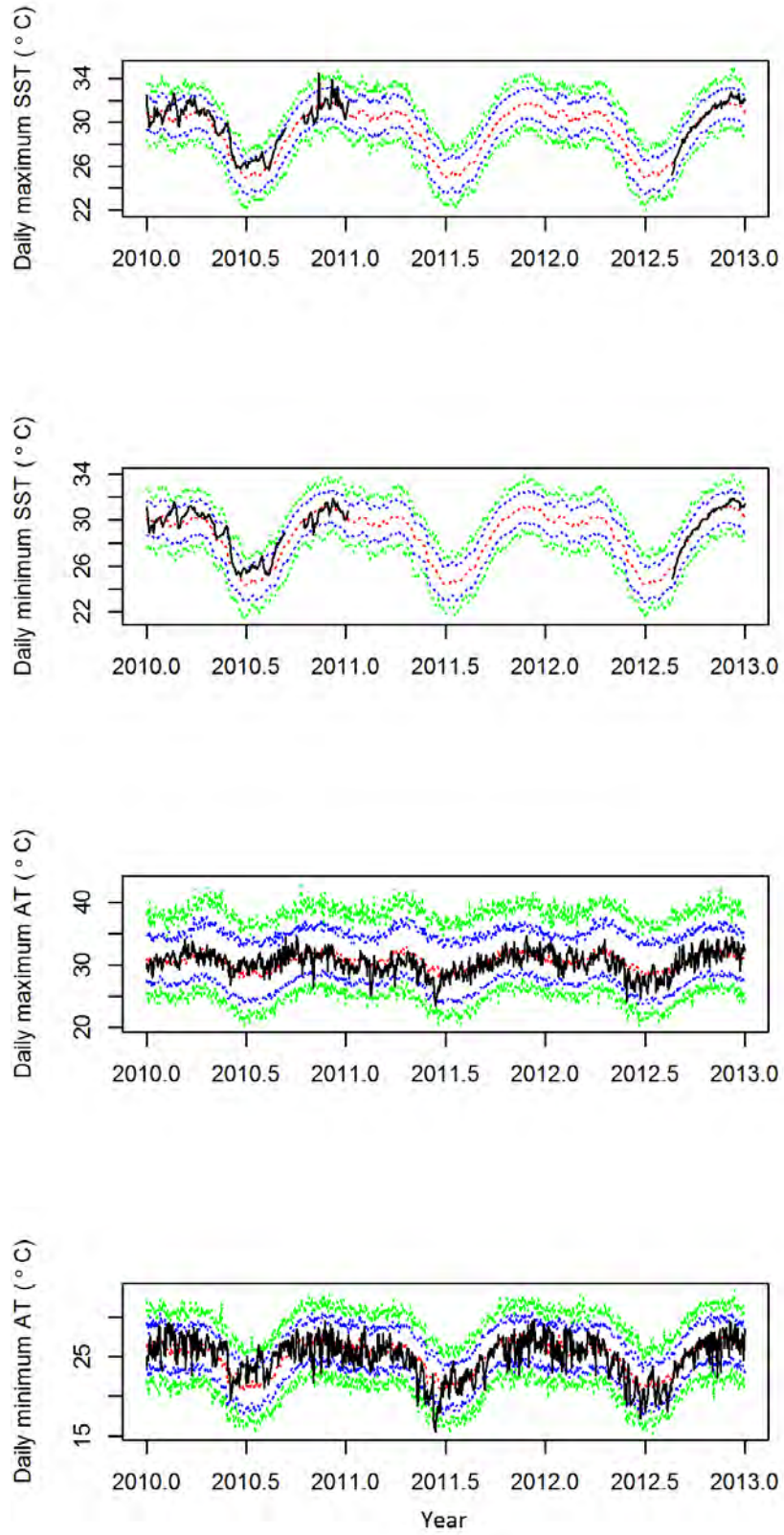
Figure A.4: Simulated and actual temperatures in Darwin. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
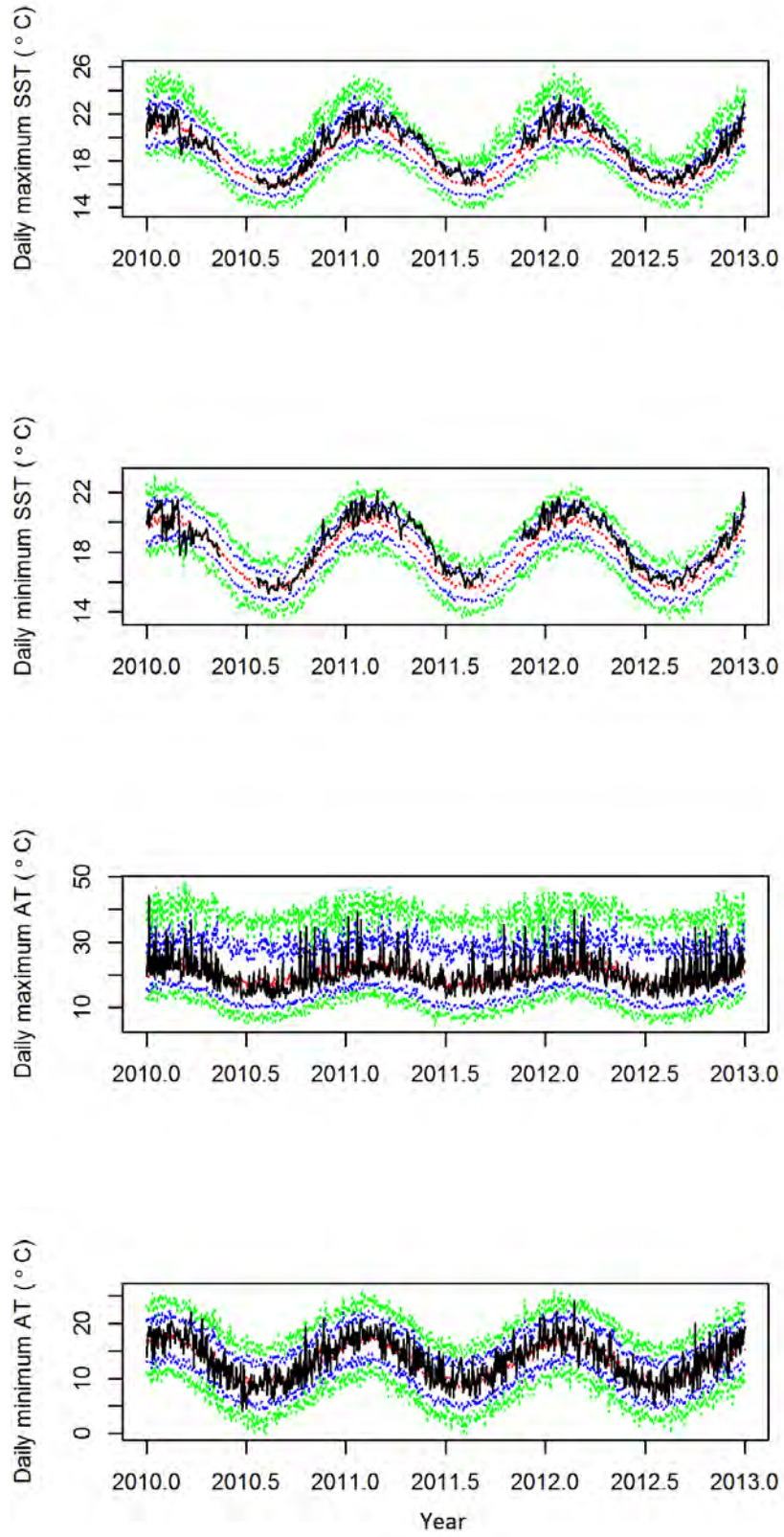
Figure A.5: Simulated and actual temperatures in Esperance. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
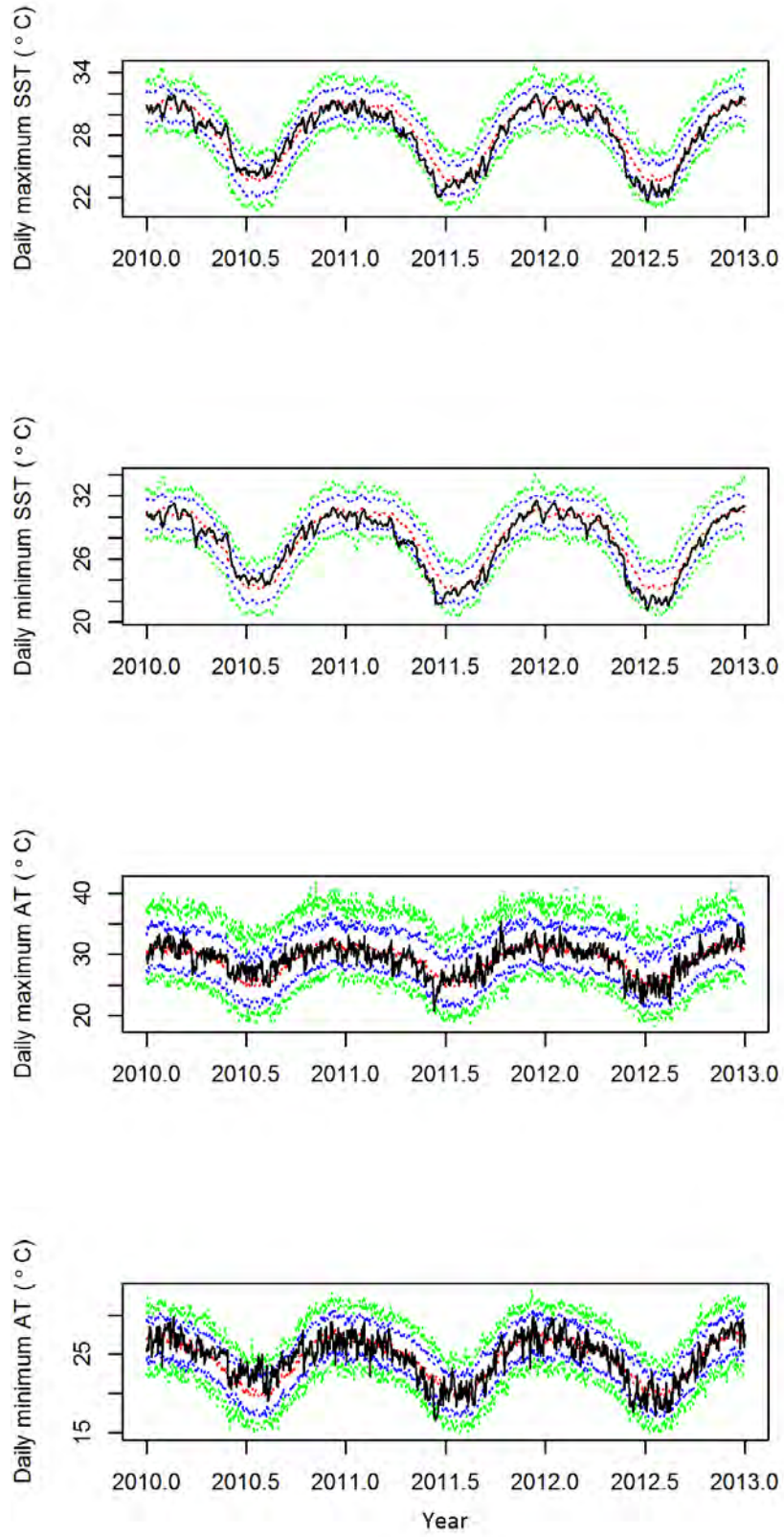
Figure A.6: Simulated and actual temperatures in Groote Eylandt. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.
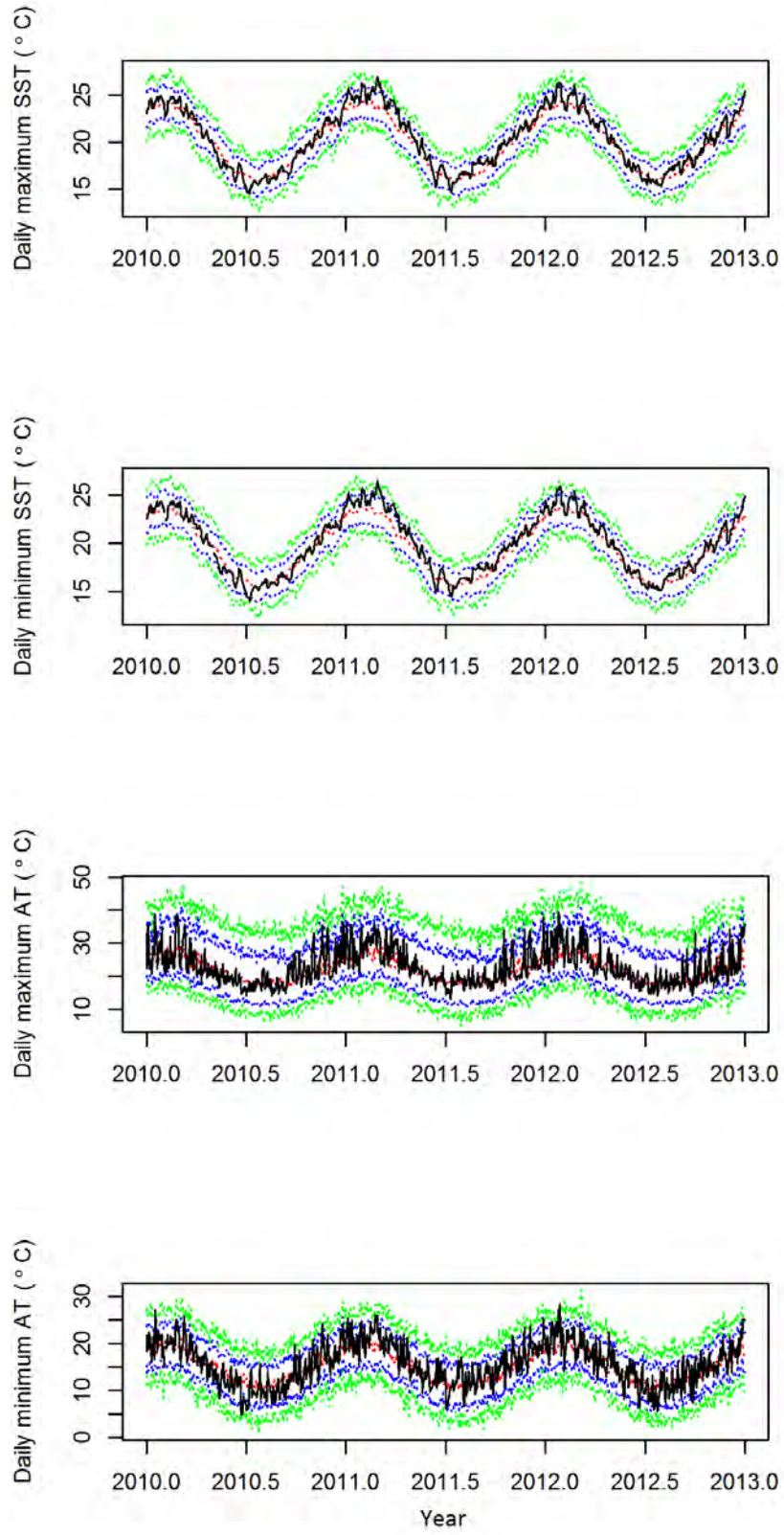
Figure A.7: Simulated and actual temperatures in Hilarys. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.

Figure A.8: Simulated and actual temperatures in Portland. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.

Figure A.9: Simulated and actual temperatures in Rosslyn Bay. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.

Figure A.10: Simulated and actual temperatures in Spring Bay. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.

Figure A.11: Simulated and actual temperatures in Thevenard. Observed data are in black. The mean simulated value is in red. 2.5% and 97.5% quantiles are in blue. Maximum and minimum values are in green.

Appendix B

Lifecycle completion

Here we show figures for lifecycle completion under the original rule and new rule for all species in all ports, as described in Section 2.3. These figures are based on the new way of simulating temperature time series (Section 2.2) and other fixes to the code described in Appendix D. We also include histograms for three select times to show the distribution in the proportion of lifecycle completed at those times. This gives insights into the critical lifestage in the model when a species does not complete 100% of its lifecycle.

B.1 Intertidal invertebrates

B.1.1 *Crassostrea gigas* - Pacific Oyster

Broome

In Broome lifecycle completion would be considered unlikely throughout the year under the old rule and the new rule.
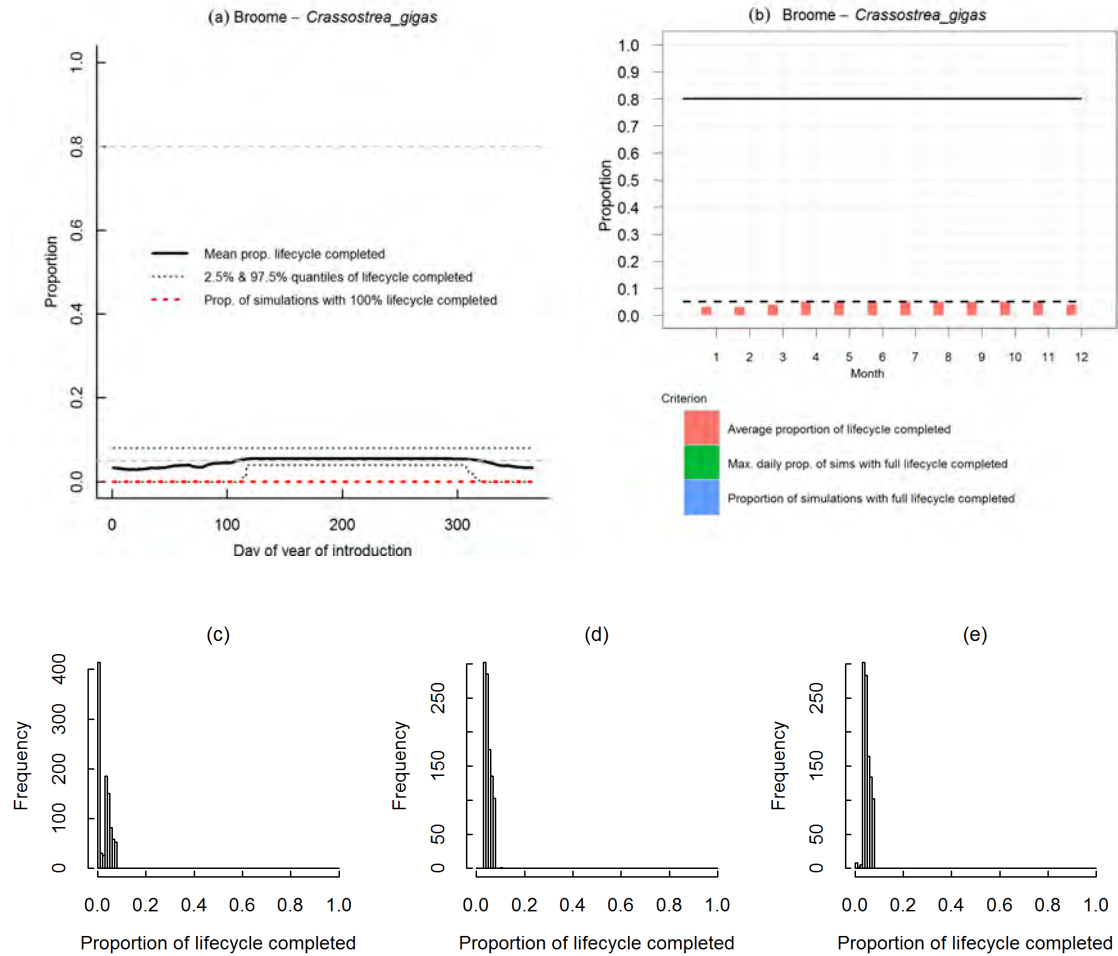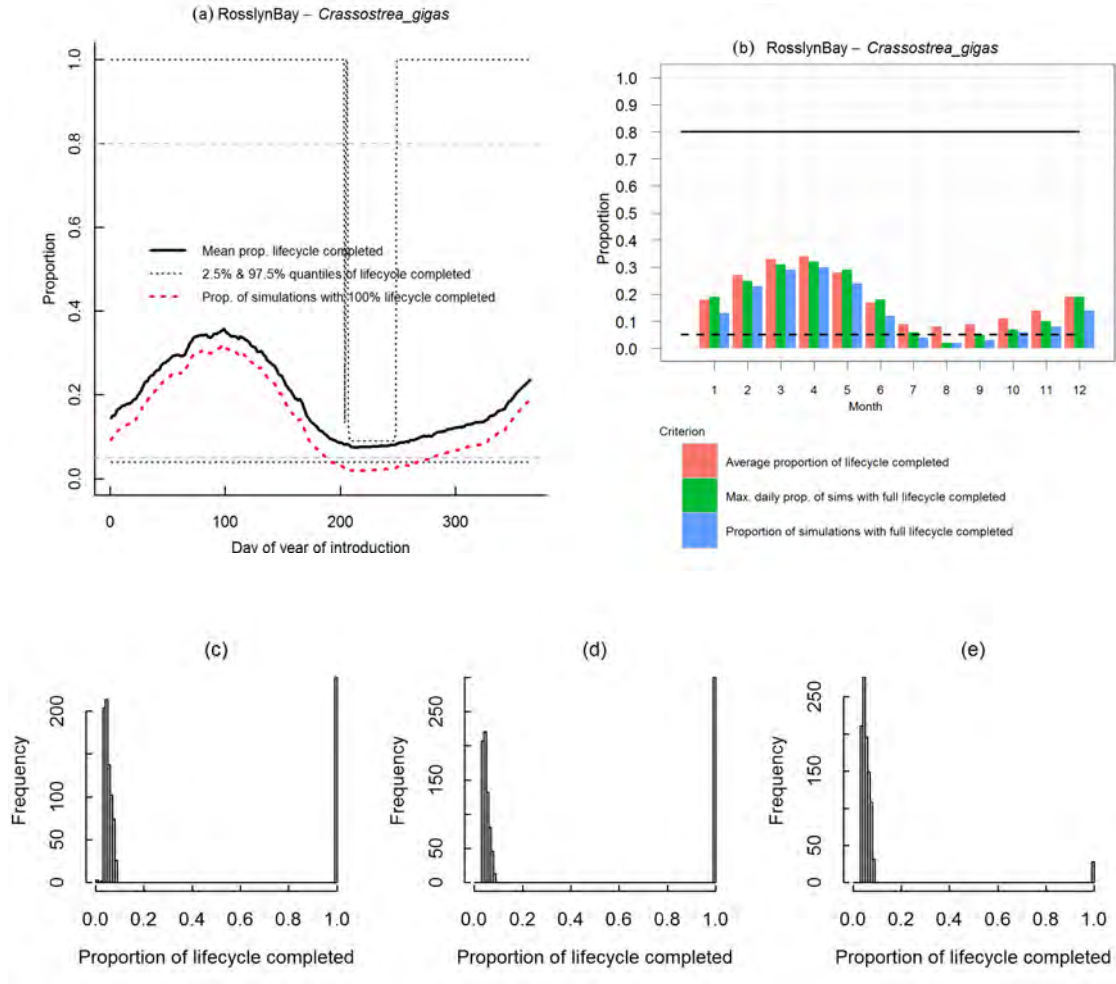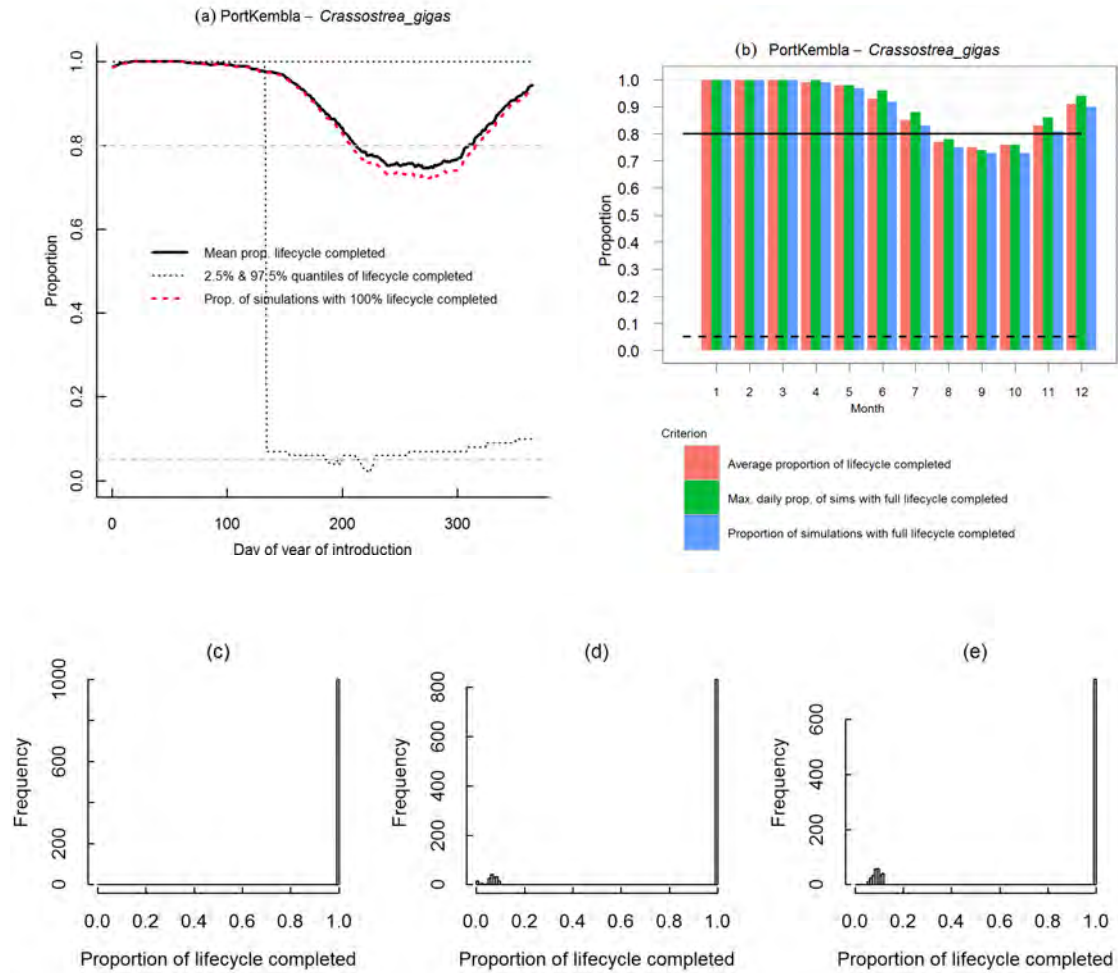

Figure B.1: Simulation results for lifecycle completion of *C. gigas* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 30; (d) day 180; (e) day 300.

Burnie

Under the old rule, *C. gigas* would be considered a risk of establishing in Burnie from day 305 to day 136, with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
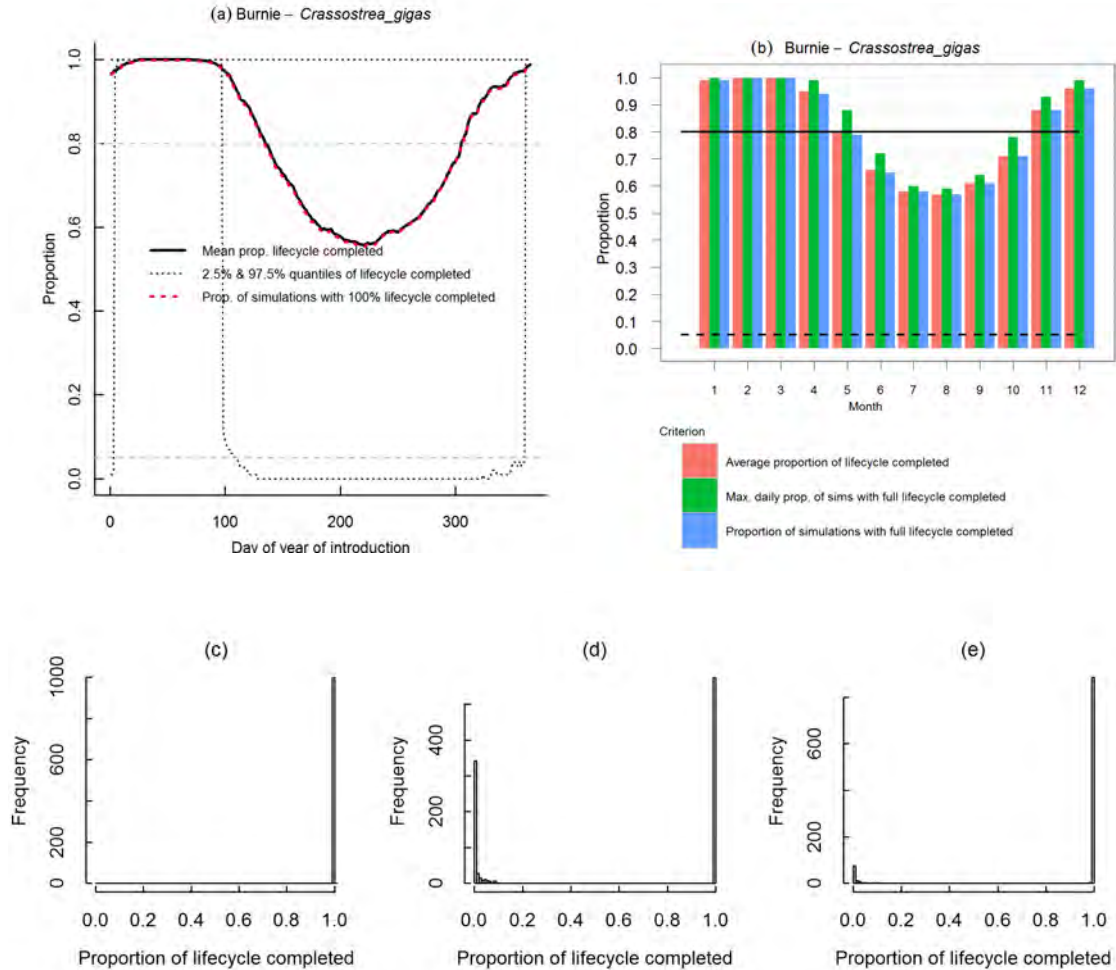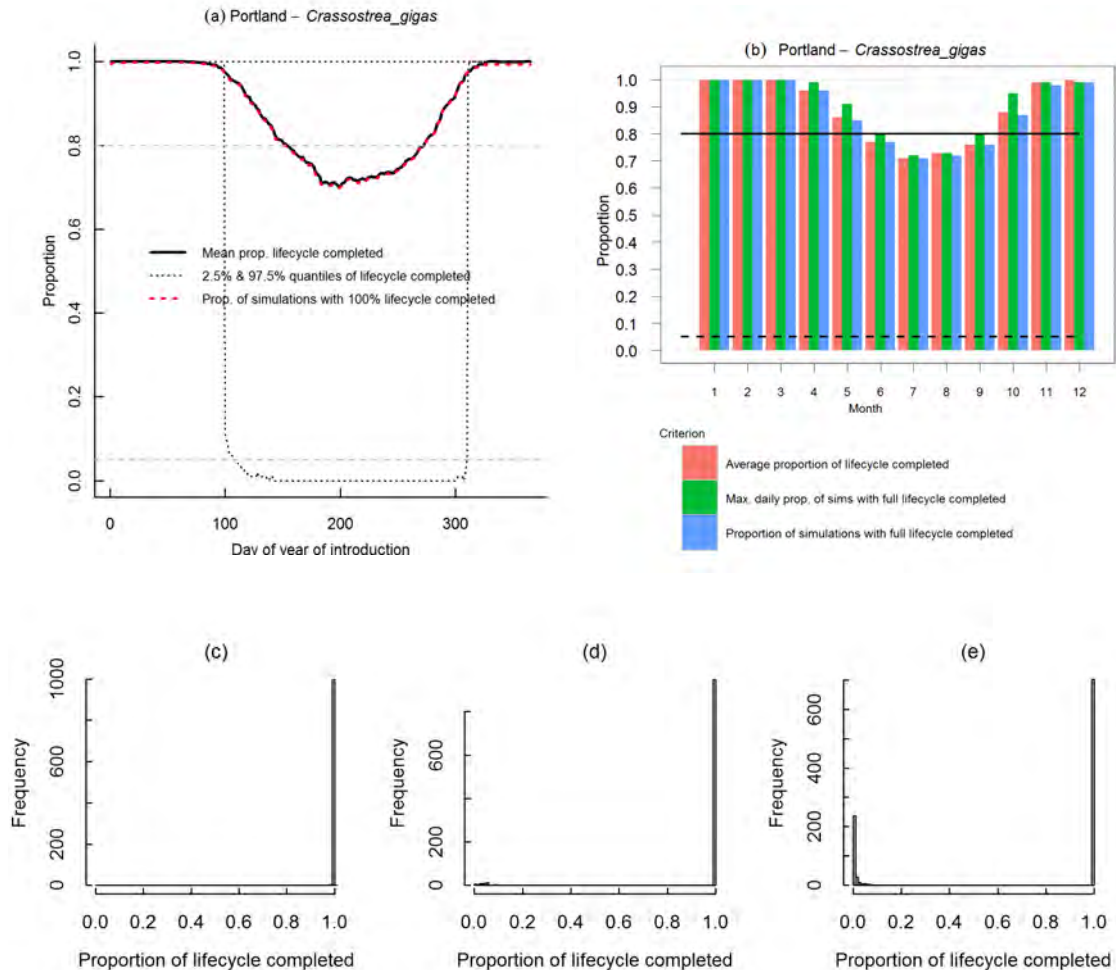

Figure B.2: Simulation results for lifecycle completion of *C. gigas* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 320.

Cape Ferguson

Under the old rule, *C. gigas* would never be considered a risk of establishing in Cape Ferguson, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 60 to day 159 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. With the monthly rule, this corresponds to the months of March – June.
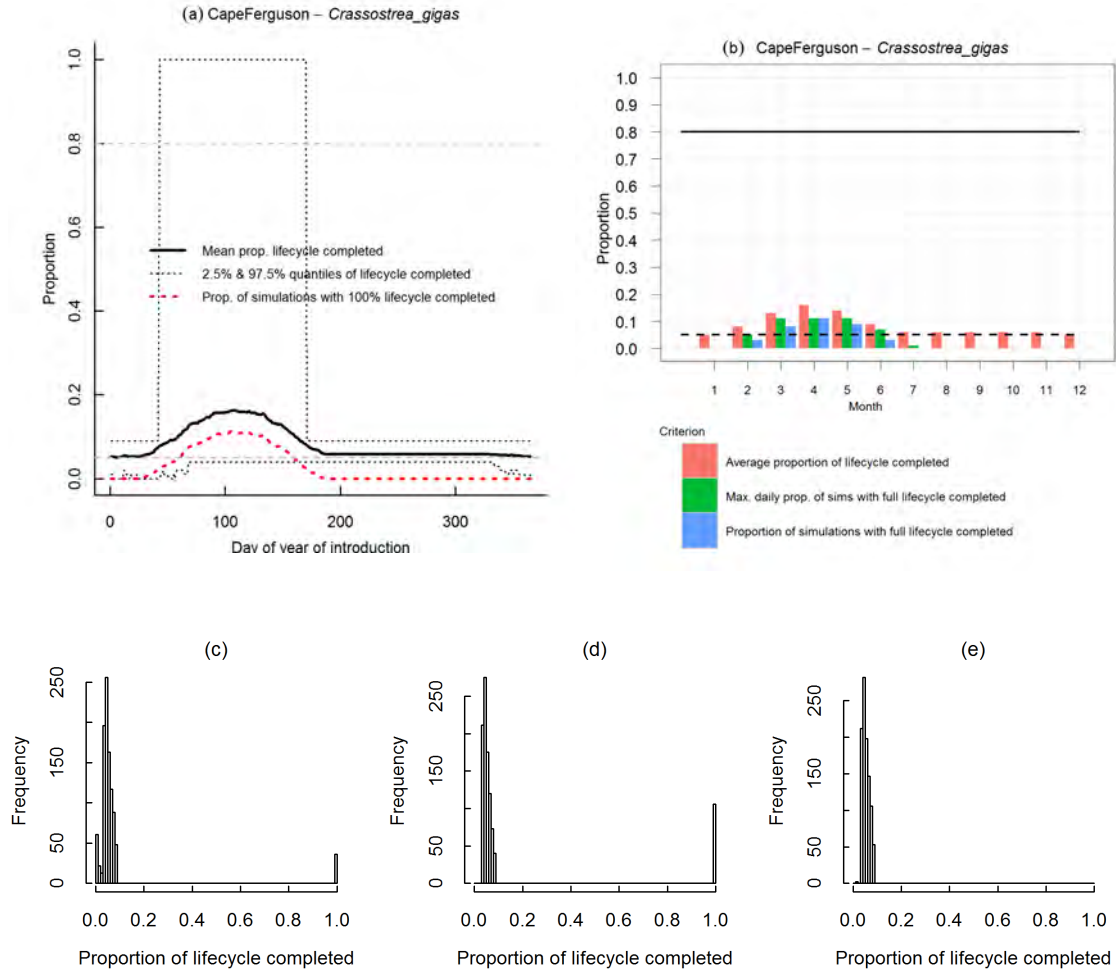
Figure B.3: Simulation results for lifecycle completion of *C. gigas* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 90; (e) day 300.

Darwin

In Darwin establishment would be considered unlikely throughout the year under the old rule and the new rule.
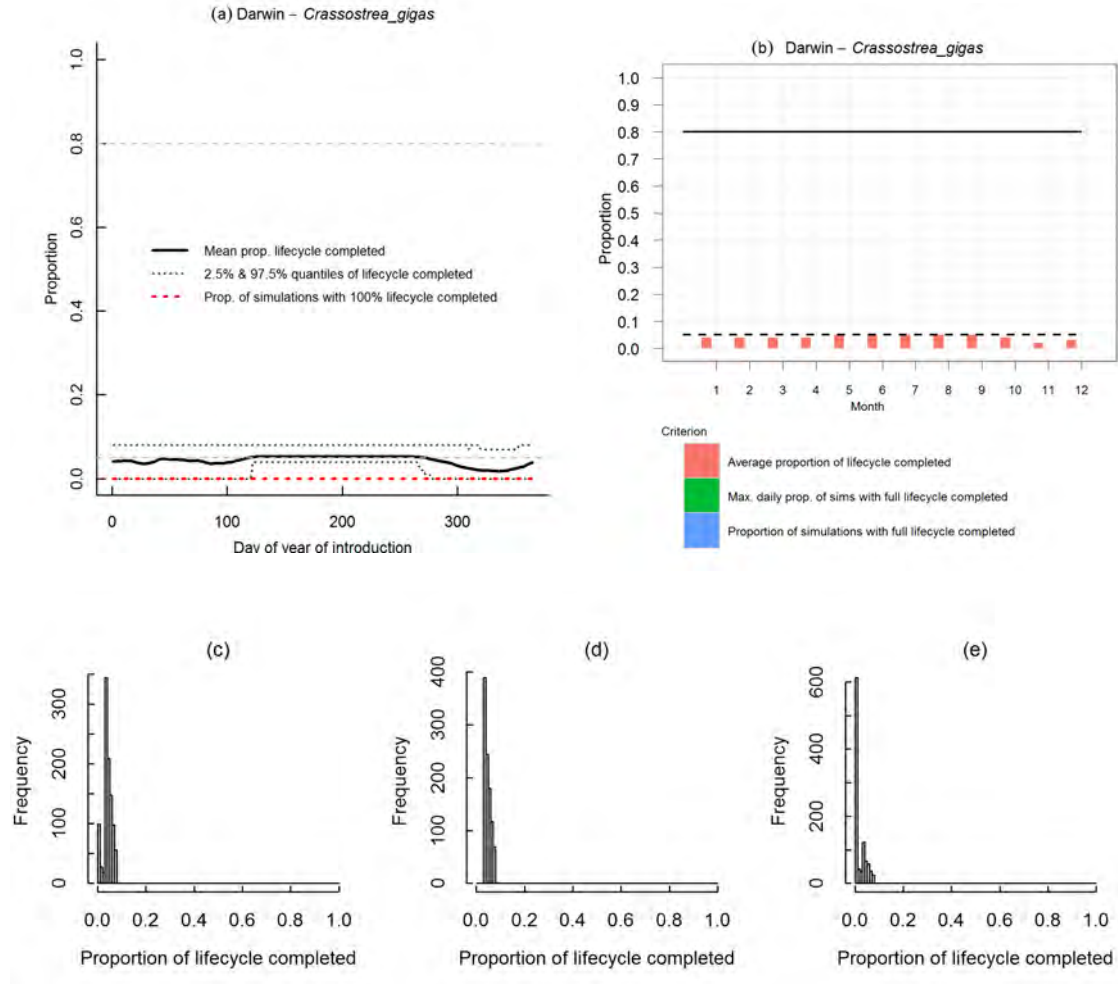
Figure B.4: Simulation results for lifecycle completion of *C. gigas* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 320.

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.
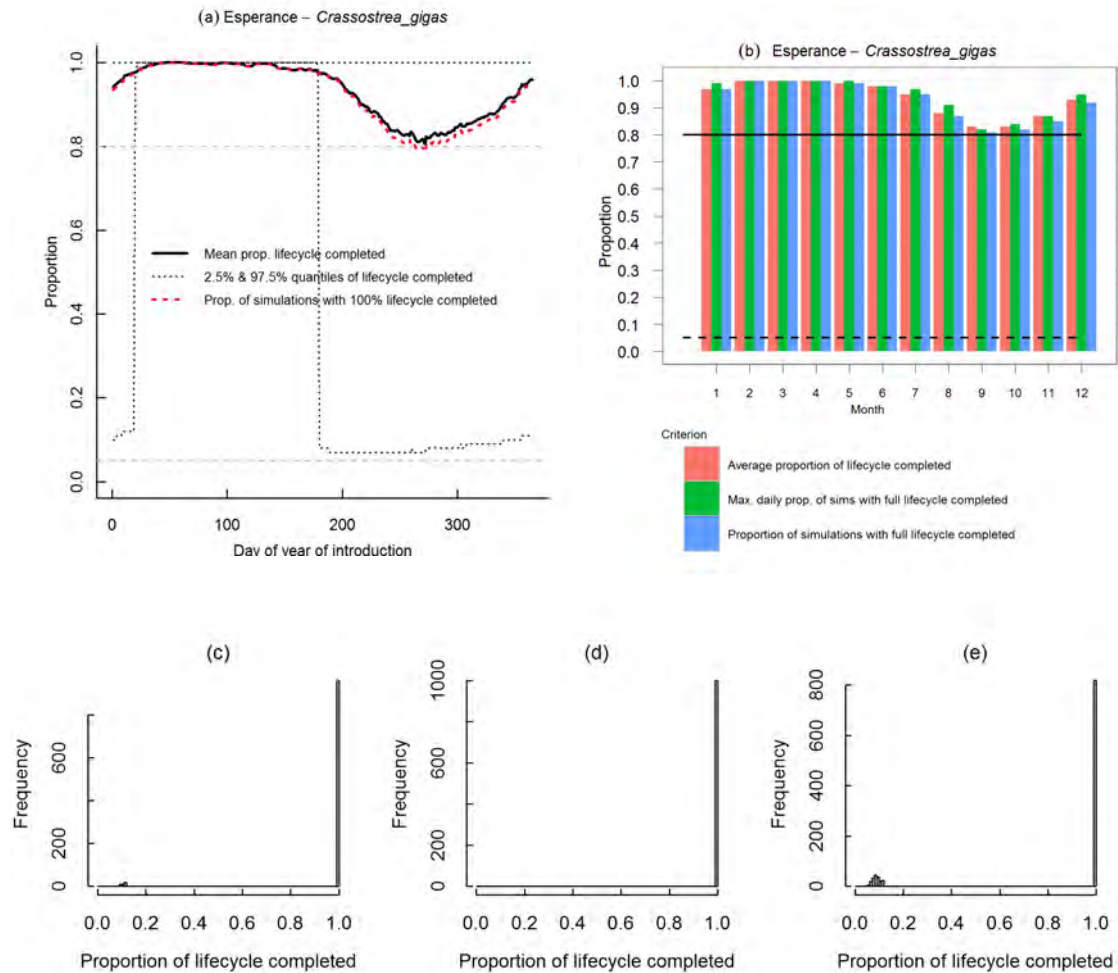
Figure B.5: Simulation results for lifecycle completion of *C. gigas* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 100; (e) day 260.

Hilarys

Under the old rule, *C. gigas* would be considered a risk of establishing in Hilarys in February – April. Establishment would be considered possible throughout the year under the new rule.
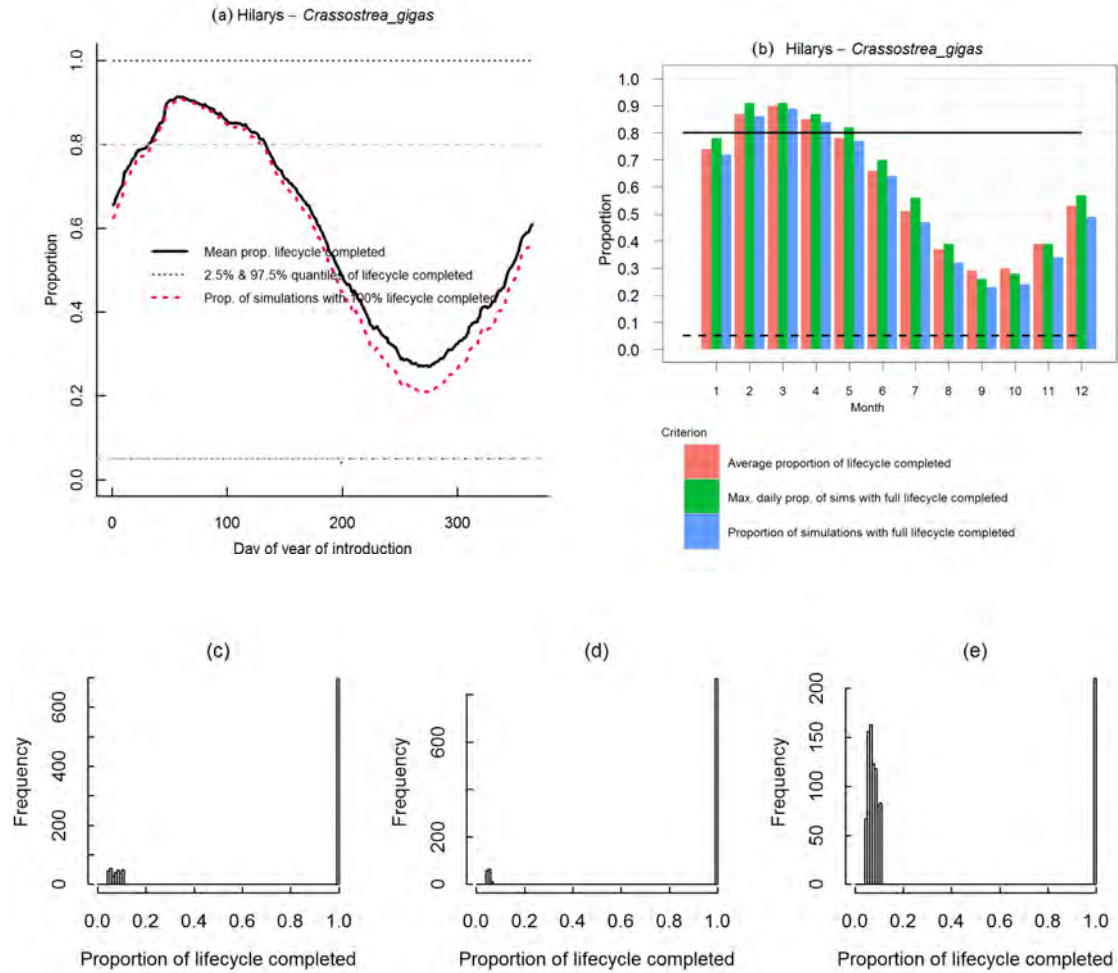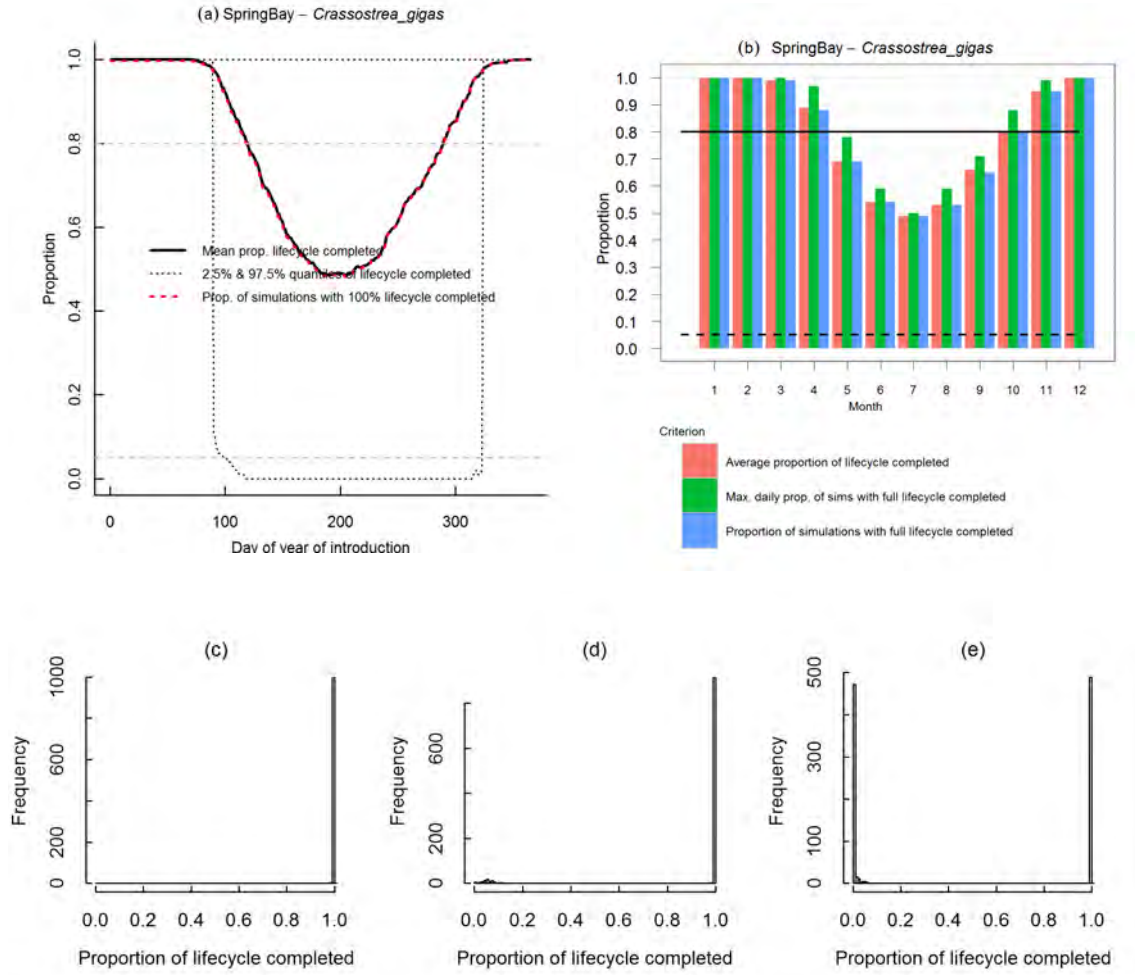

Figure B.6: Simulation results for lifecycle completion of *C. gigas* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 90; (e) day 270.

Groote Eylandt

In Groote Eylandt establishment would be considered unlikely throughout the year under the old rule and the new rule.
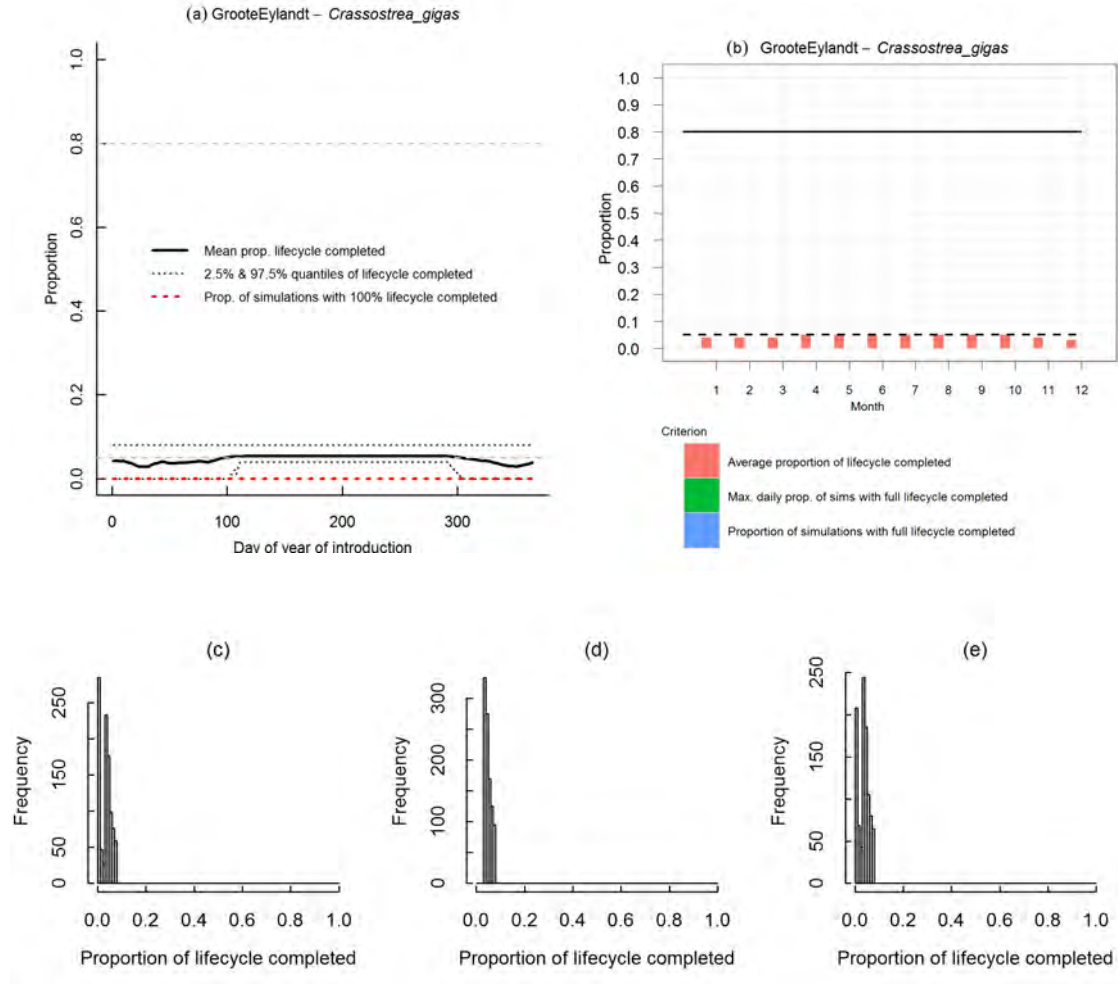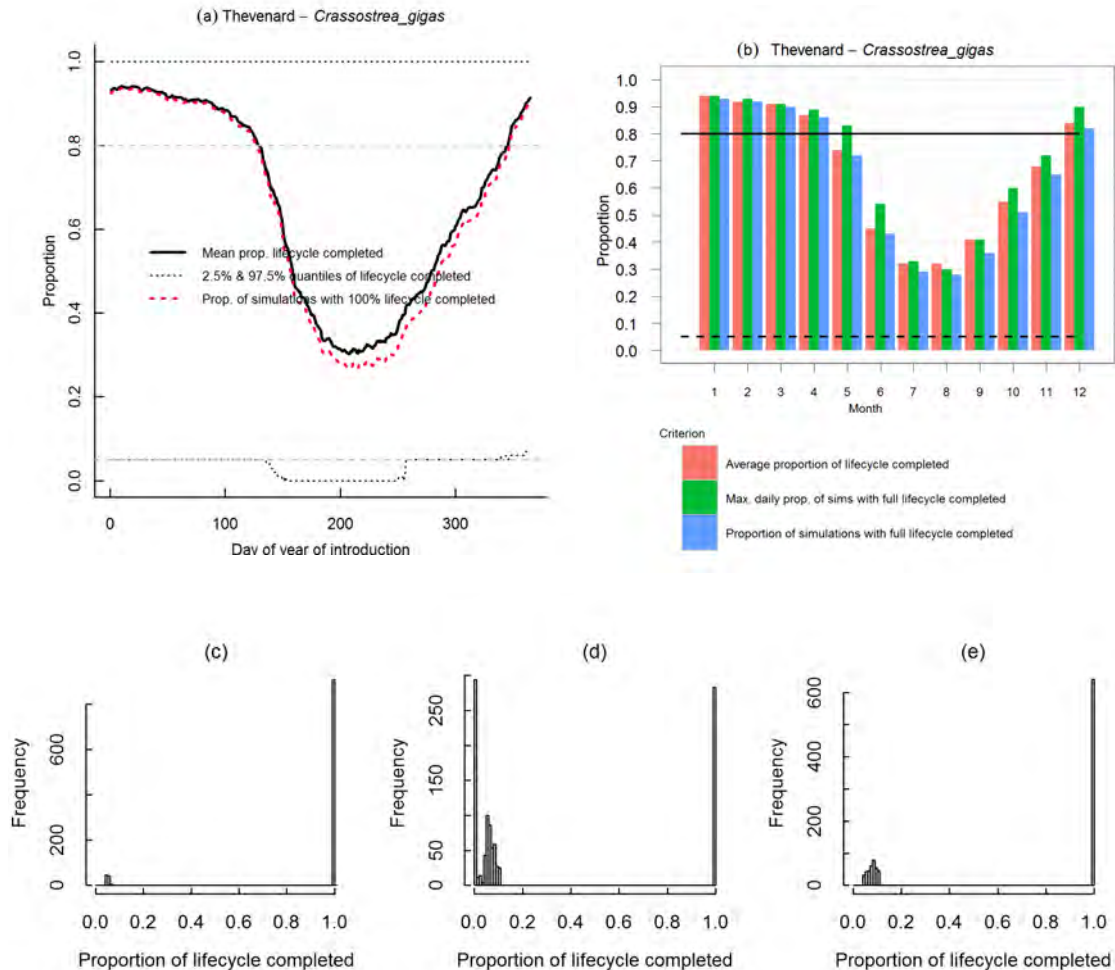

Figure B.7: Simulation results for lifecycle completion of *C. gigas* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 330.

Rosslyn Bay

Under the old rule, *C. gigas* would never be considered a risk of establishing in Rosslyn Bay, with the average proportion of lifecycle completed always less than 0.8. However, establishment would be considered possible under the new rule In all months except August.
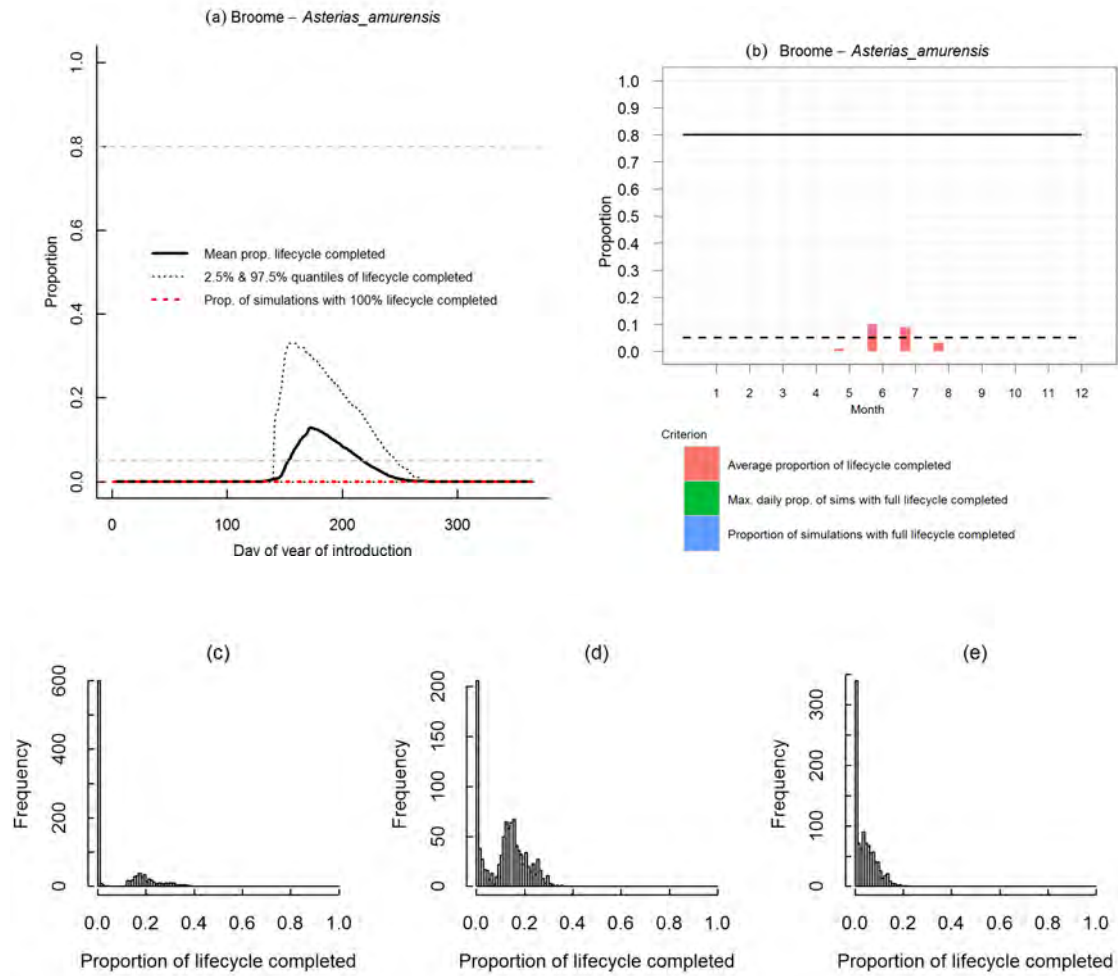

Figure B.8: Simulation results for lifecycle completion of *C. gigas* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 110; (e) day 250.

Port Kembla

In Port Kembla establishment would be considered possible in all months except August – October, while under the new rule establishment would be considered possible throughout the year.
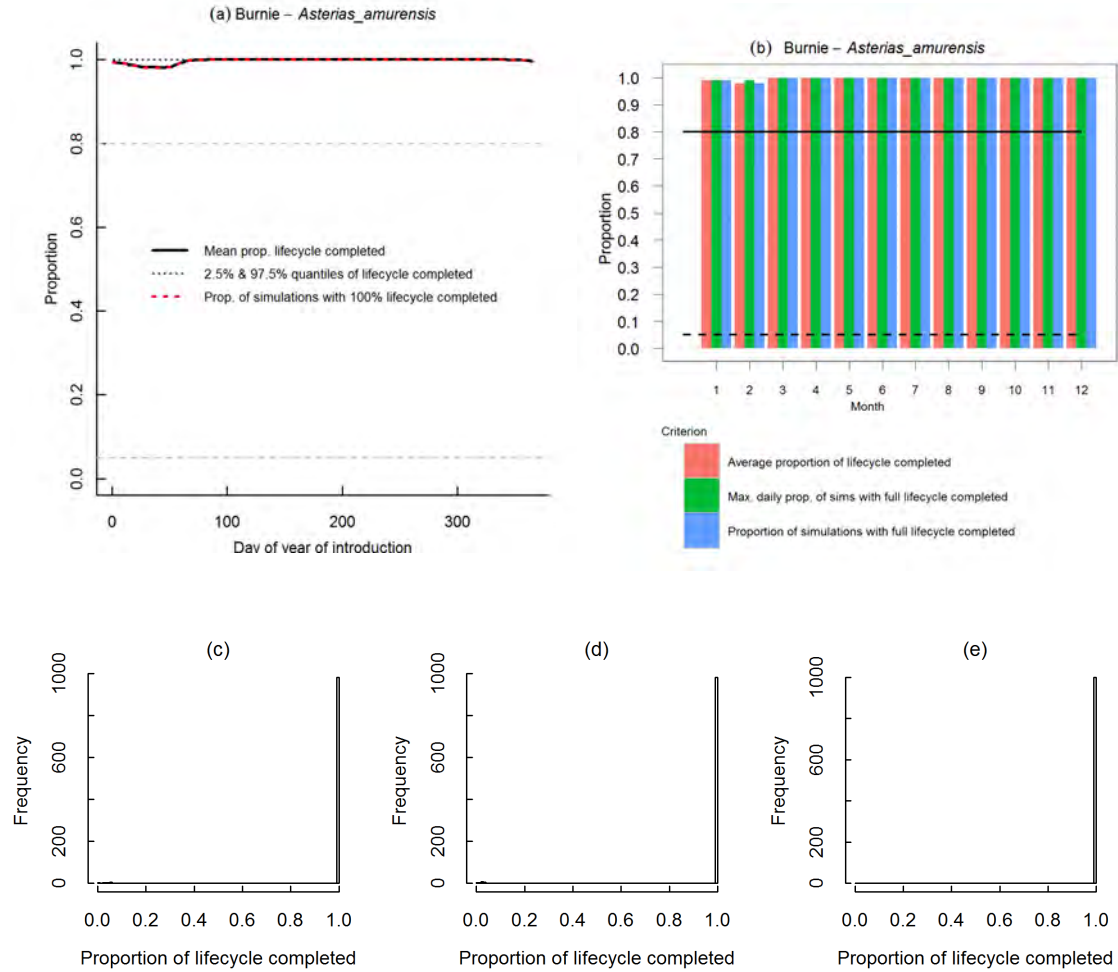

Figure B.9: Simulation results for lifecycle completion of *C. gigas* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Under the old rule, *C. gigas* would be considered a risk of establishing in Portland from day 272 to day 154 (all months except June – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.

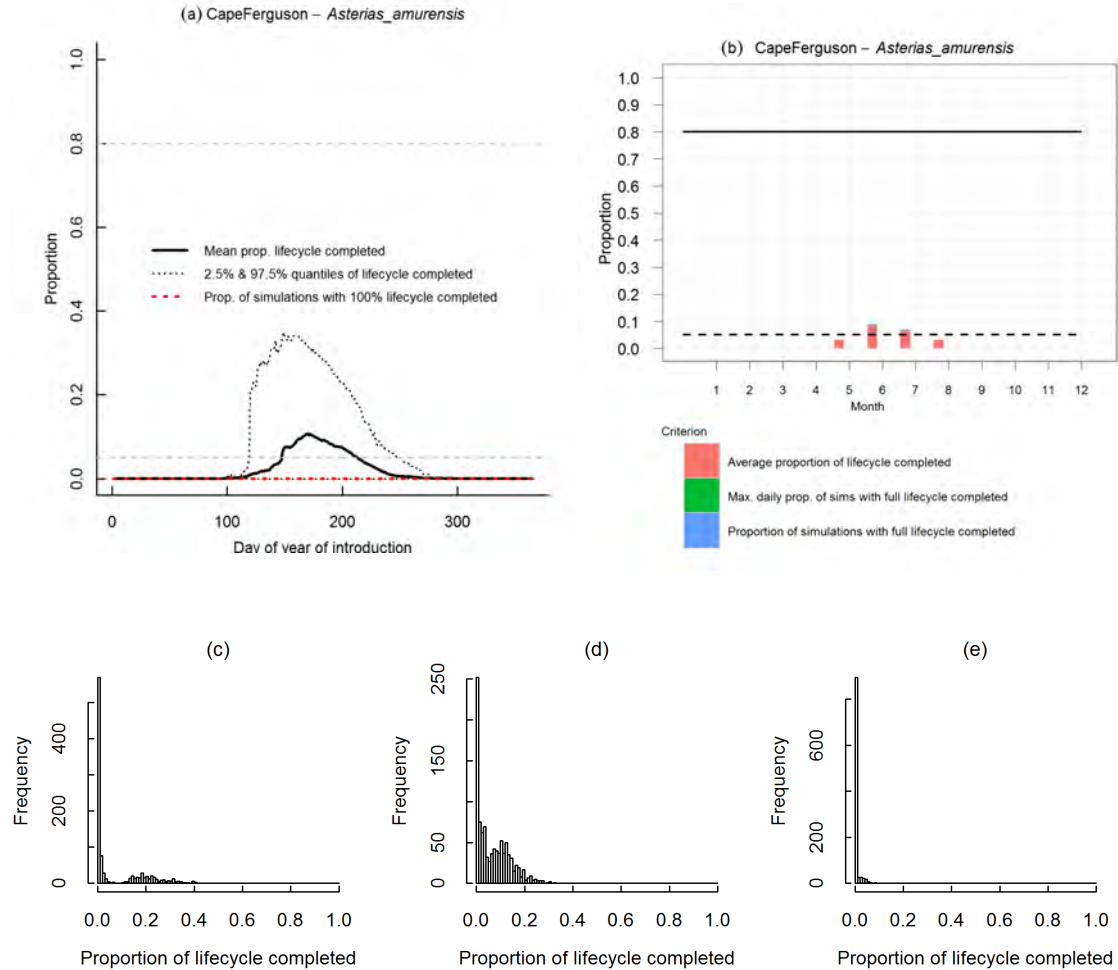**Figure B.10:** Simulation results for lifecycle completion of *C. gigas* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 40; (d) day 110; (e) day 200.

Port Stanvac

Under the old rule, *C. gigas* would be considered a risk of establishing in Port Stanvac from day 303 to day 169 (all months except July – October), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
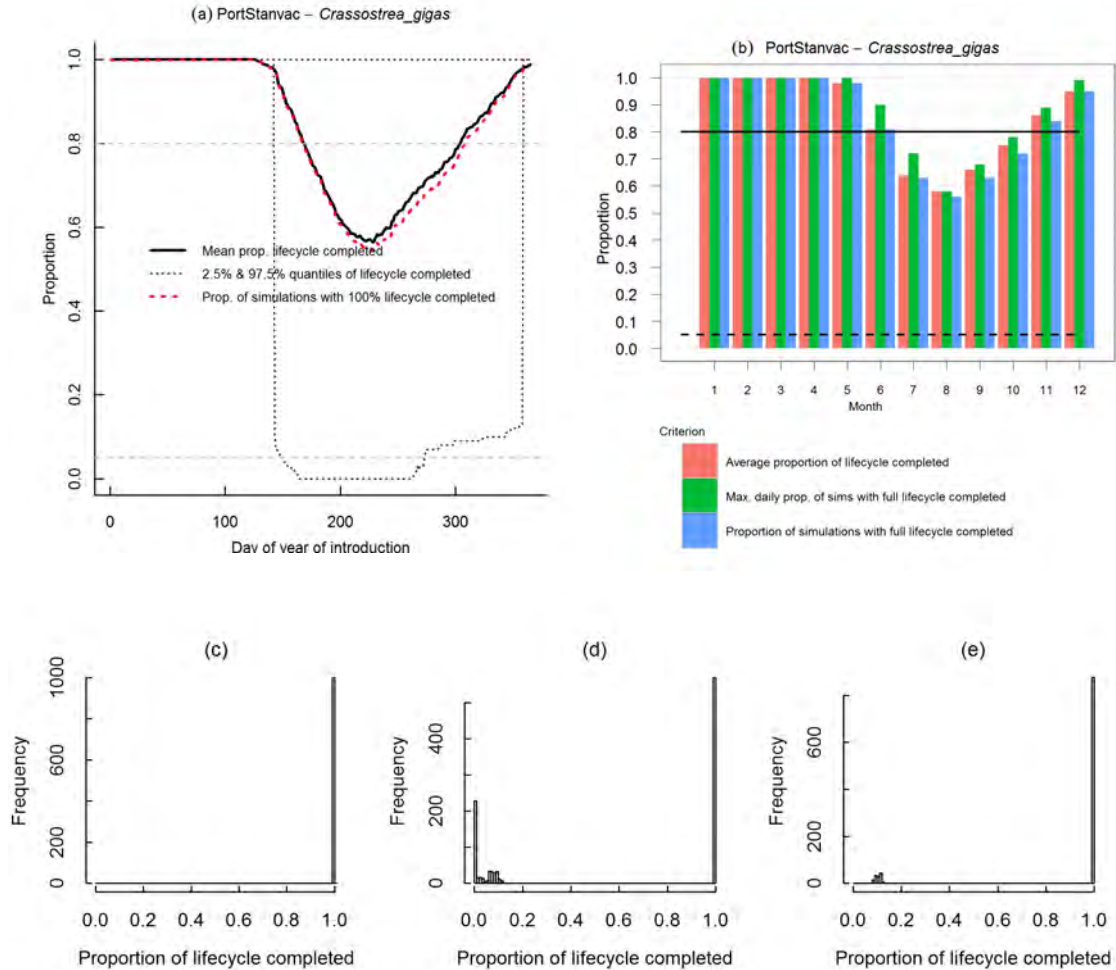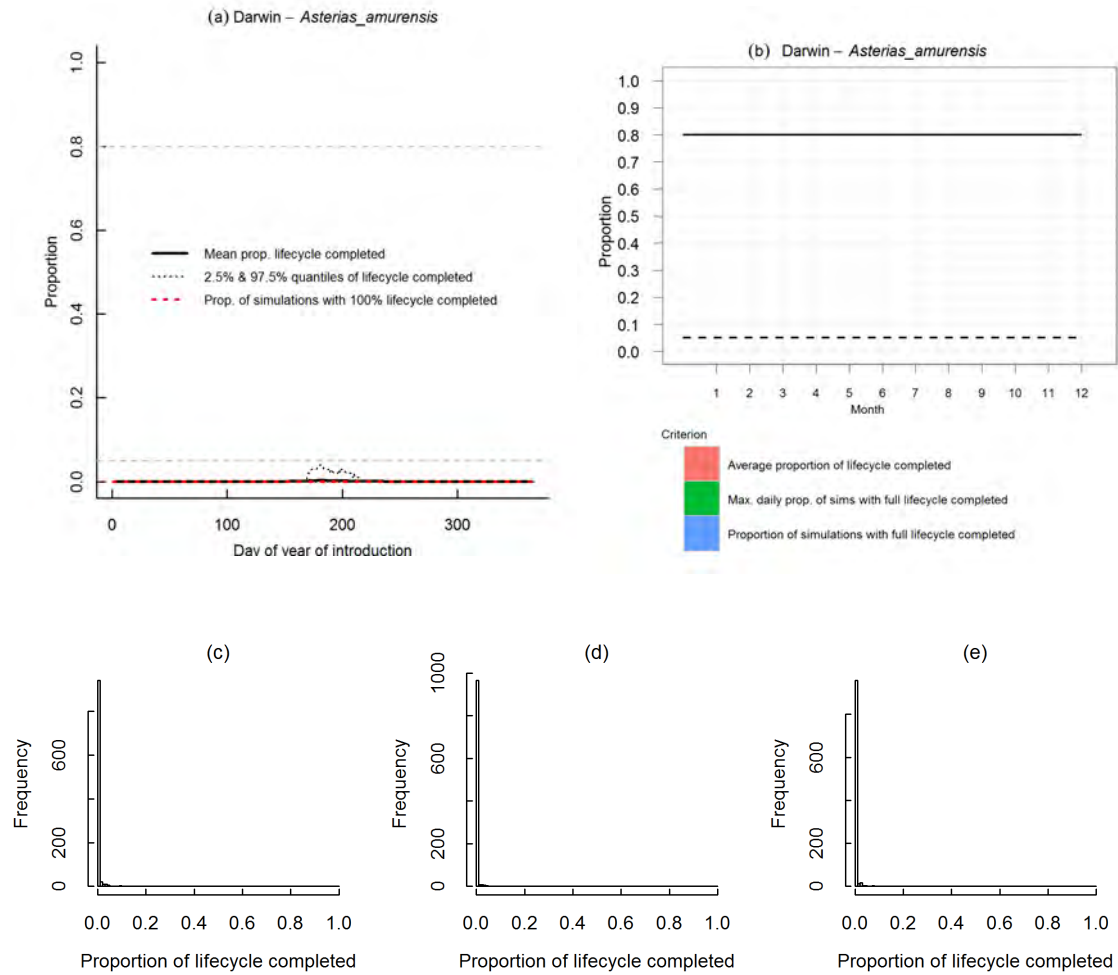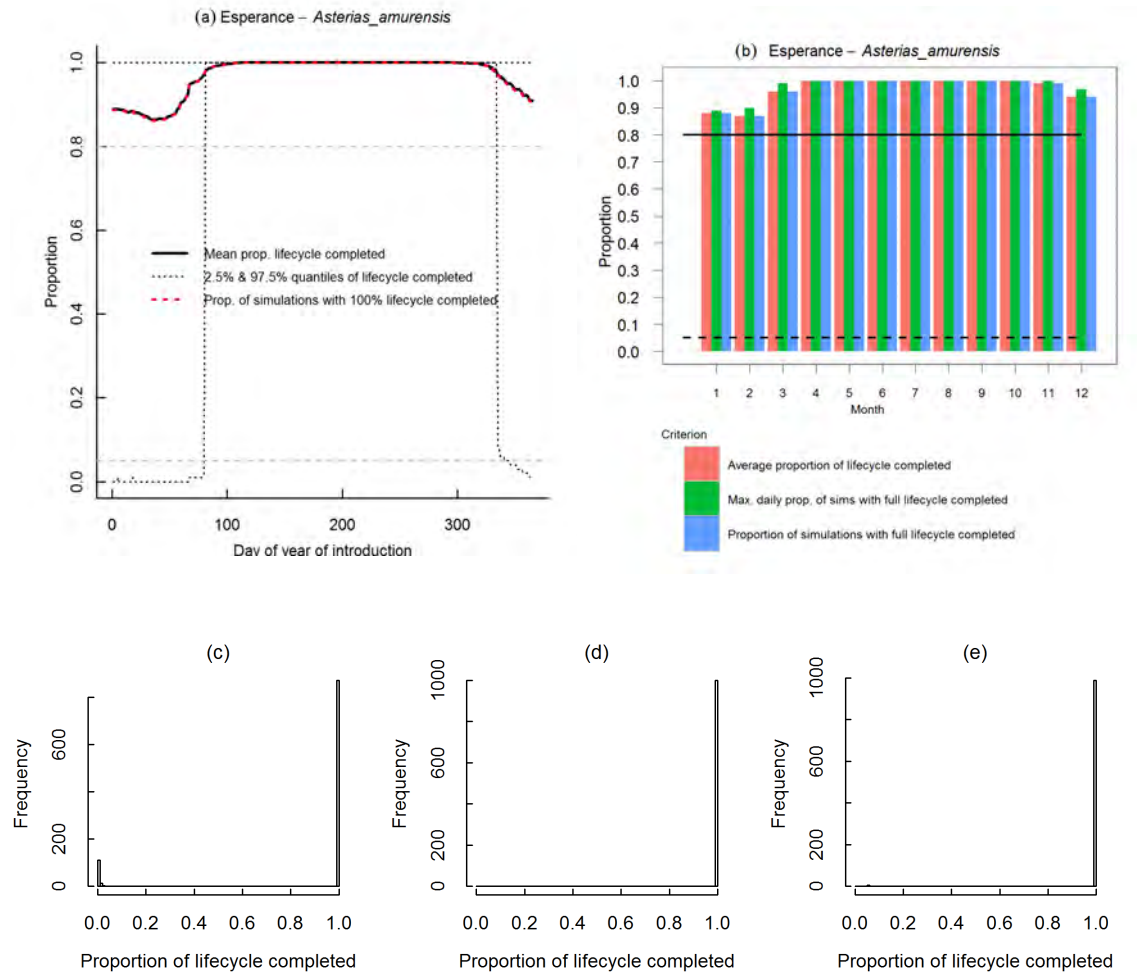

Figure B.11: Simulation results for lifecycle completion of *C. gigas* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 210; (e) day 330.

Spring Bay

Under the old rule, *C. gigas* would be considered a risk of establishing in Spring Bay from day 289 to day 120 (all months except May – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
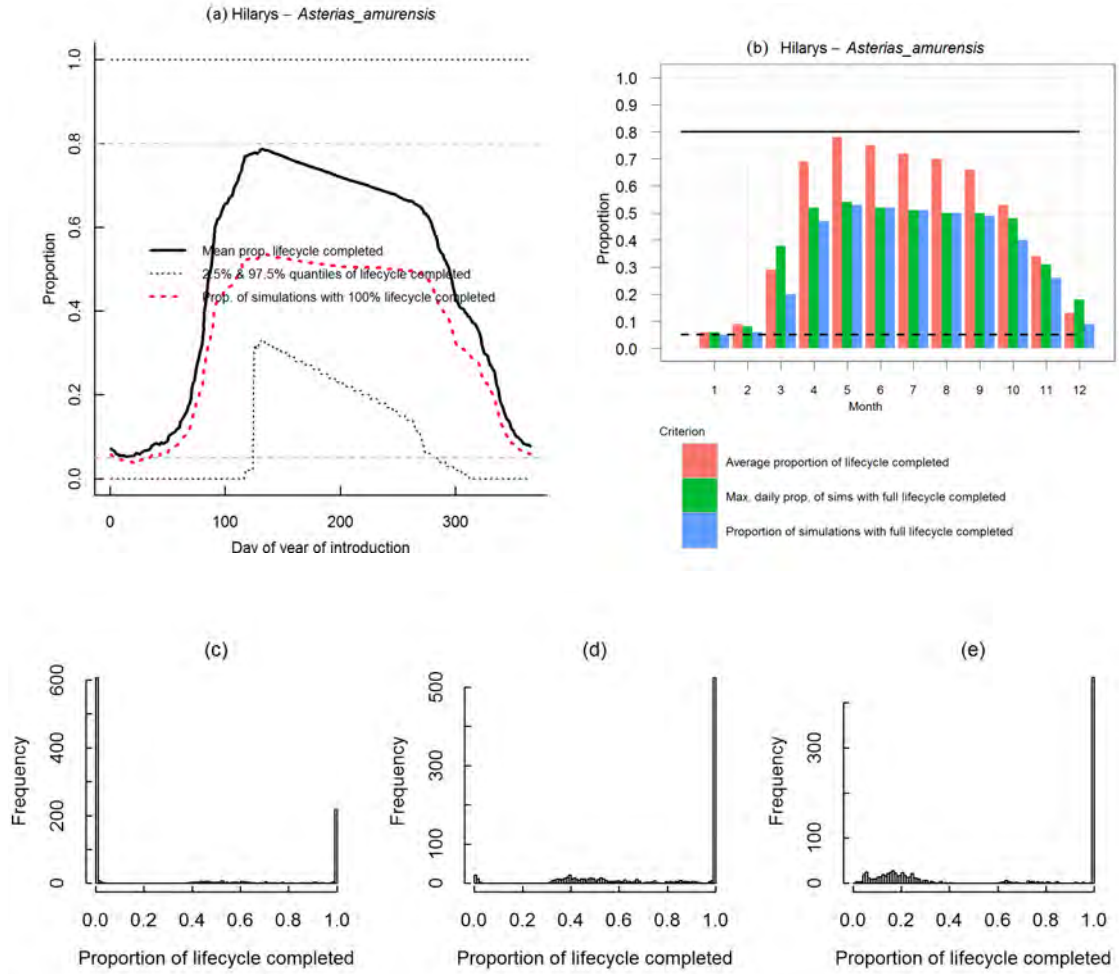

Figure B.12: Simulation results for lifecycle completion of *C. gigas* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 100; (e) day 200.

Thevenard

Under the old rule, *C. gigas* would be considered a risk of establishing in Thevenard from day 345 to day 130 (December – April), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.

Figure B.13: Simulation results for lifecycle completion of *C. gigas* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 320.

B.2 Sub-tidal invertebrates

B.2.1 *Asterias amurensis* - Northern Pacific Seastar

Broome

In Broome establishment would be considered unlikely throughout the year under the old rule and the new rule.

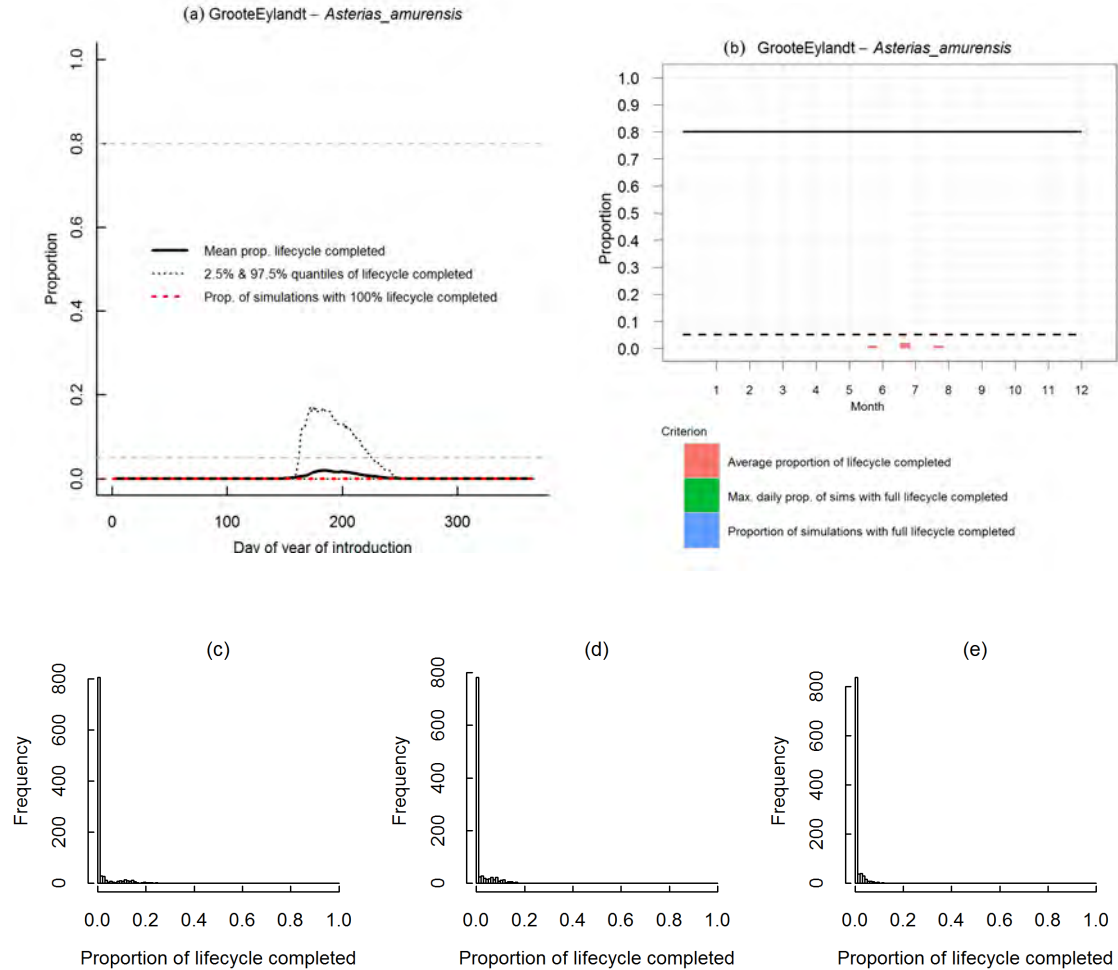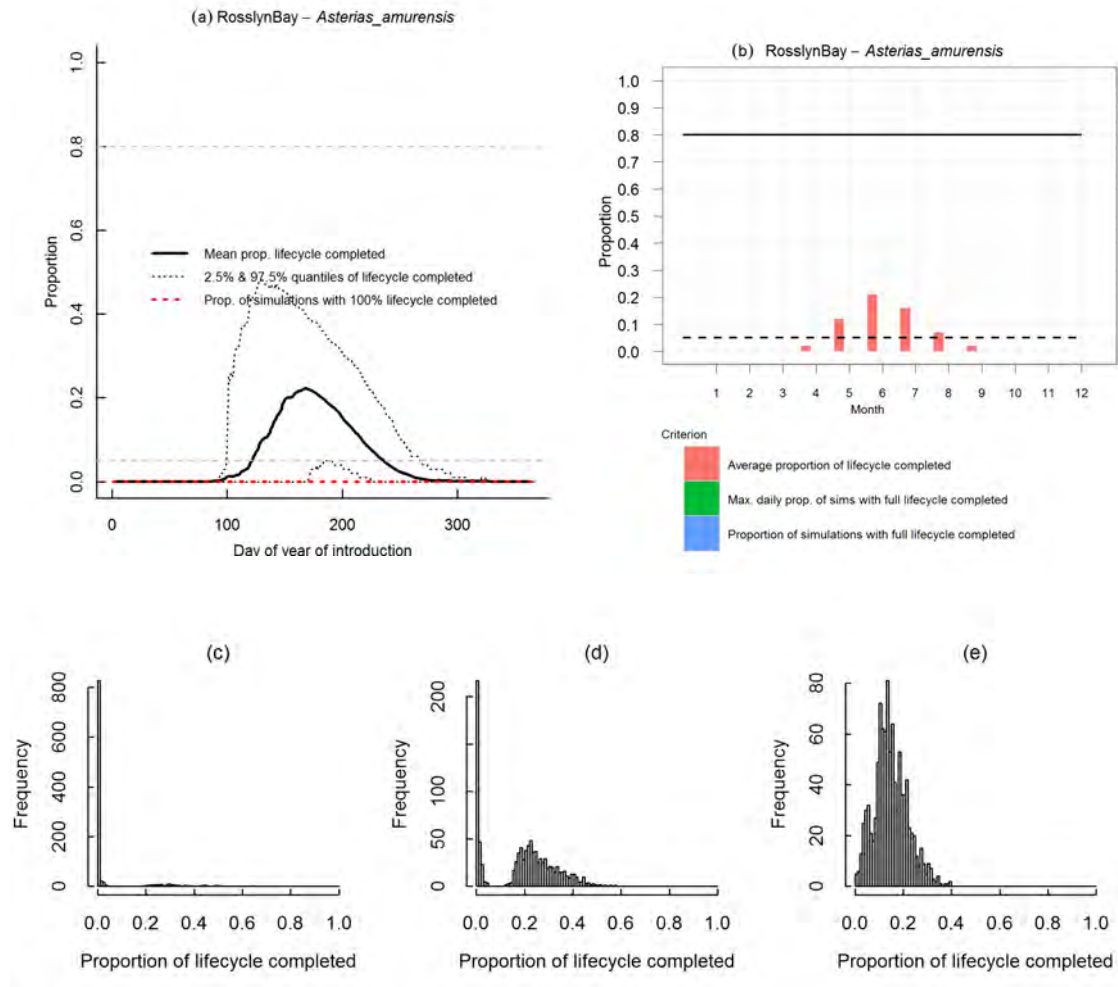**Figure B.14:** Simulation results for lifecycle completion of *A. amurensis* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 160; (d) day 180; (e) day 220.

Burnie

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.15: Simulation results for lifecycle completion of *A. amurensis* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 30; (d) day 40; (e) day 200.

Cape Ferguson

In Cape Ferguson establishment would be considered unlikely throughout the year under the old rule and the new rule.
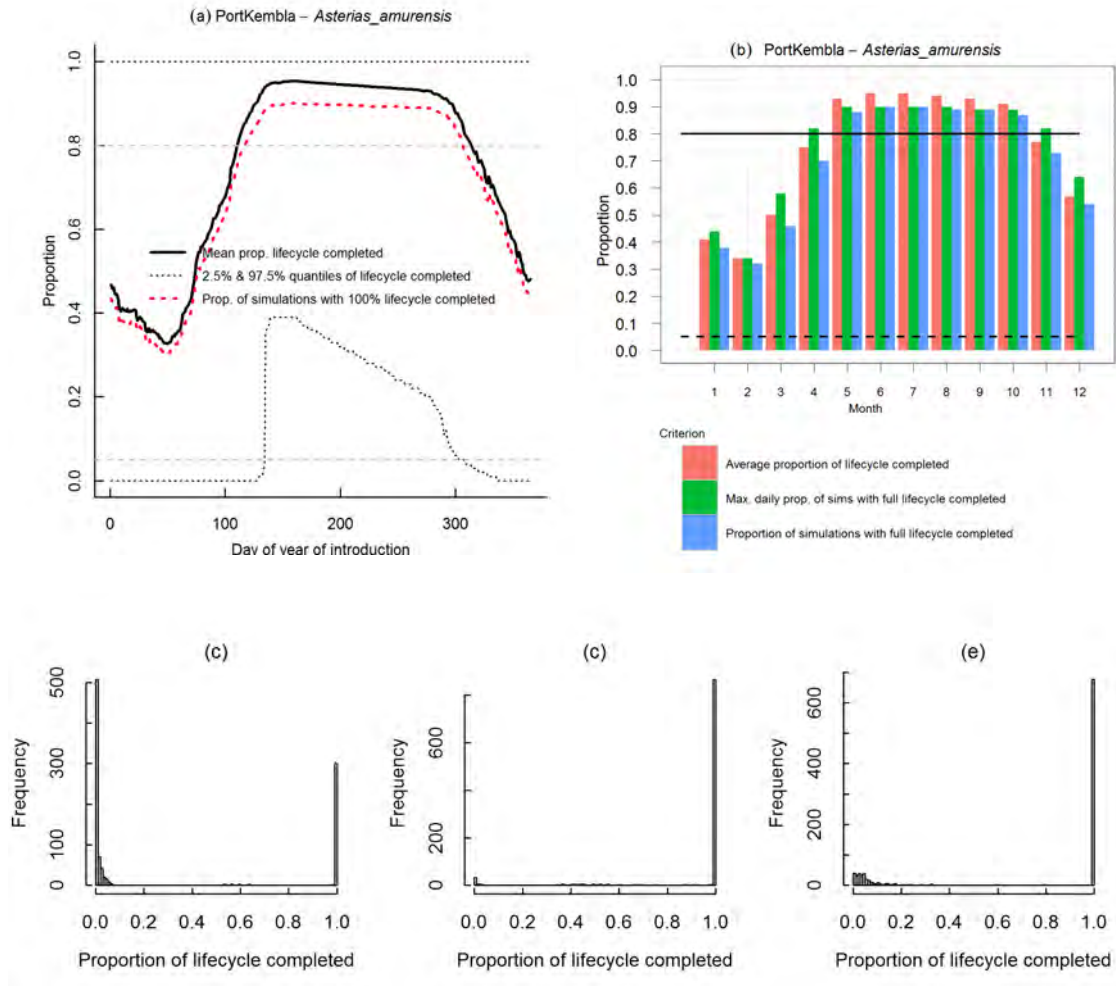

Figure B.16: Simulation results for lifecycle completion of *A. amurensis* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 150; (d) day 200; (e) day 250.

Darwin

In Darwin establishment would be considered unlikely throughout the year under the old rule and the new rule.
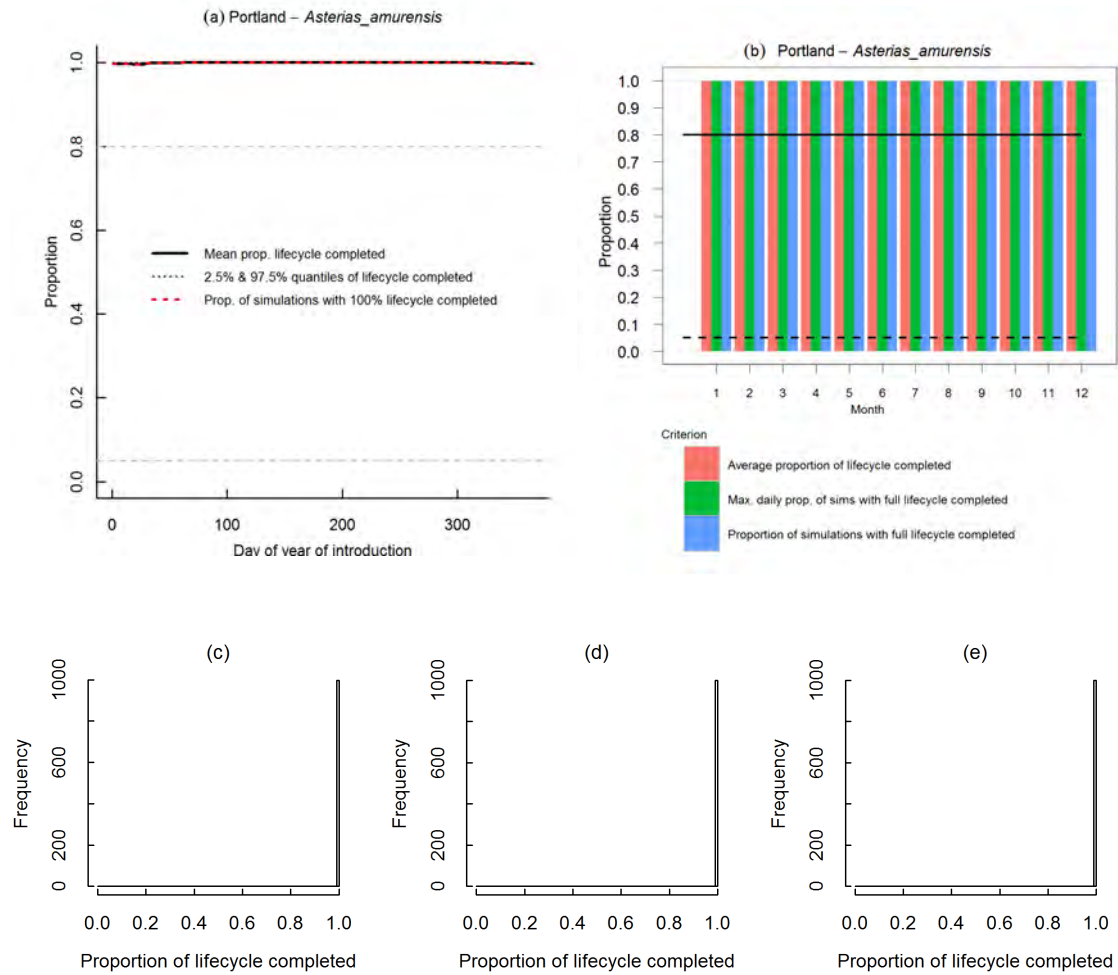

Figure B.17: Simulation results for lifecycle completion of *A. amurensis* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 180; (d) day 190; (e) day 200.

Esperance

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.18: Simulation results for lifecycle completion of *A. amurensis* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 330.

Hilarys

Under the old rule, *A. amurensis* would never be considered a risk of establishing in Hilarys, with the average proportion of lifecycle completed always less than 0.8. However, we see that for most of the year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over those periods under the new rule. We also see that a number of additional simulations also get close to 100% of the lifecycle completed.
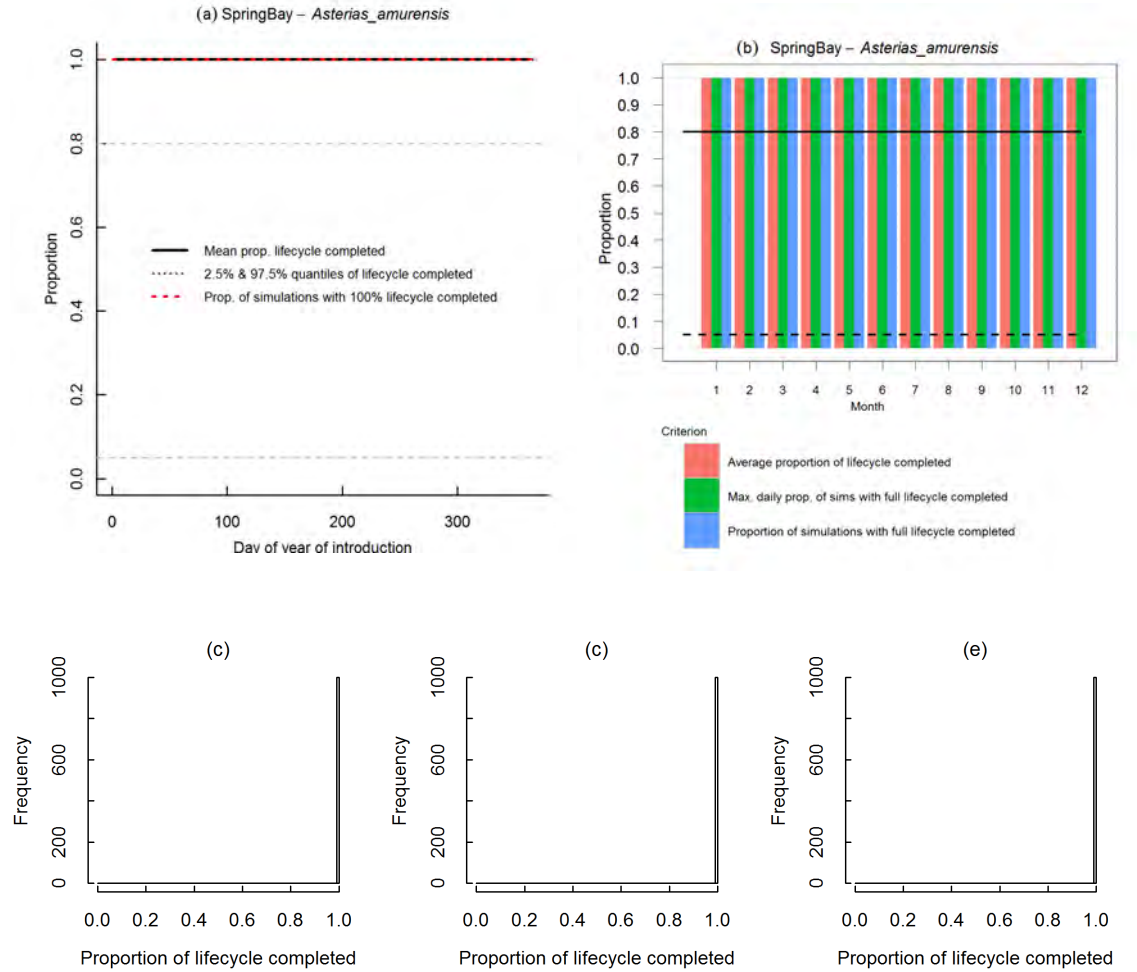

Figure B.19: Simulation results for lifecycle completion of *A. amurensis* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 80; (d) day 120; (e) day 280.

Groote Eylandt

In Groote Eylandt establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.20: Simulation results for lifecycle completion of *A. amurensis* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 180; (d) day 200; (e) day 220.

Rosslyn Bay

In Rosslyn Bay establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.21: Simulation results for lifecycle completion of *A. amurensis* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 120; (d) day 150; (e) day 200.

Port Kembla

Under the old rule, *A. amurensis* would be considered a risk of establishing in Port Kembla from day 111 to day 313 (months May – October), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
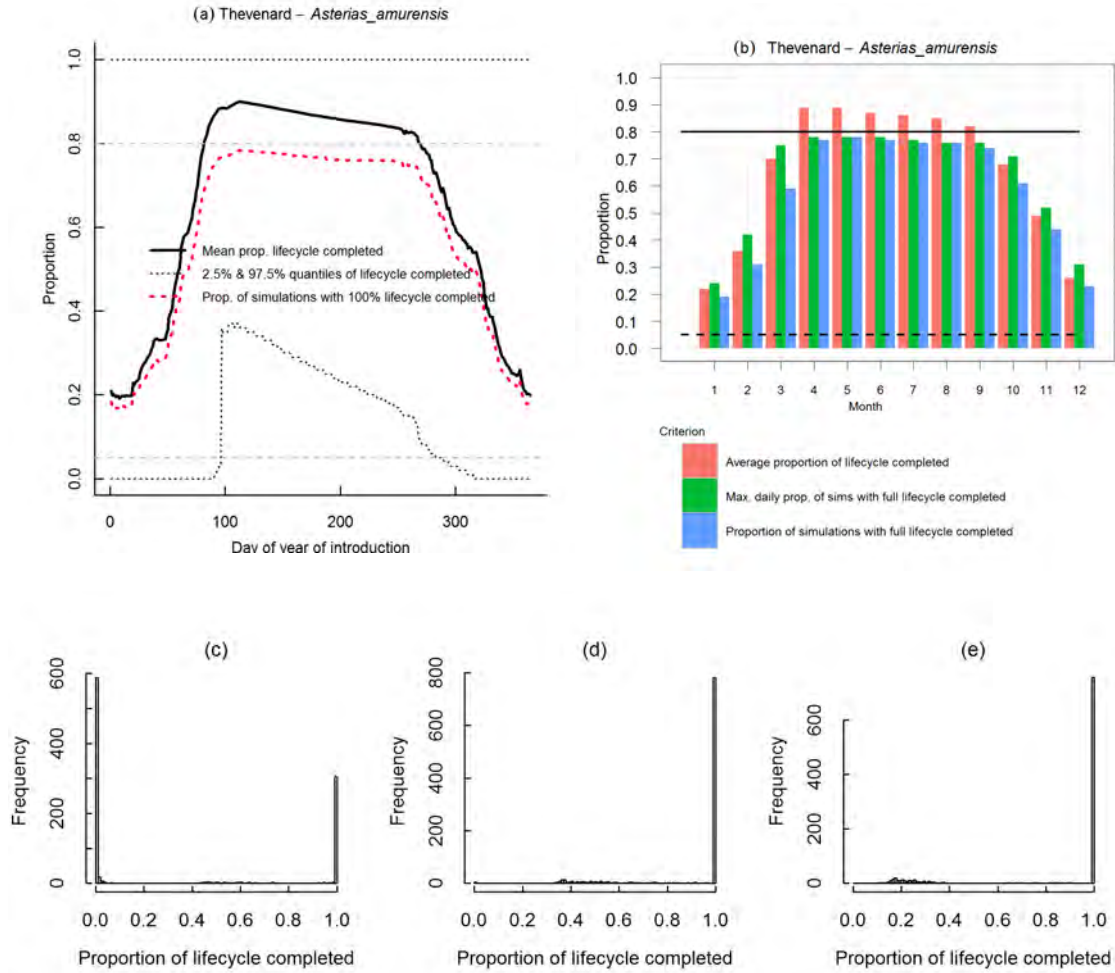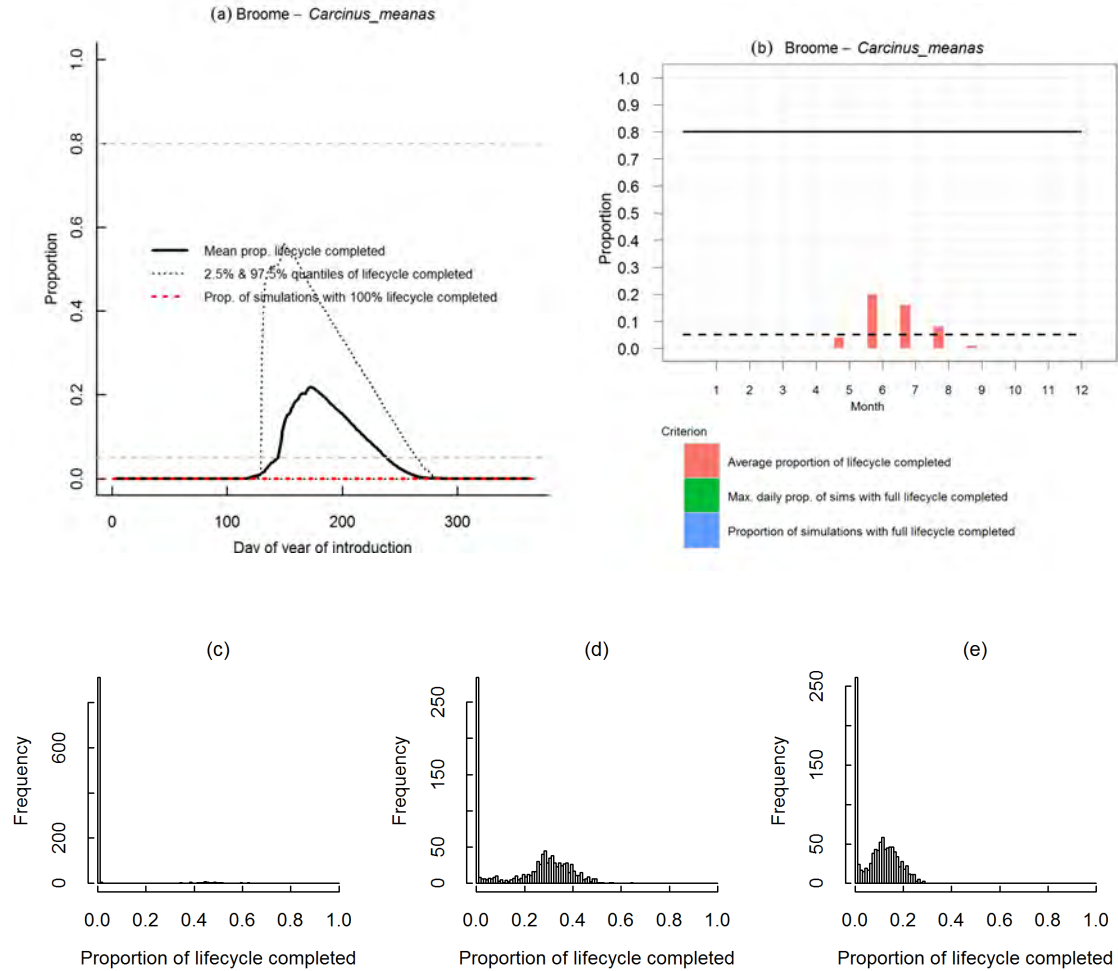

Figure B.22: Simulation results for lifecycle completion of *A. amurensis* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 130; (e) day 330.

Portland

900 full completions and 100 0.99

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.
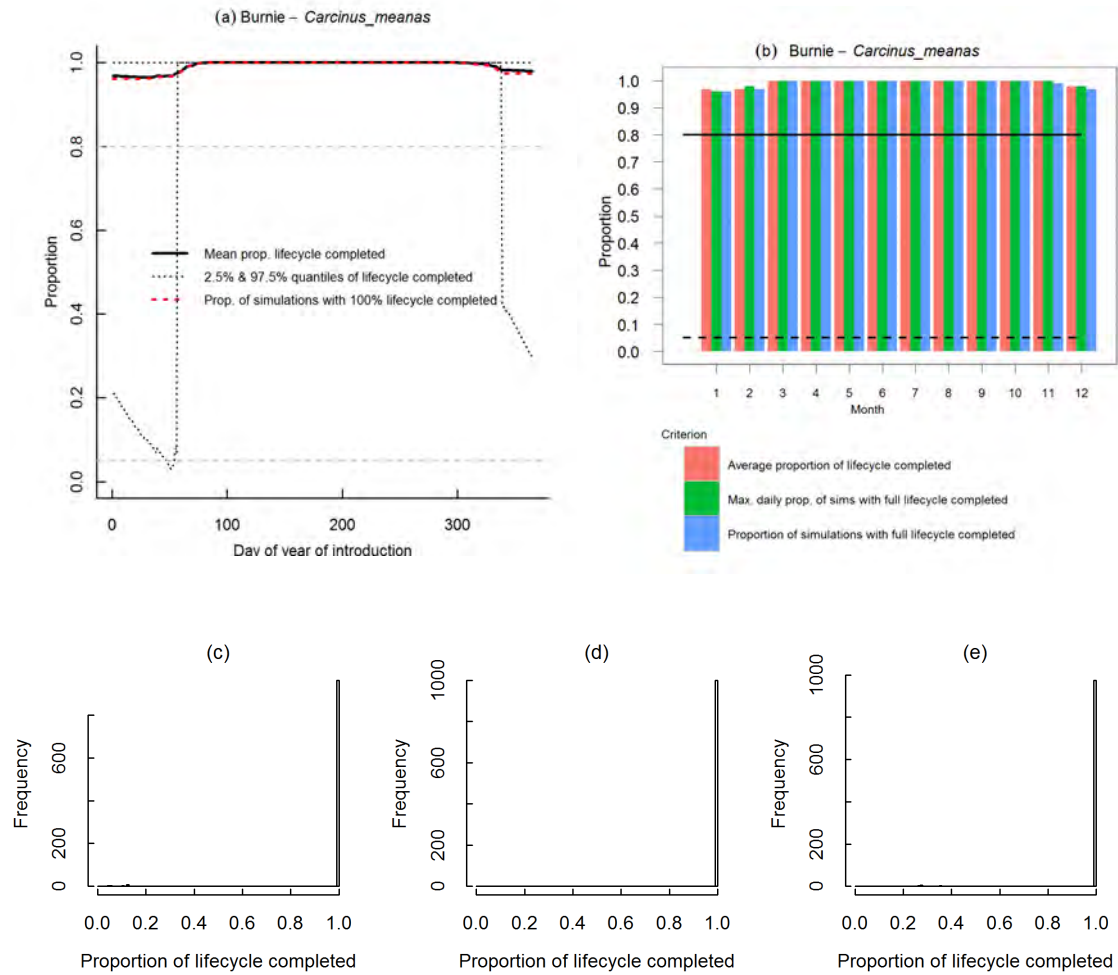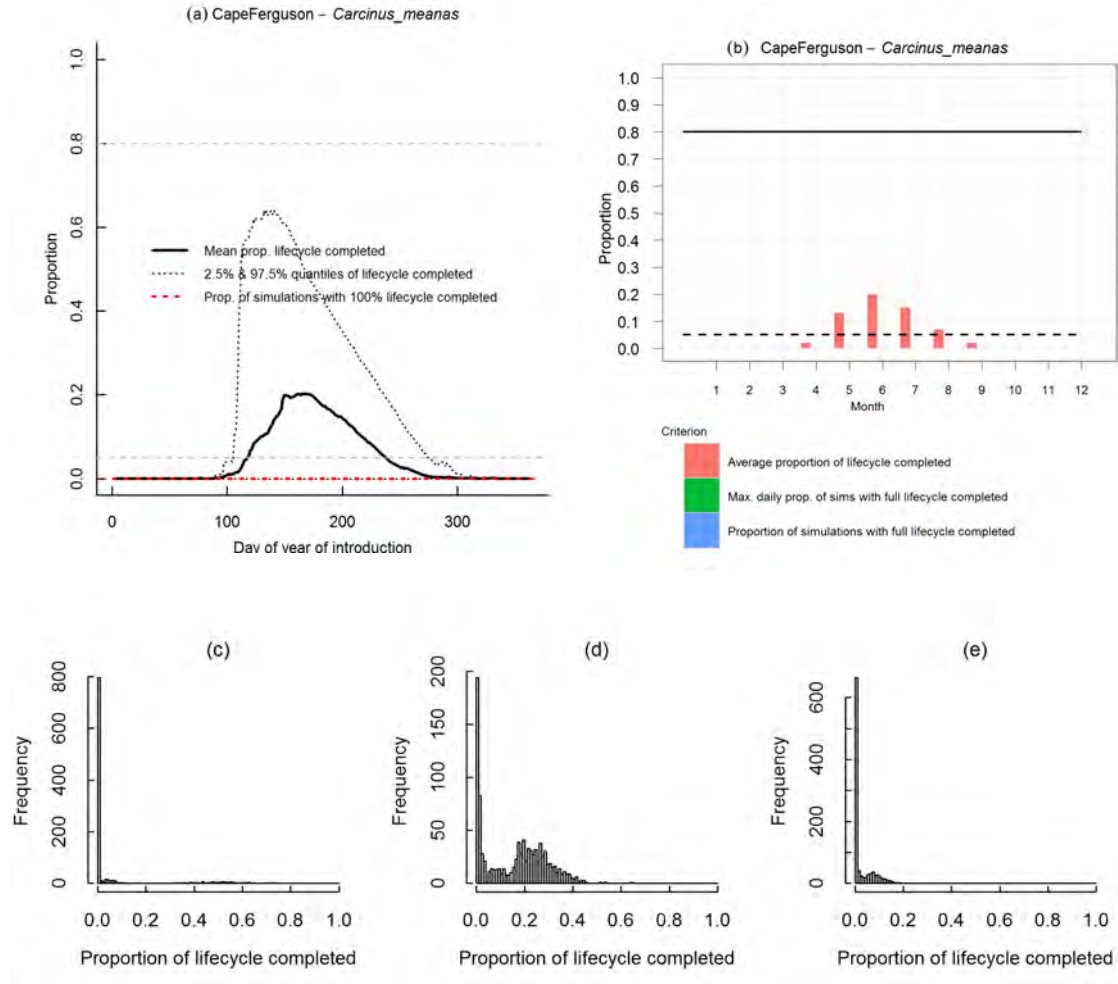

Figure B.23: Simulation results for lifecycle completion of *A. amurensis* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 300.

Port Stanvac

Under the old rule, *A. amurensis* would be considered a risk of establishing in Port Stanvac from day 79 to day 342 (months April – November), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
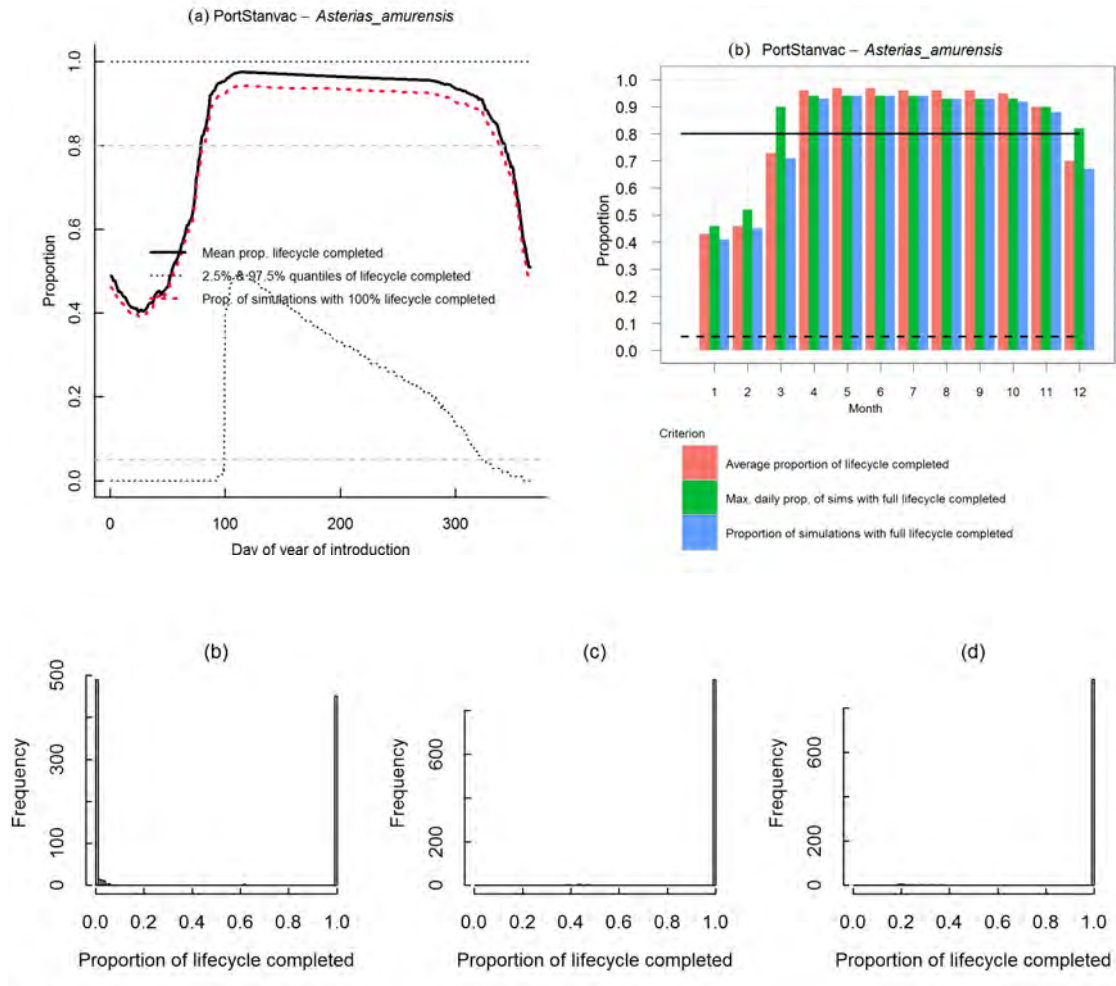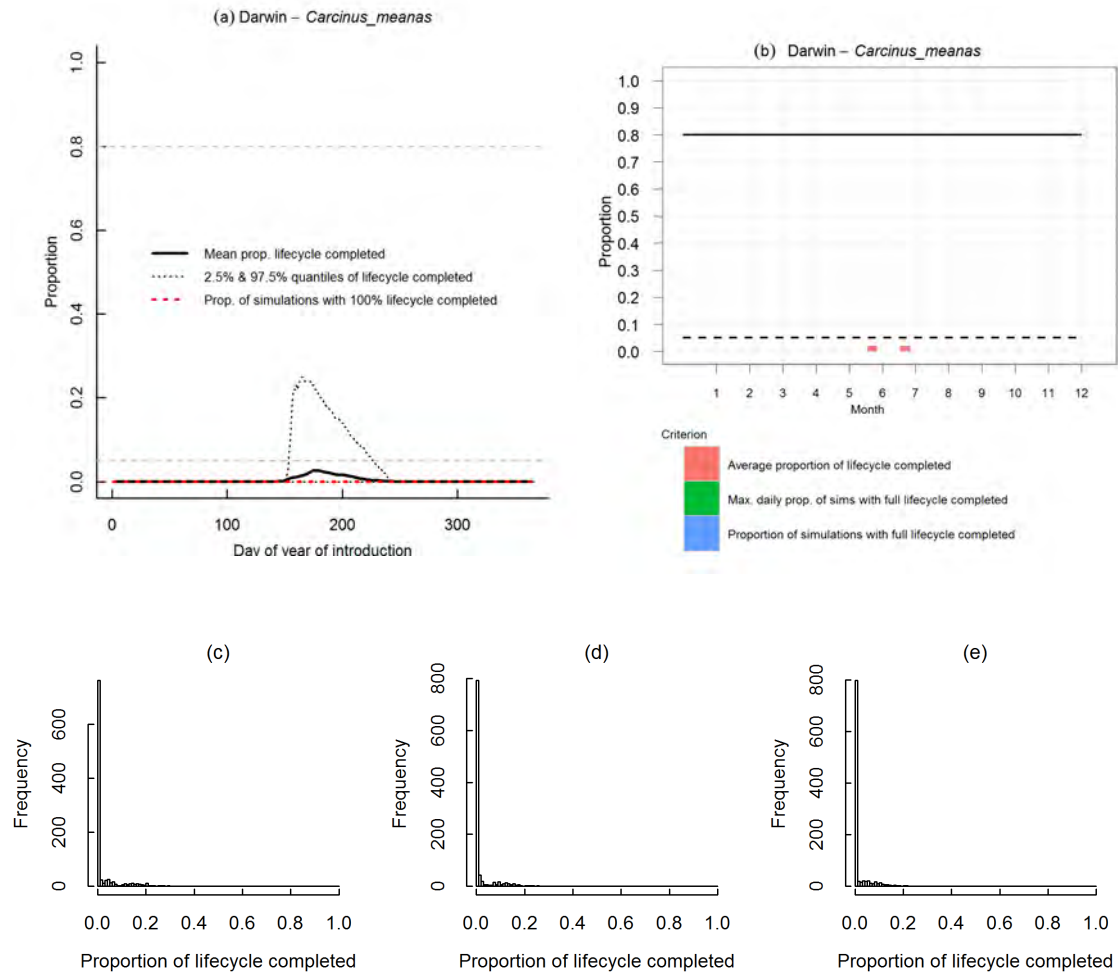

Figure B.24: Simulation results for lifecycle completion of *A. amurensis* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 120; (e) day 250.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.
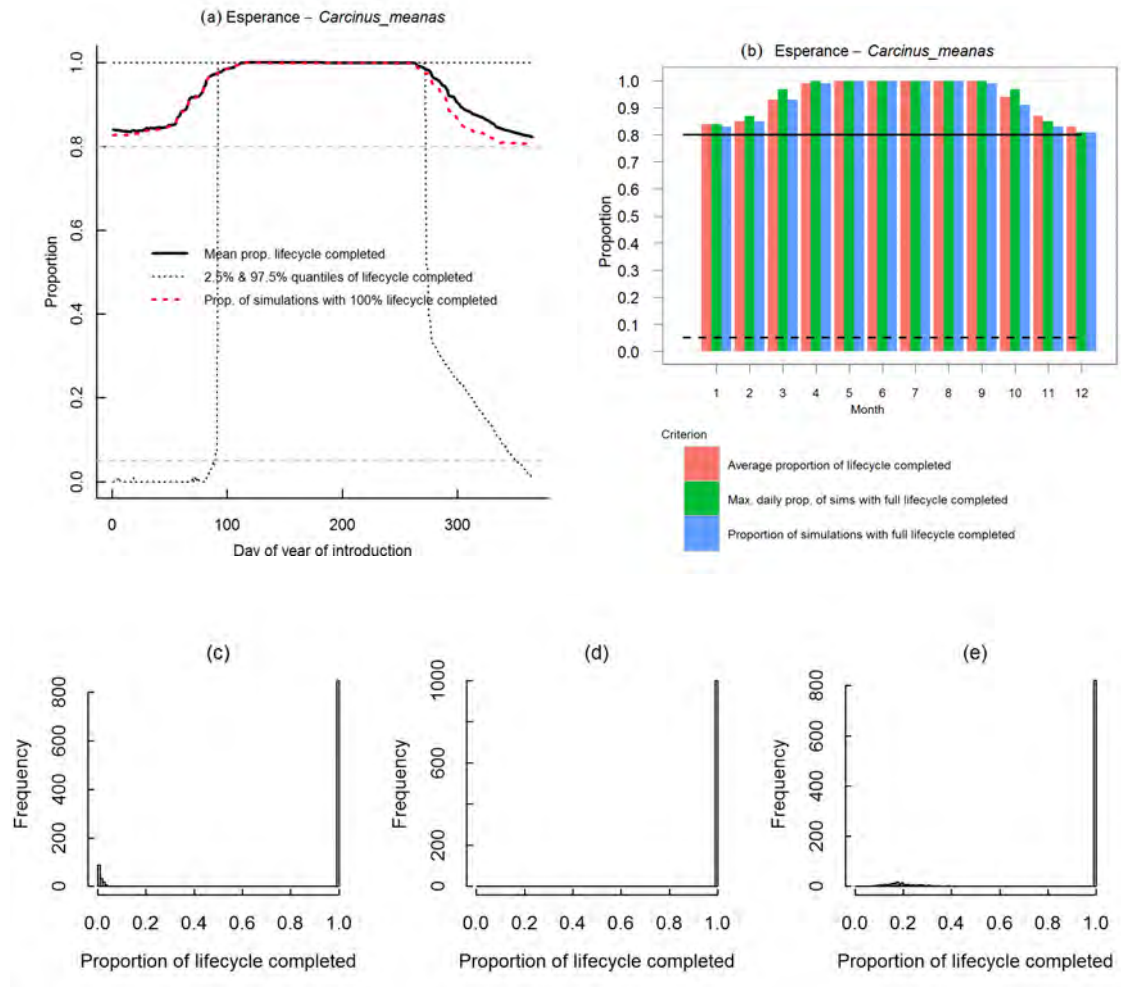

Figure B.25: Simulation results for lifecycle completion of *A. amurensis* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 150; (e) day 300.

Thevenard

Under the old rule, *A. amurensis* would be considered a risk of establishing in Thevenard from day 82 to day 268 (months April – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
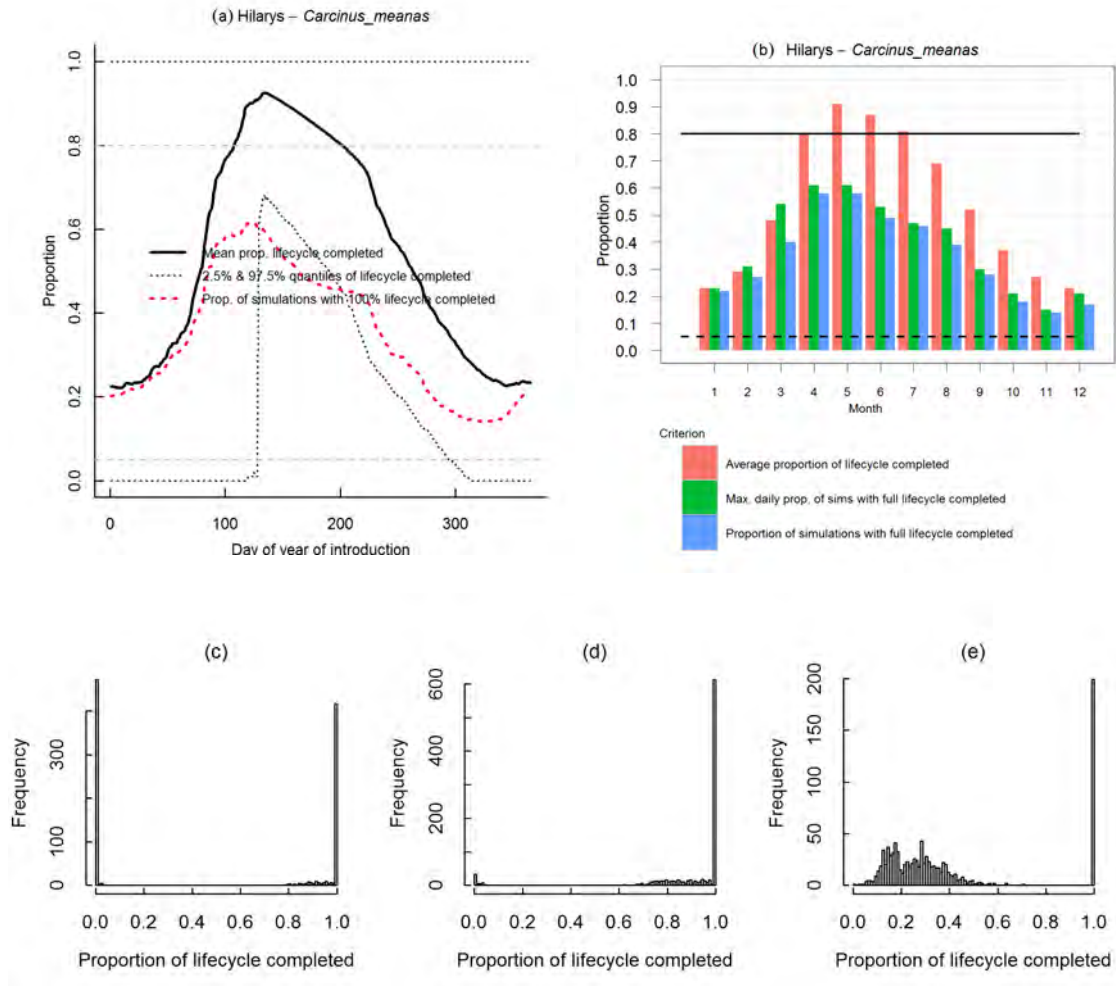

Figure B.26: Simulation results for lifecycle completion of *A. amurensis* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 110; (e) day 250.

B.2.2 *Carcinus meanas* - European Green Crab

Broome

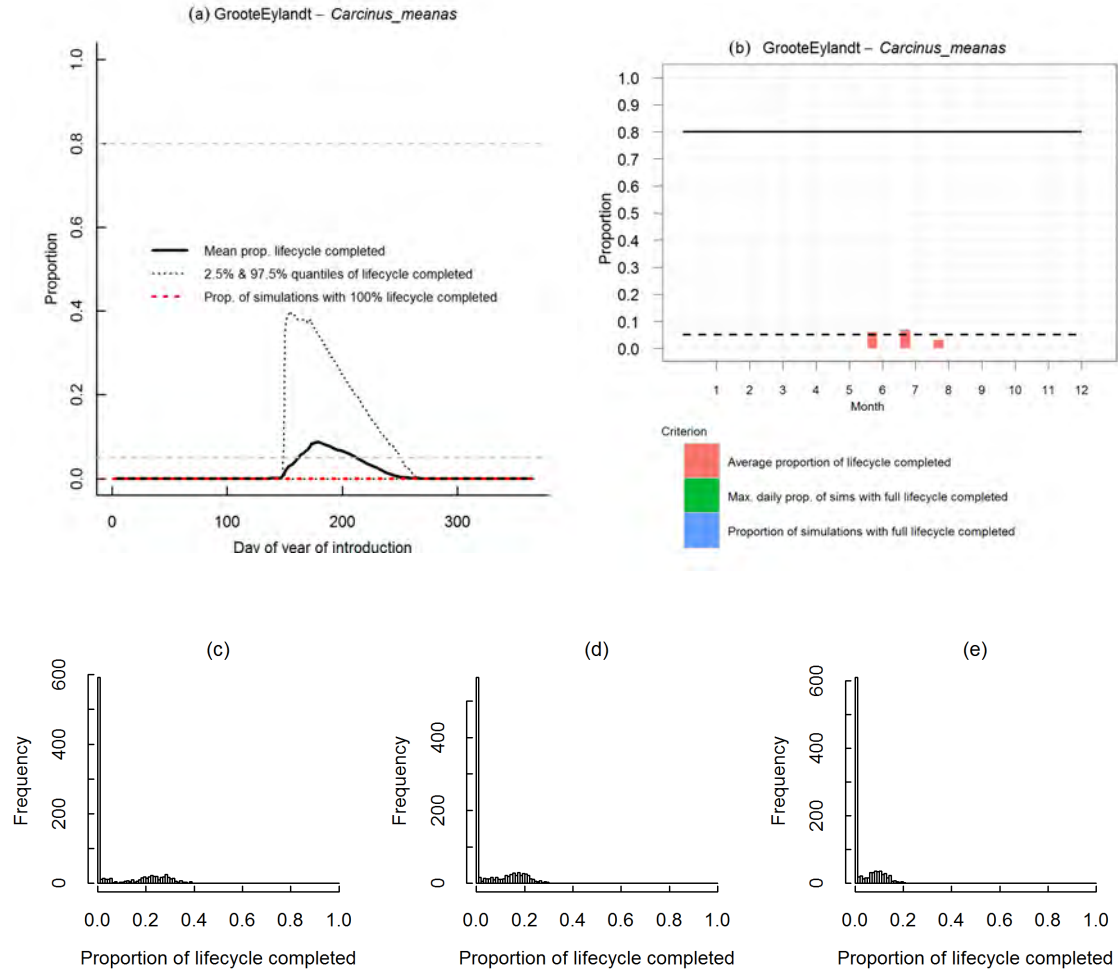In Broome establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.27: Simulation results for lifecycle completion of *C. meanas* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 140; (d) day 170; (e) day 220.

Burnie

In this case,

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.28: Simulation results for lifecycle completion of *C. meanas* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 340.

Cape Ferguson

In Cape Ferguson establishment would be considered unlikely throughout the year under the old rule and the new rule.
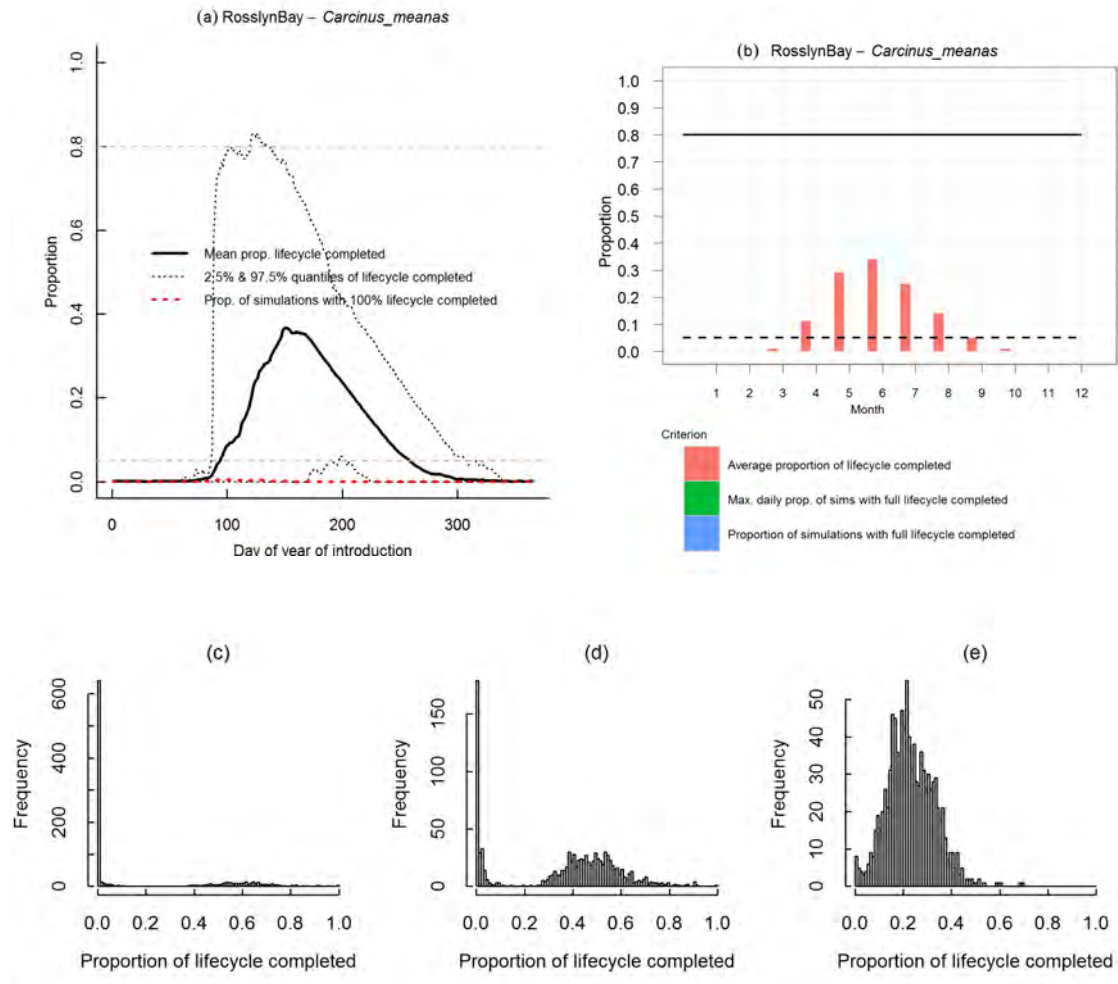

Figure B.29: Simulation results for lifecycle completion of *C. meanas* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 120; (d) day 190; (e) day 250.

Darwin

In Darwin establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.30: Simulation results for lifecycle completion of *C. meanas* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 180; (d) day 190; (e) day 200.

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.
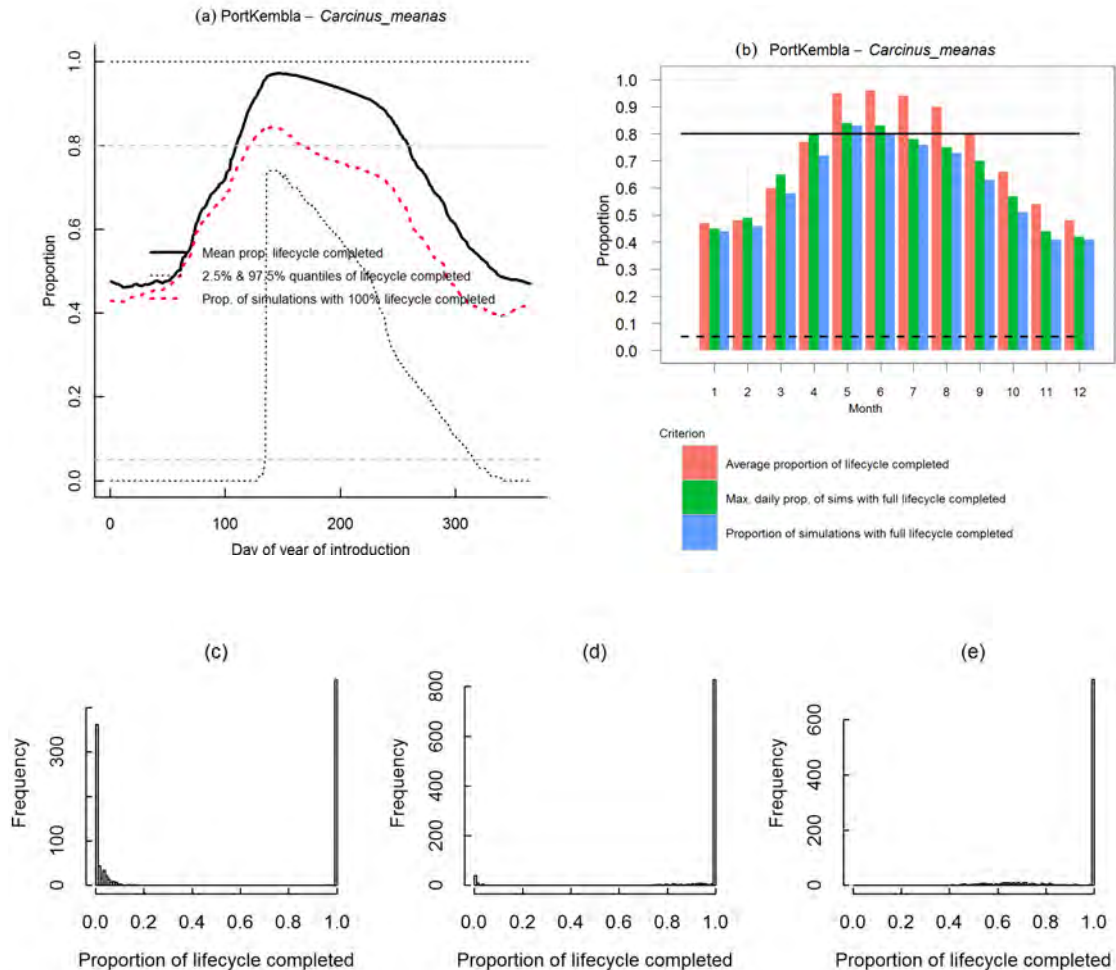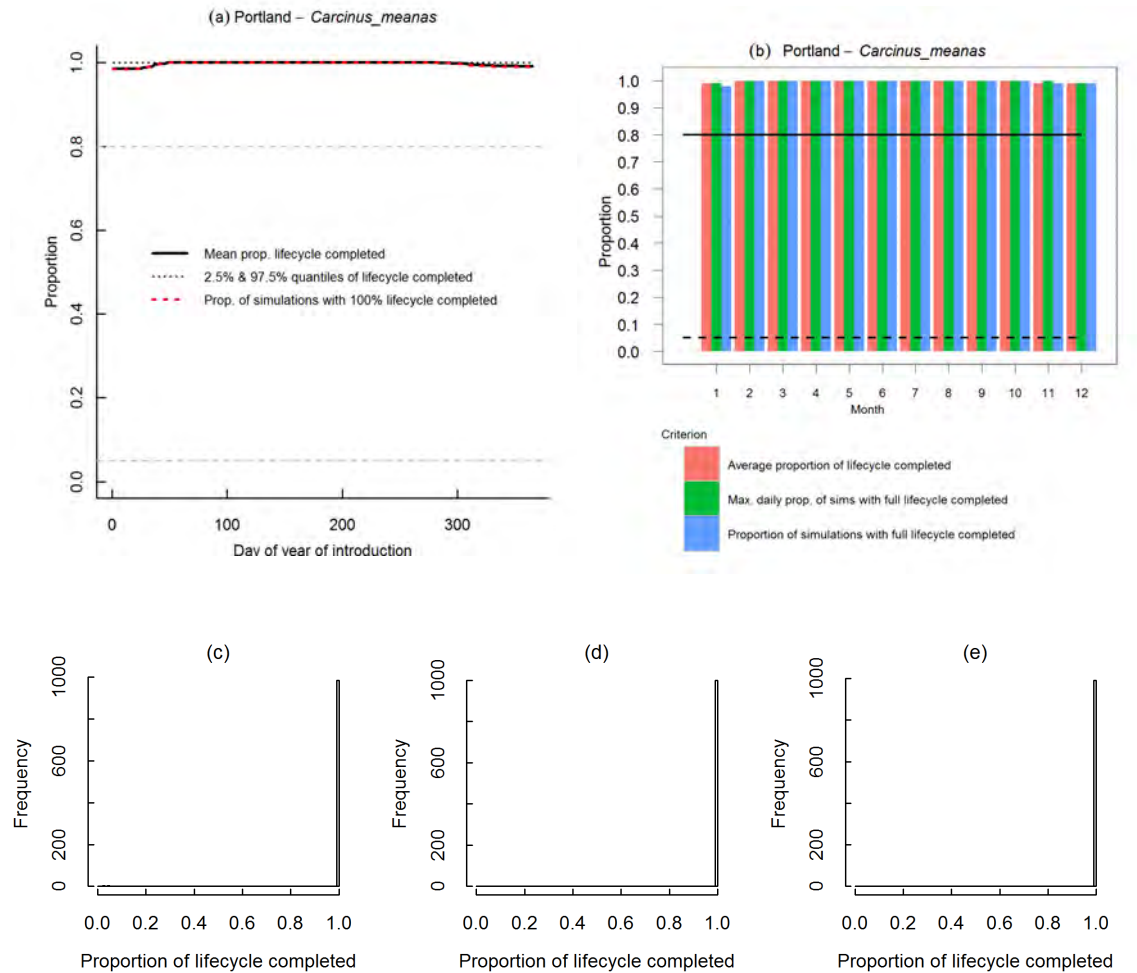

Figure B.31: Simulation results for lifecycle completion of *C. meanas* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 330.

Hilarys

Under the old rule, *C. meanas* would be considered a risk of establishing in Hilarys from day 108 to day 201 (months April - July), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.

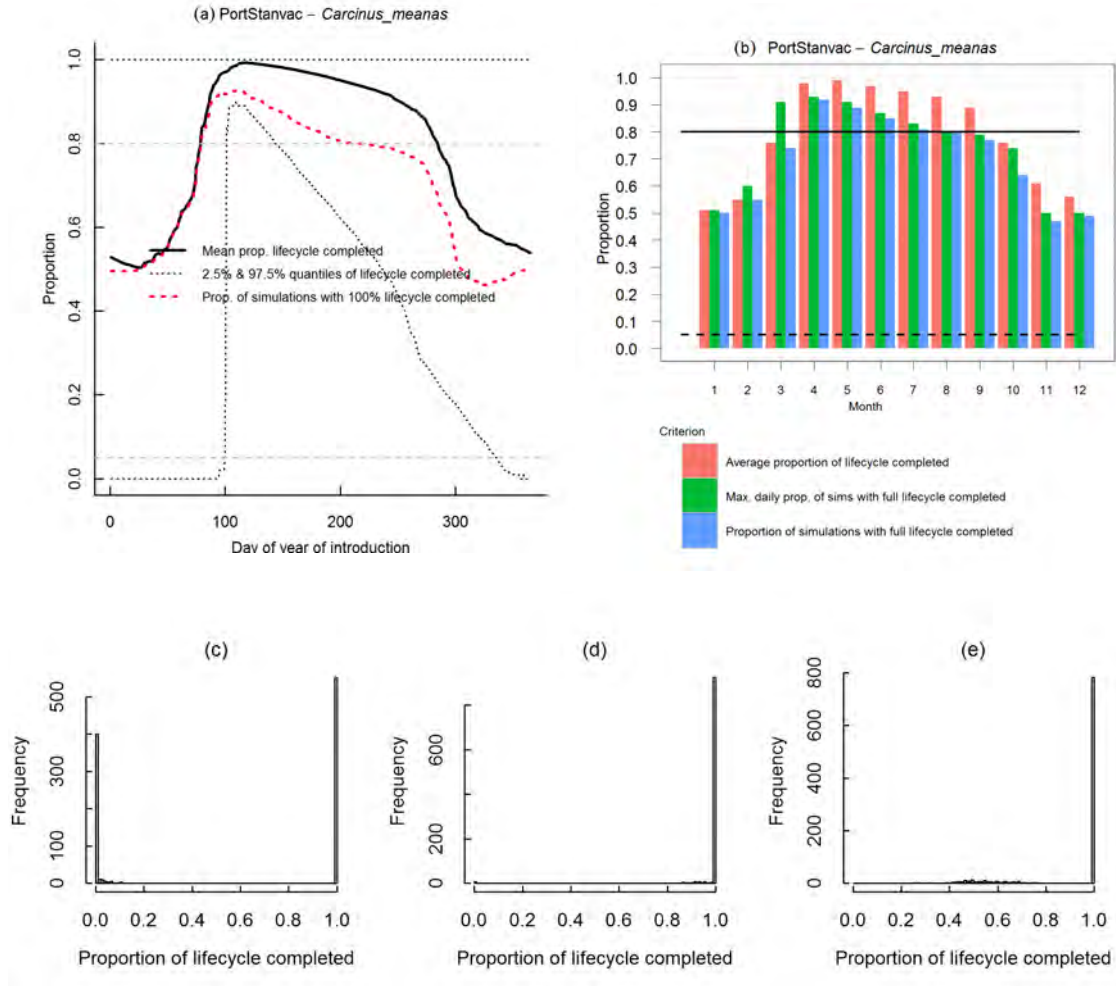

Figure B.32: Simulation results for lifecycle completion of *C. meanas* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 80; (d) day 120; (e) day 280.

Groote Eylandt

In Groote Eylandt establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.33: Simulation results for lifecycle completion of *C. meanas* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 180; (d) day 200; (e) day 220.

Rosslyn Bay

In Rosslyn Bay establishment would be considered unlikely throughout the year under the old rule and the new rule.
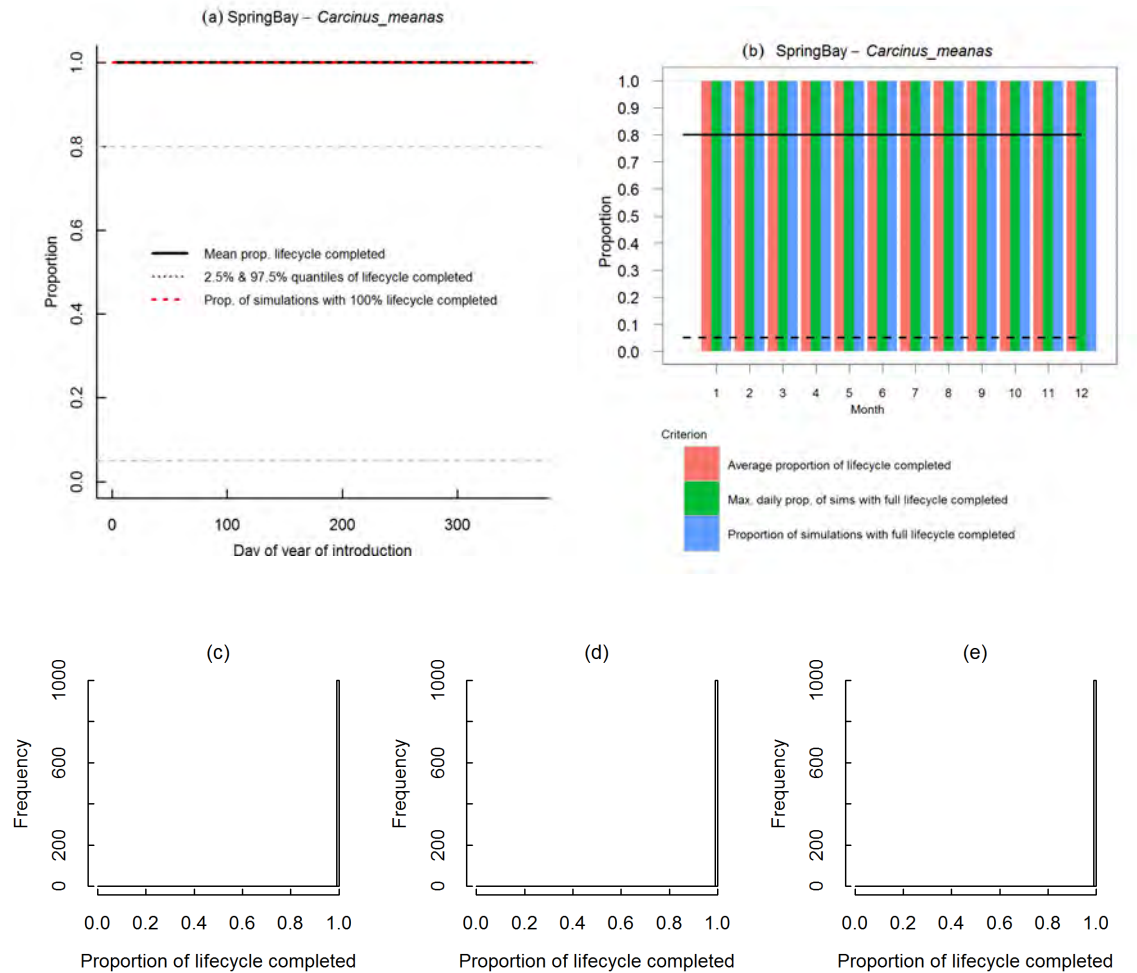

Figure B.34: Simulation results for lifecycle completion of *C. meanas* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 120; (d) day 150; (e) day 200.

Port Kembla

Under the old rule, *C. meanas* would be considered a risk of establishing in Port Kembla from day 110 to day 258 (months May - September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
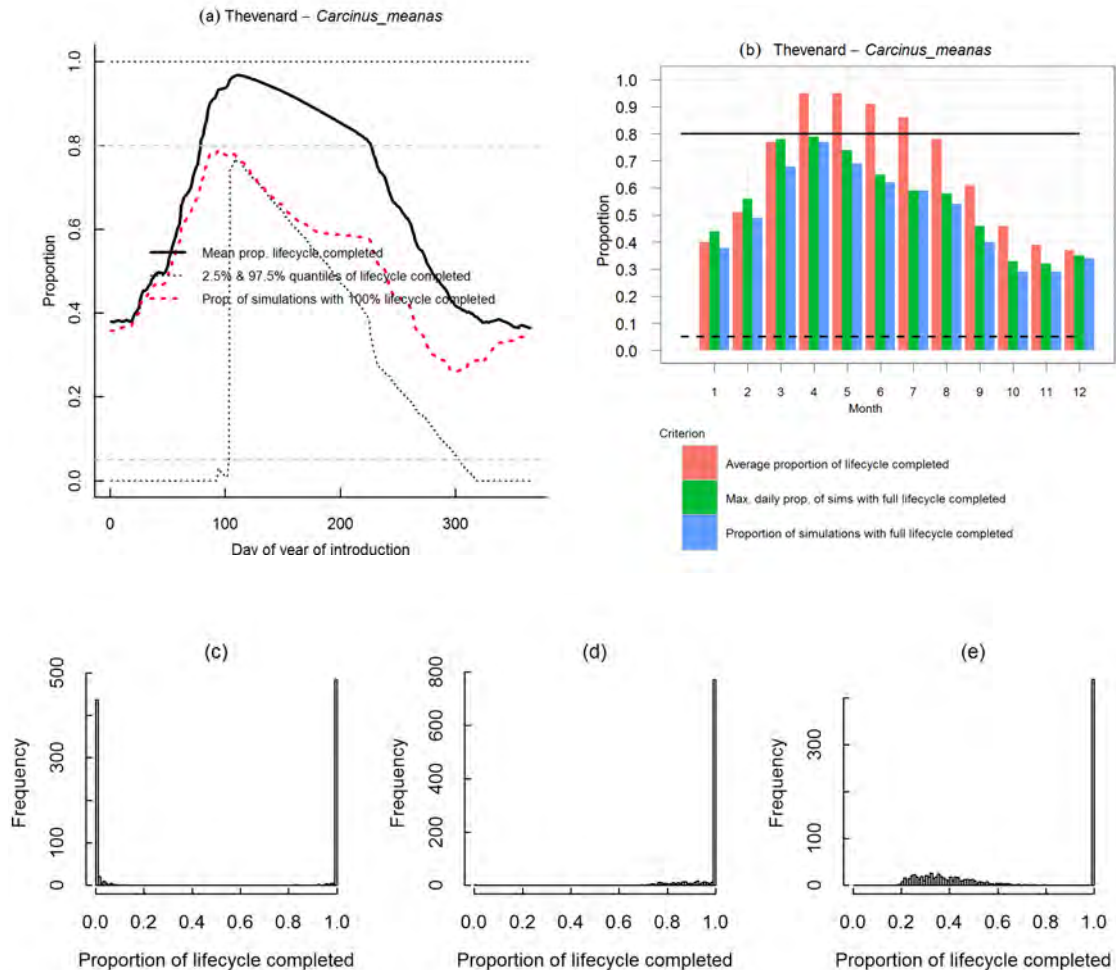

Figure B.35: Simulation results for lifecycle completion of *C. meanas* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 130; (e) day 220.

Portland

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.36: Simulation results for lifecycle completion of *C. meanas* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 330.

Port Stanvac

Under the old rule, *C. meanas* would be considered a risk of establishing in Port Stanvac from day 79 to day 284 (months April – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
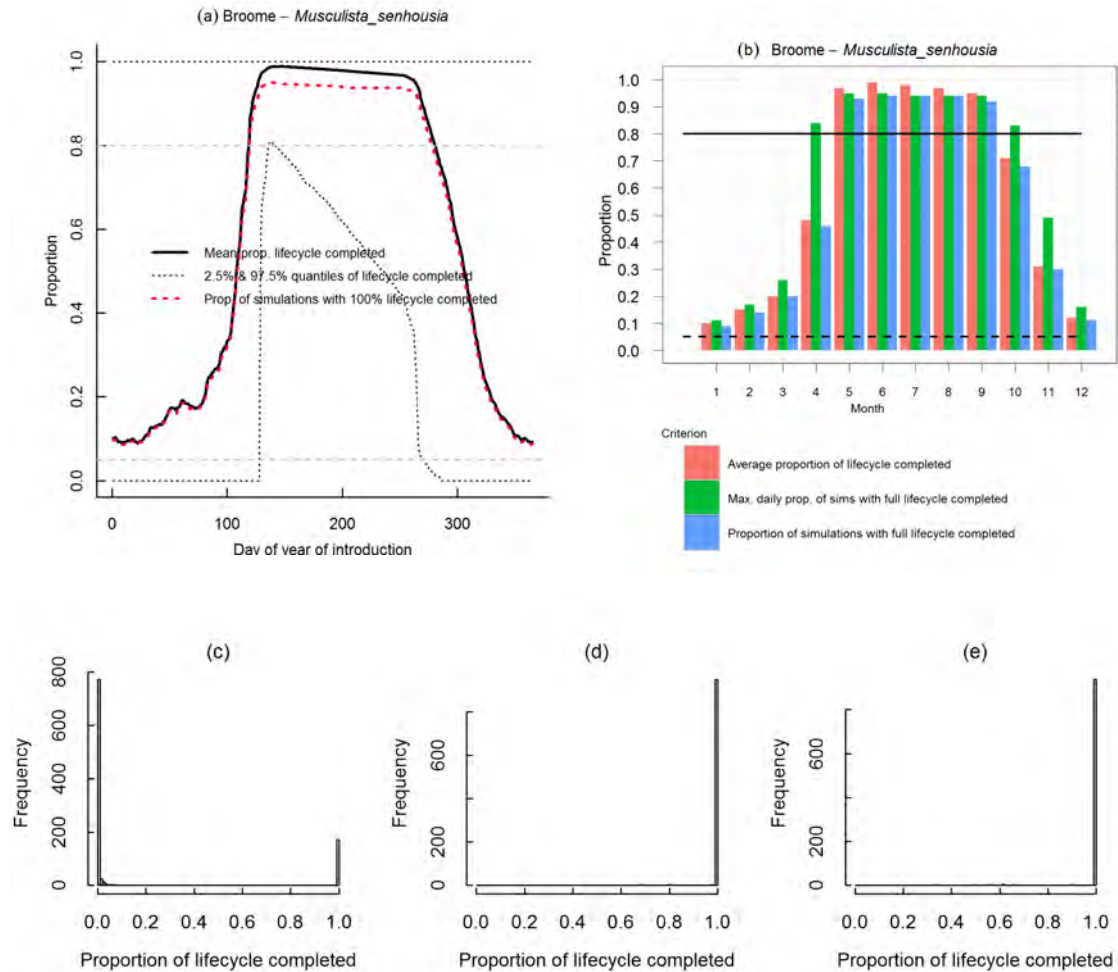

Figure B.37: Simulation results for lifecycle completion of *C. meanas* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 110; (e) day 250.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.
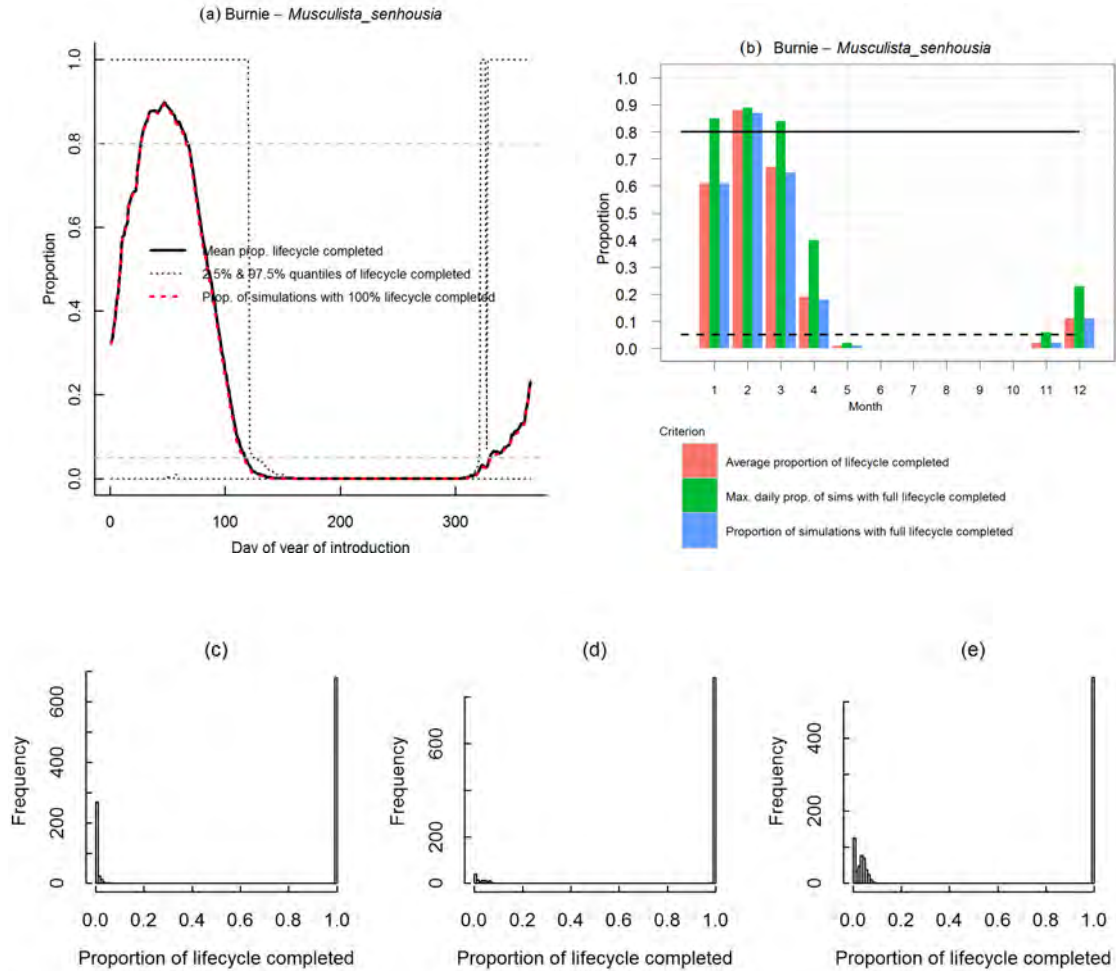

Figure B.38: Simulation results for lifecycle completion of *C. meanas* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 150; (e) day 320.

Thevenard

Under the old rule, *C. meanas* would be considered a risk of establishing in Thevenard from day 79 to day 226 (months April – July), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
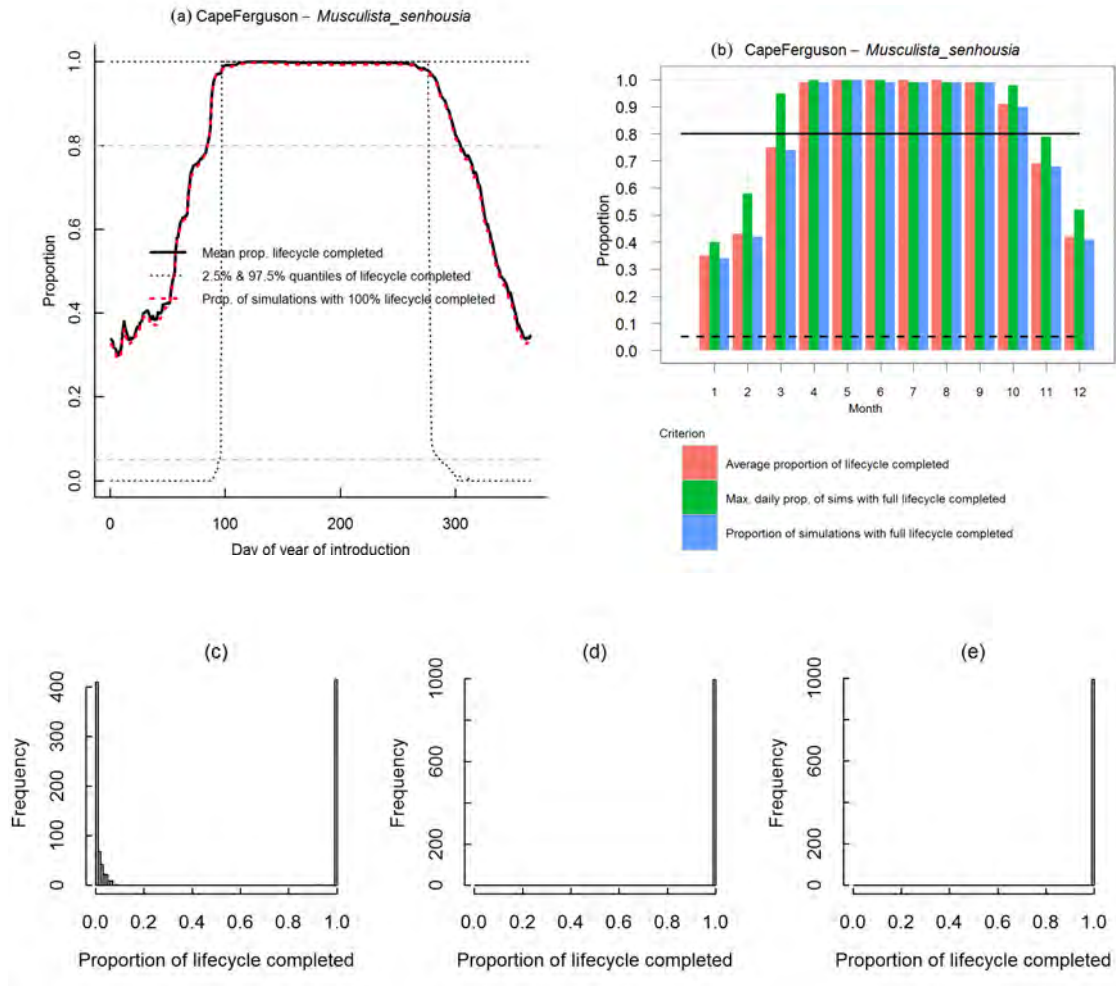

Figure B.39: Simulation results for lifecycle completion of *C. meanas* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 110; (e) day 250.

B.2.3 *Musculista senhousia* - Asian Date or Bag Mussel

Broome

Under the old rule, *M. senhousia* would be considered a risk of establishing in Broome from day 119 to day 280 (months May – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire period.
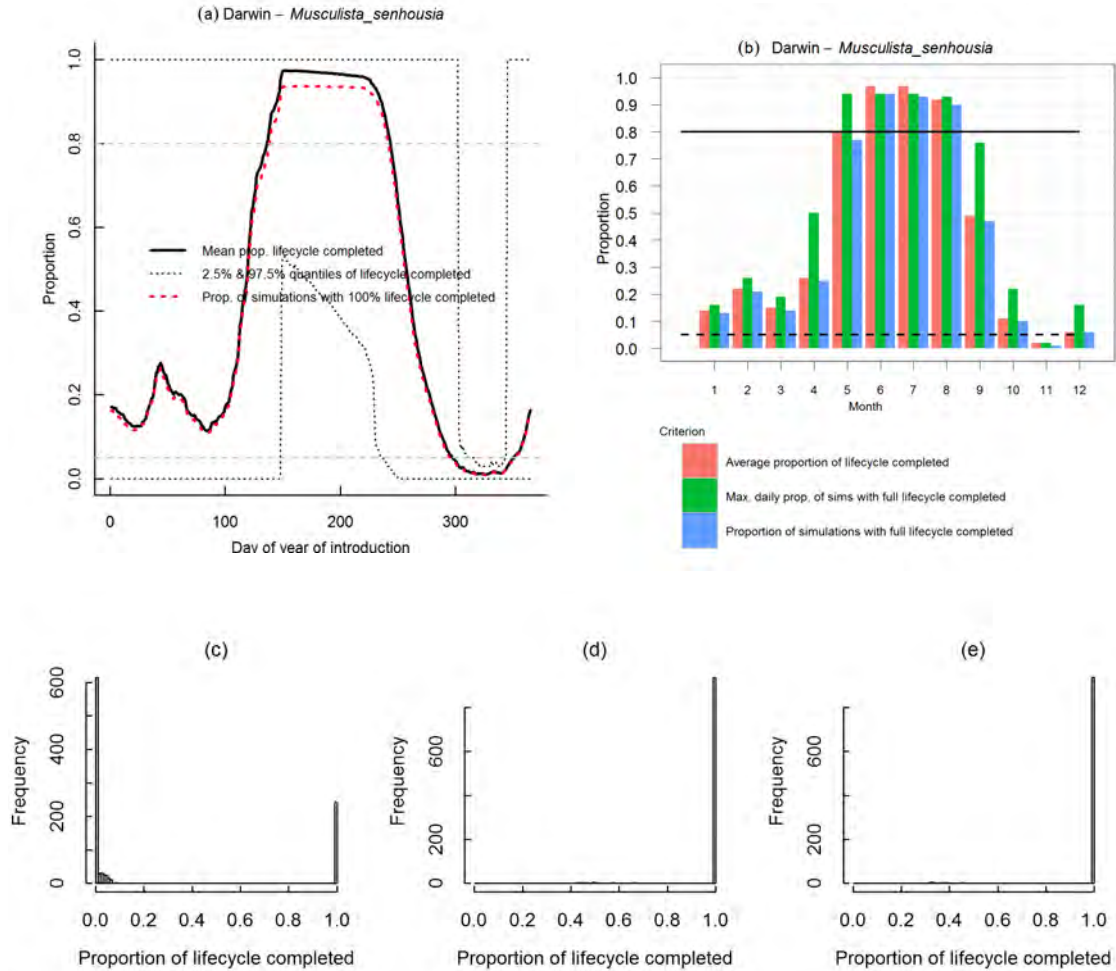

Figure B.40: Simulation results for lifecycle completion of *M. senhousia* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 75; (d) day 140; (e) day 220.

Burnie

Under the old rule, *M. senhousia* would be considered a risk of establishing in Burnie from day 27 to day 67 (February), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 330 to day 117 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule, this corresponds to November – April.

Figure B.41: Simulation results for lifecycle completion of *M. senhousia* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 50; (e) day 80.

Cape Ferguson

Under the old rule, *M. senhousia* would be considered a risk of establishing in Cape Ferguson from day 85 to day 304 (months April – October), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
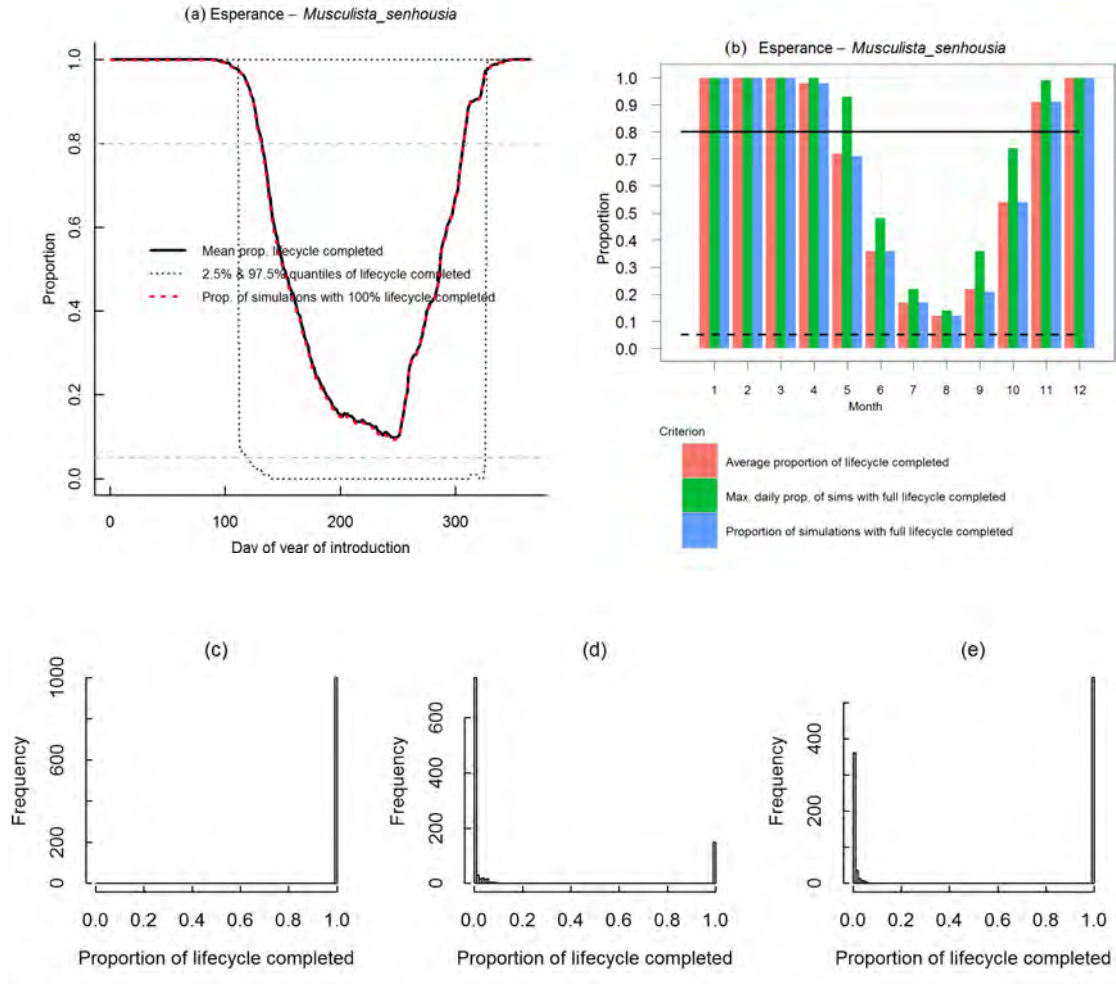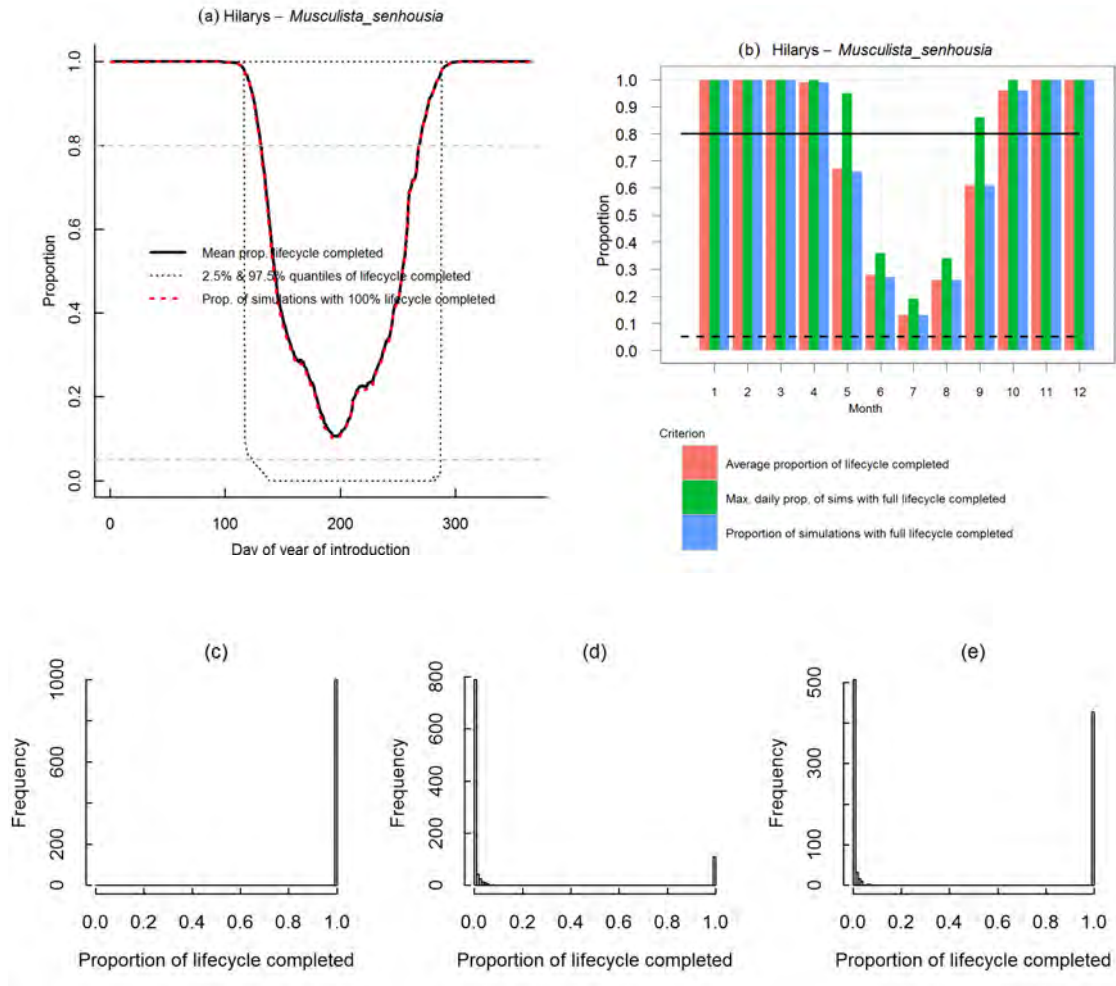

Figure B.42: Simulation results for lifecycle completion of *M. senhousia* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 150; (e) day 250.

Darwin

Under the old rule, *M. senhousia* would be considered a risk of establishing in Darwin from day 137 to day 243 (months May – August), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 351 to day 296 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to all months except November.

Figure B.43: Simulation results for lifecycle completion of *M. senhousia* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 40; (d) day 160; (e) day 200.

Esperance

Under the old rule, *M. senhousia* would be considered a risk of establishing in Esperance from day 306 to day 132 (months November – April), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
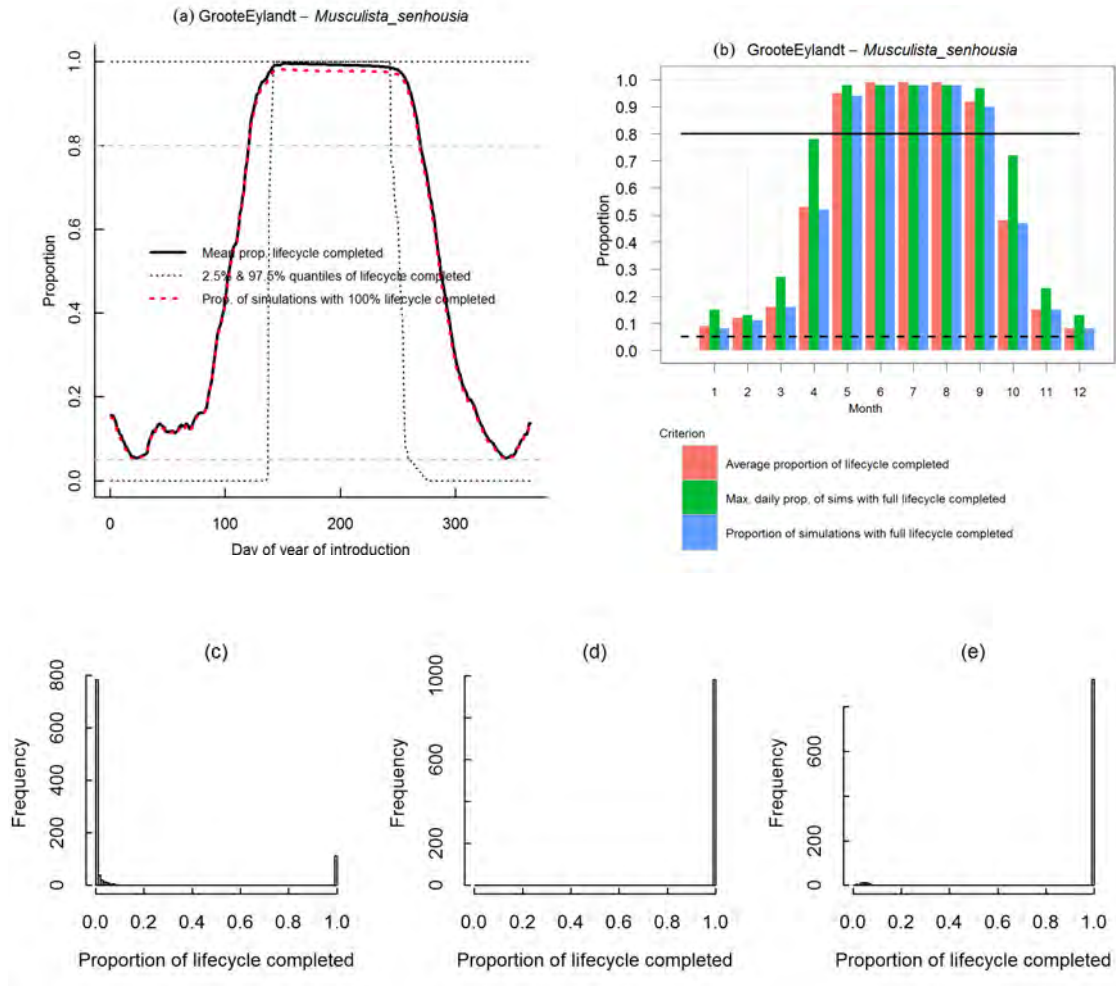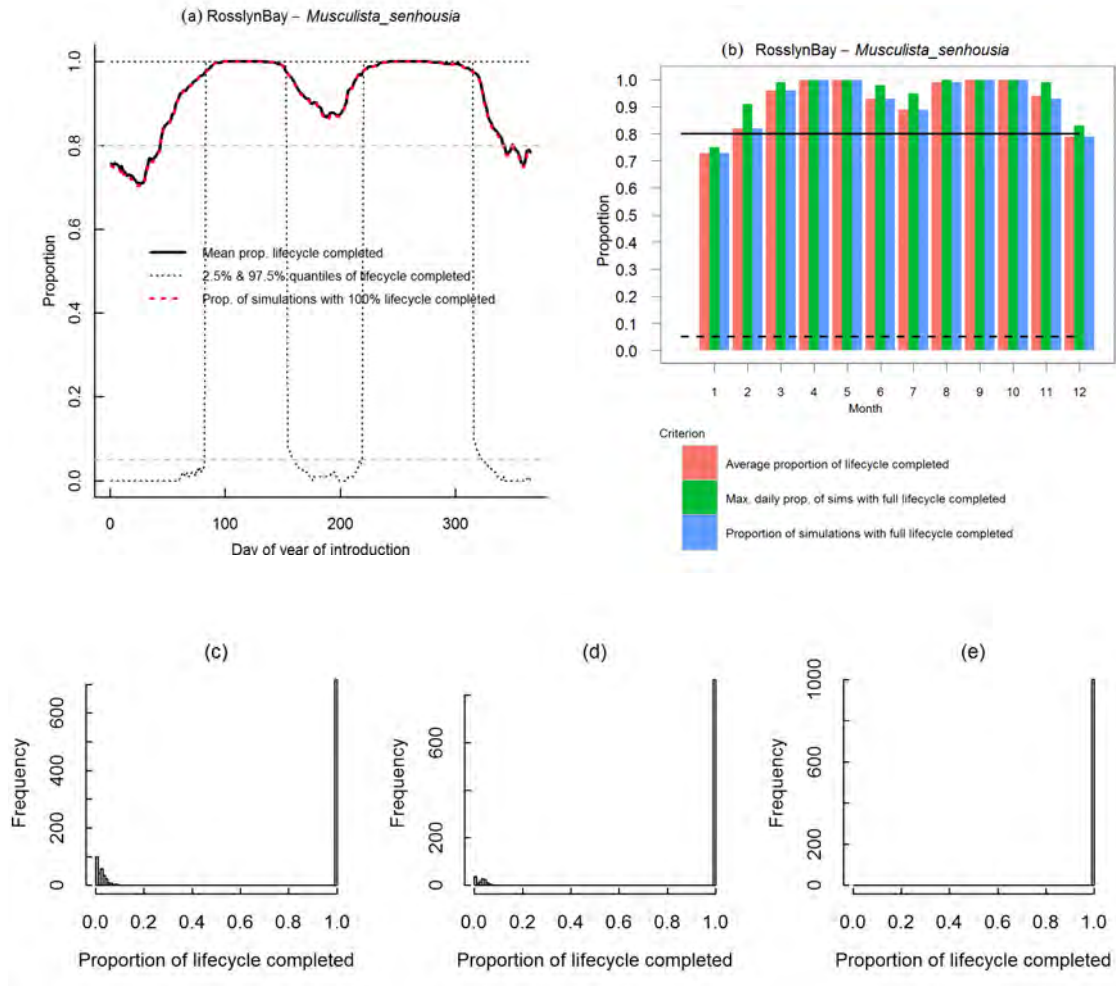

Figure B.44: Simulation results for lifecycle completion of *M. senhousia* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 290.

Hilarys

Under the old rule, *M. senhousia* would be considered a risk of establishing in Hilarys from day 268 to day 131 (months September – May), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.

Figure B.45: Simulation results for lifecycle completion of *M. senhousia* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 250.

Groote Eylandt

Under the old rule, *M. senhousia* would be considered a risk of establishing in Groote Eylandt from day 121 to day 269 (months May – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over most of the year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
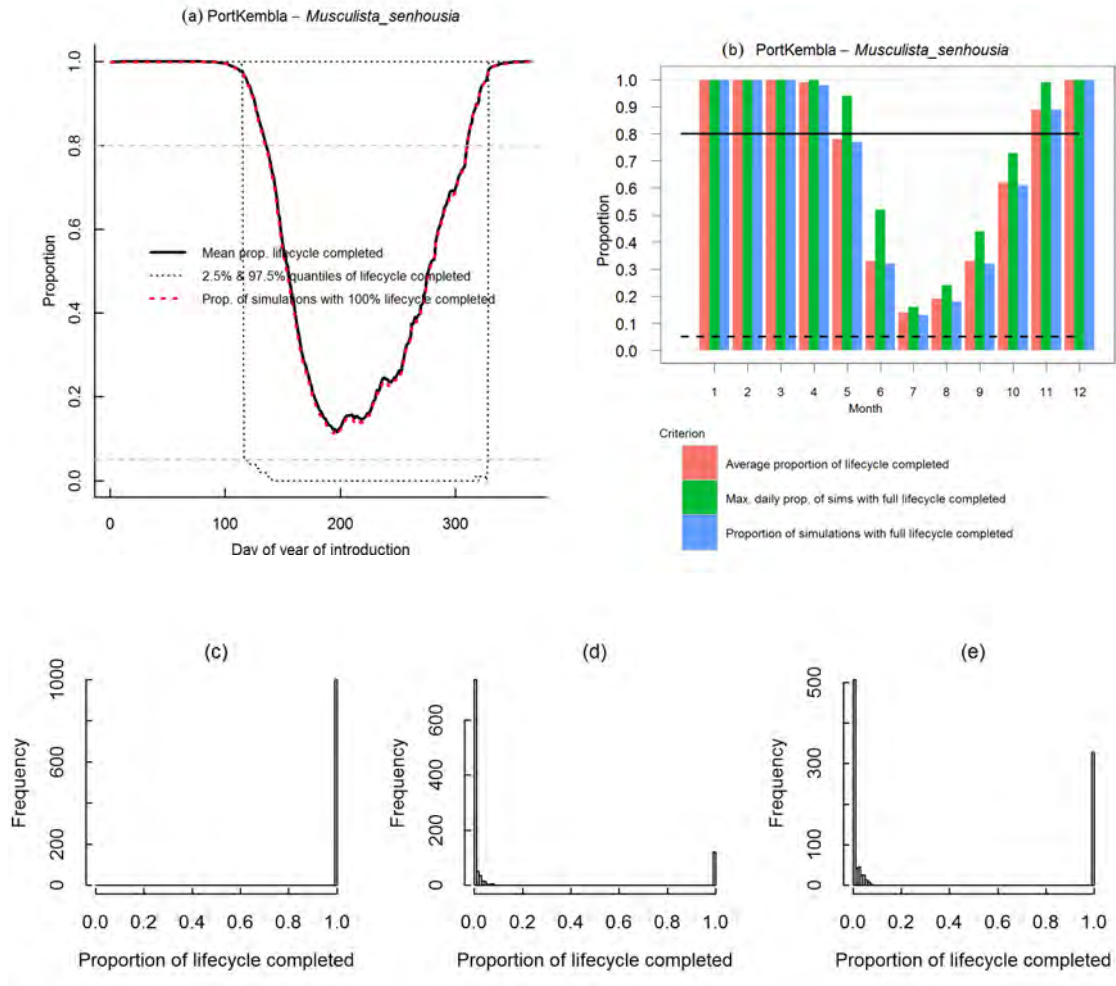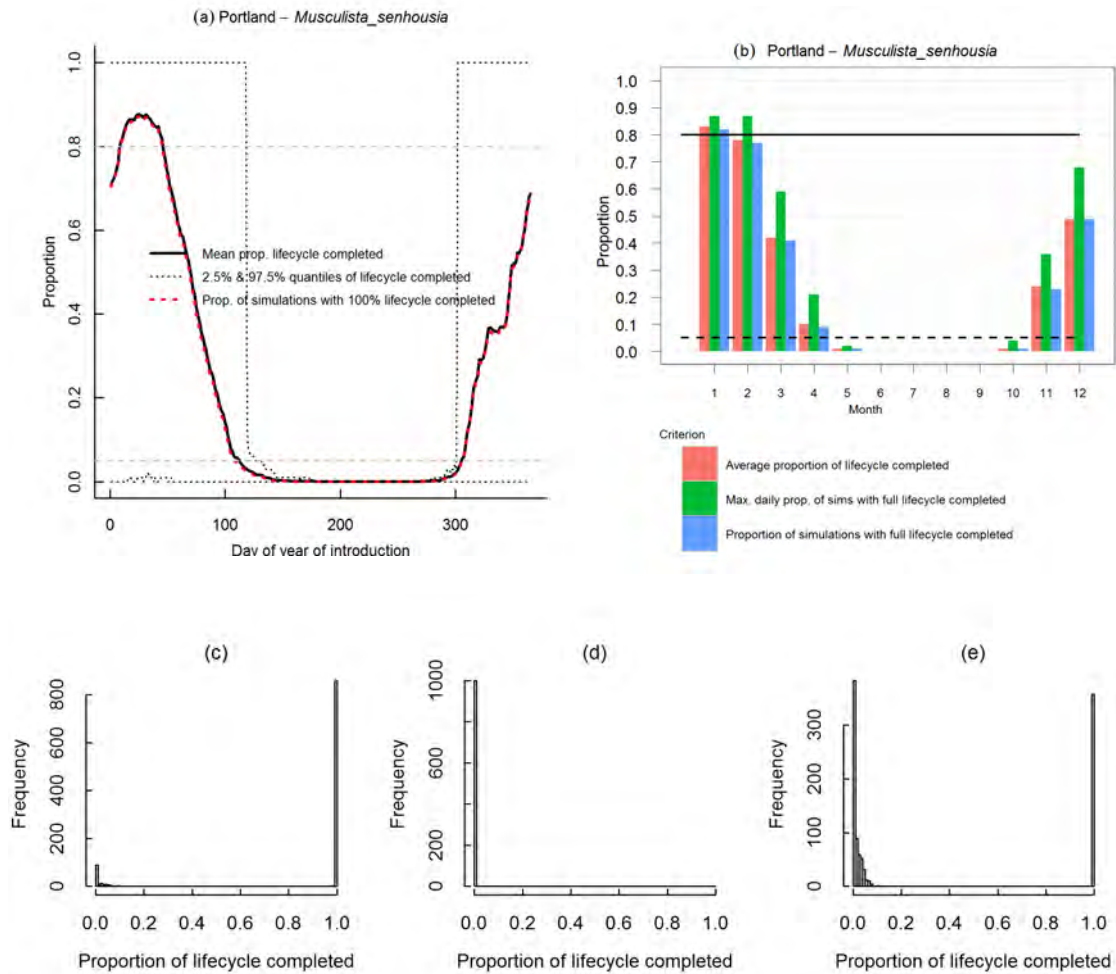

Figure B.46: Simulation results for lifecycle completion of *M. senhousia* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 150; (e) day 260.

Rosslyn Bay

Under the old rule, *M. senhousia* would be considered a risk of establishing in Rosslyn Bay from day 44 to day 350 (months February – November), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.

Figure B.47: Simulation results for lifecycle completion of *M. senhousia* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 190; (e) day 250.

Port Kembla

Under the old rule, *M. senhousia* would be considered a risk of establishing in Port Kembla from day 309 to day 136 (months November – April), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.

Figure B.48: Simulation results for lifecycle completion of *M. senhousia* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 260.

83

Portland

Under the old rule, *M. senhousia* would be considered a risk of establishing in Portland from day 9 to day 45 (January), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 305 to day 108 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to November – April.
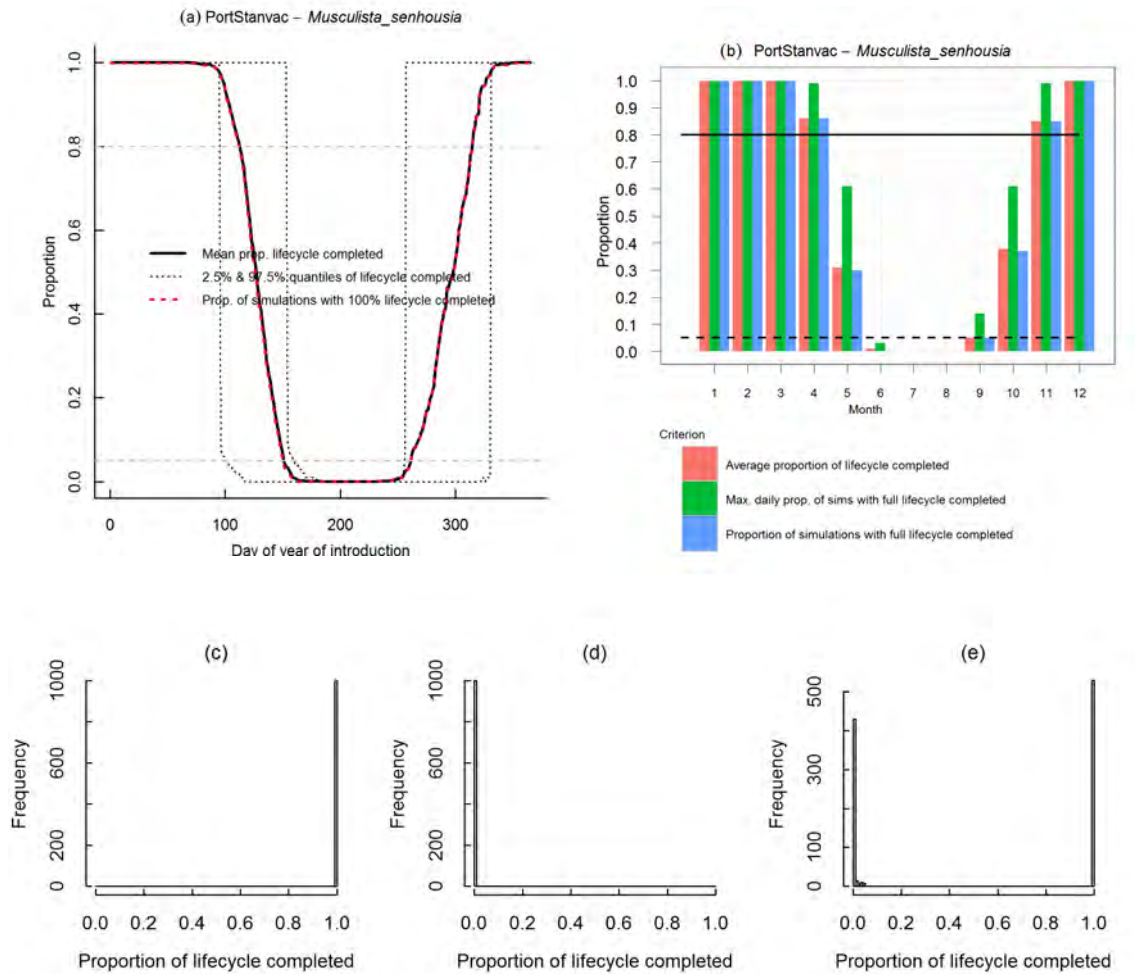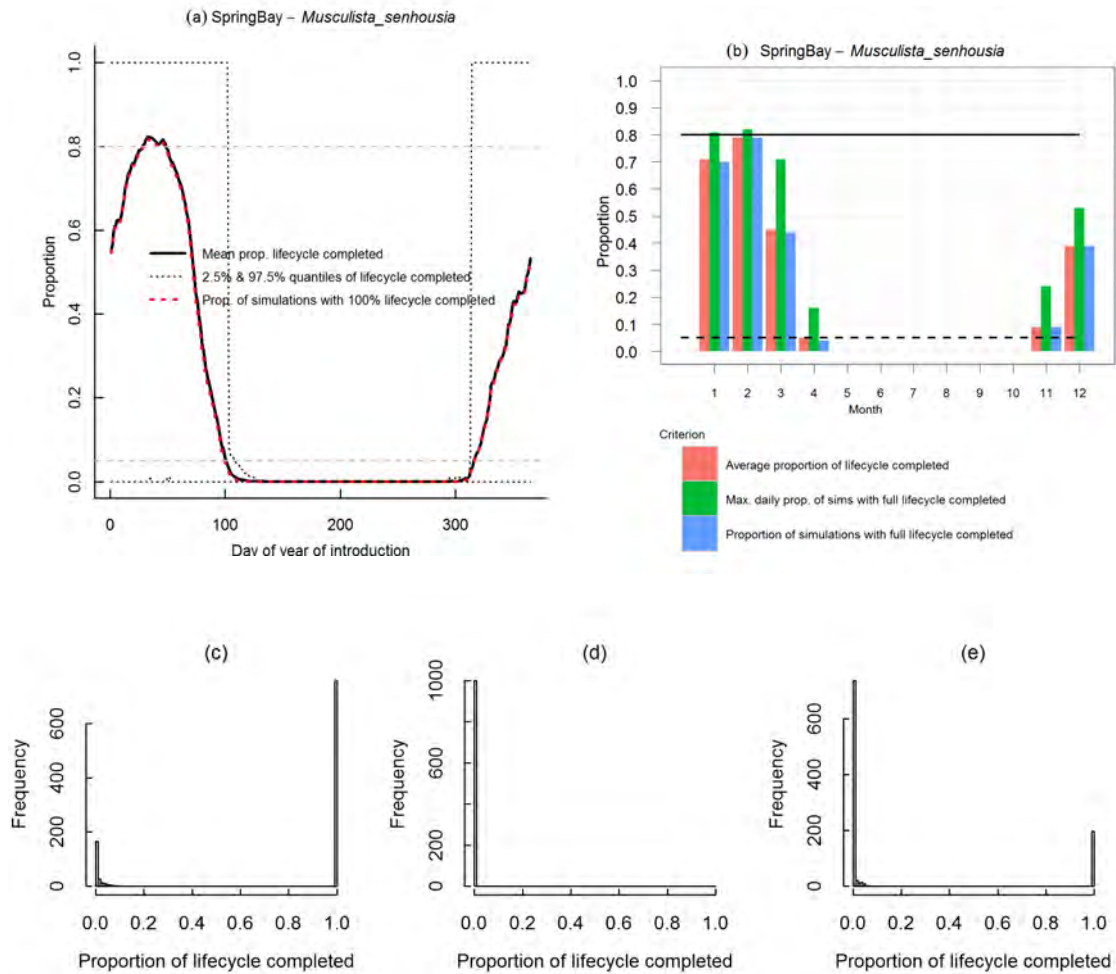

Figure B.49: Simulation results for lifecycle completion of *M. senhousia* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 330.

Port Stanvac

Under the old rule, *M. senhousia* would be considered a risk of establishing in Port Stanvac from day 314 to day 113 (months November – April), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 261 to day 151 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to September – May.
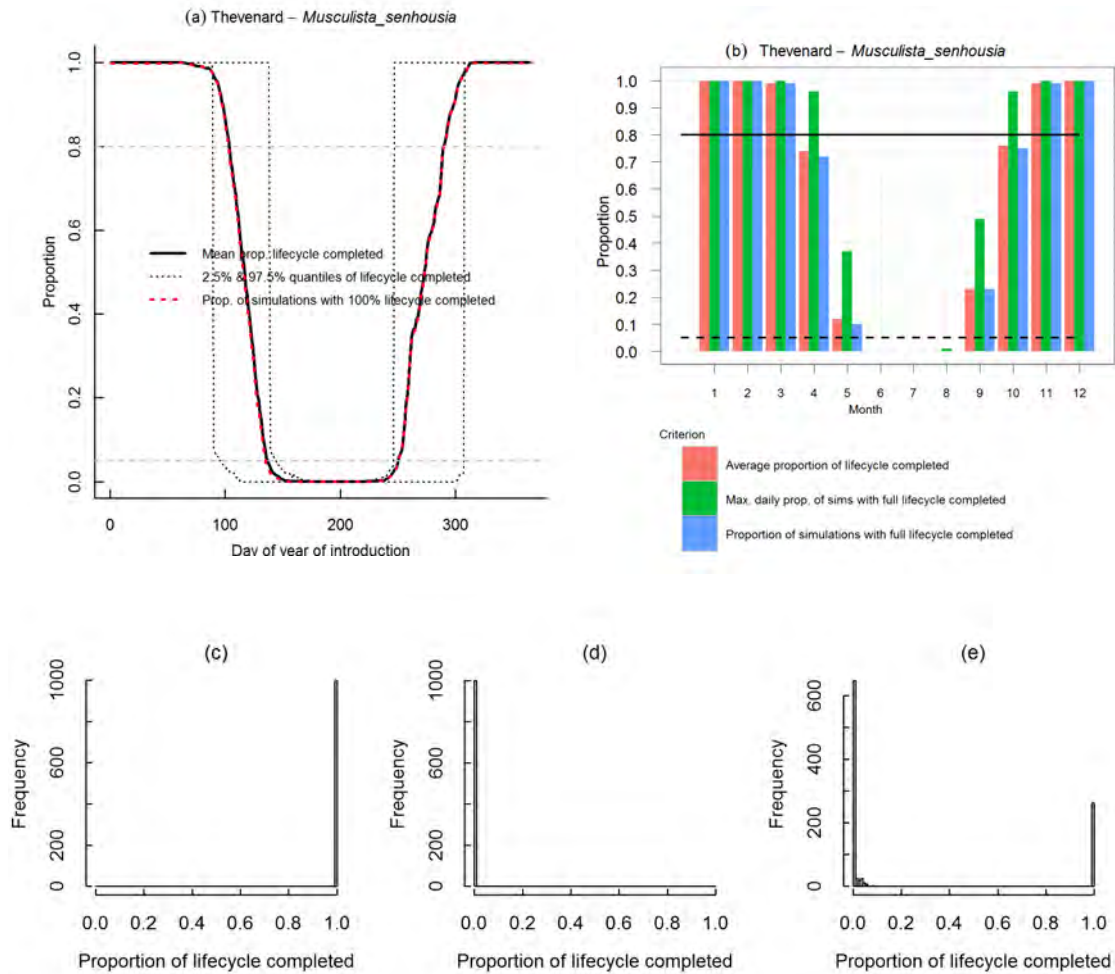

Figure B.50: Simulation results for lifecycle completion of *M. senhousia* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Spring Bay

Under the old rule, *M. senhousia* would be considered a risk of establishing in Spring Bay from day 28 to day 48, with the average proportion of lifecycle completed over that period greater than 0.8, but under the old monthly rule there were no months with likelihood of establishment. Under the new rule, we see that from day 316 to day 100 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to November – April.
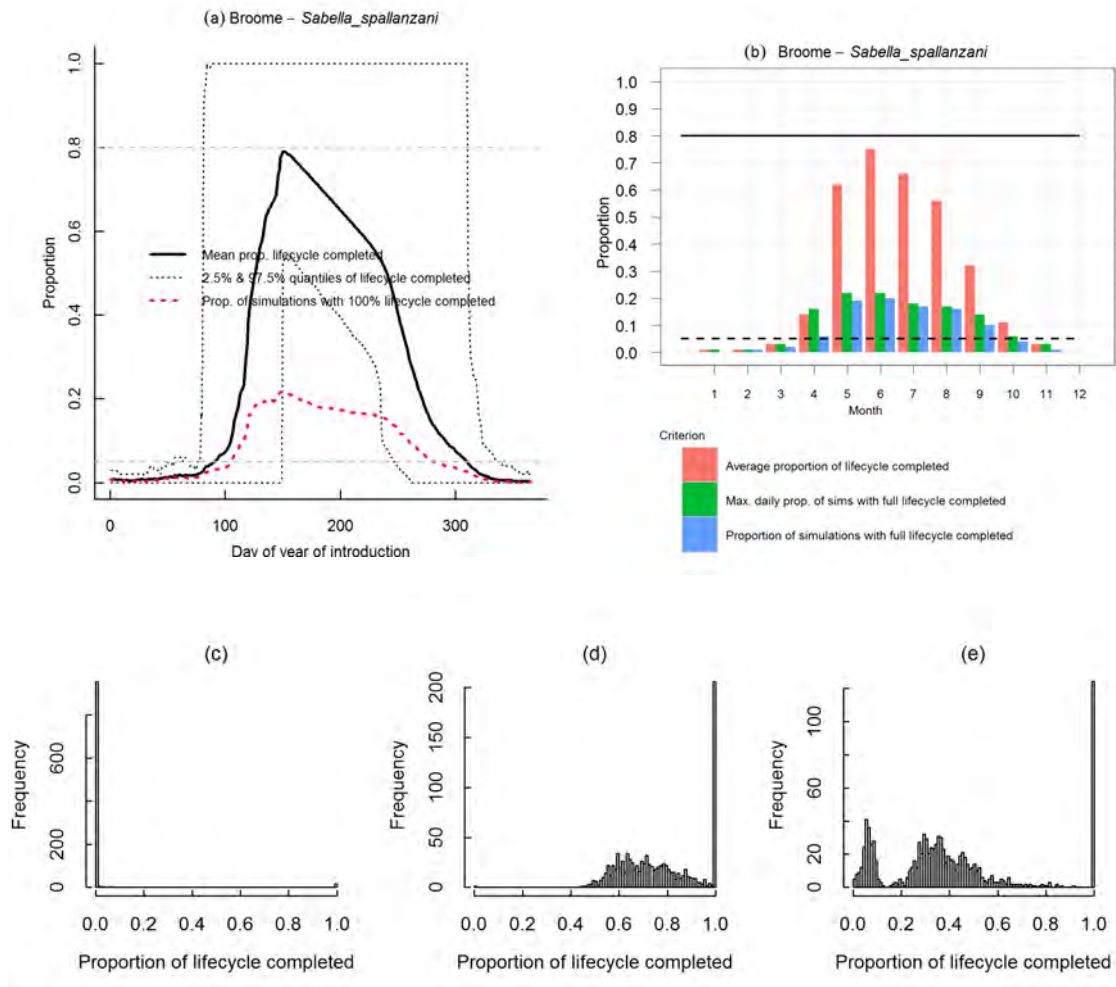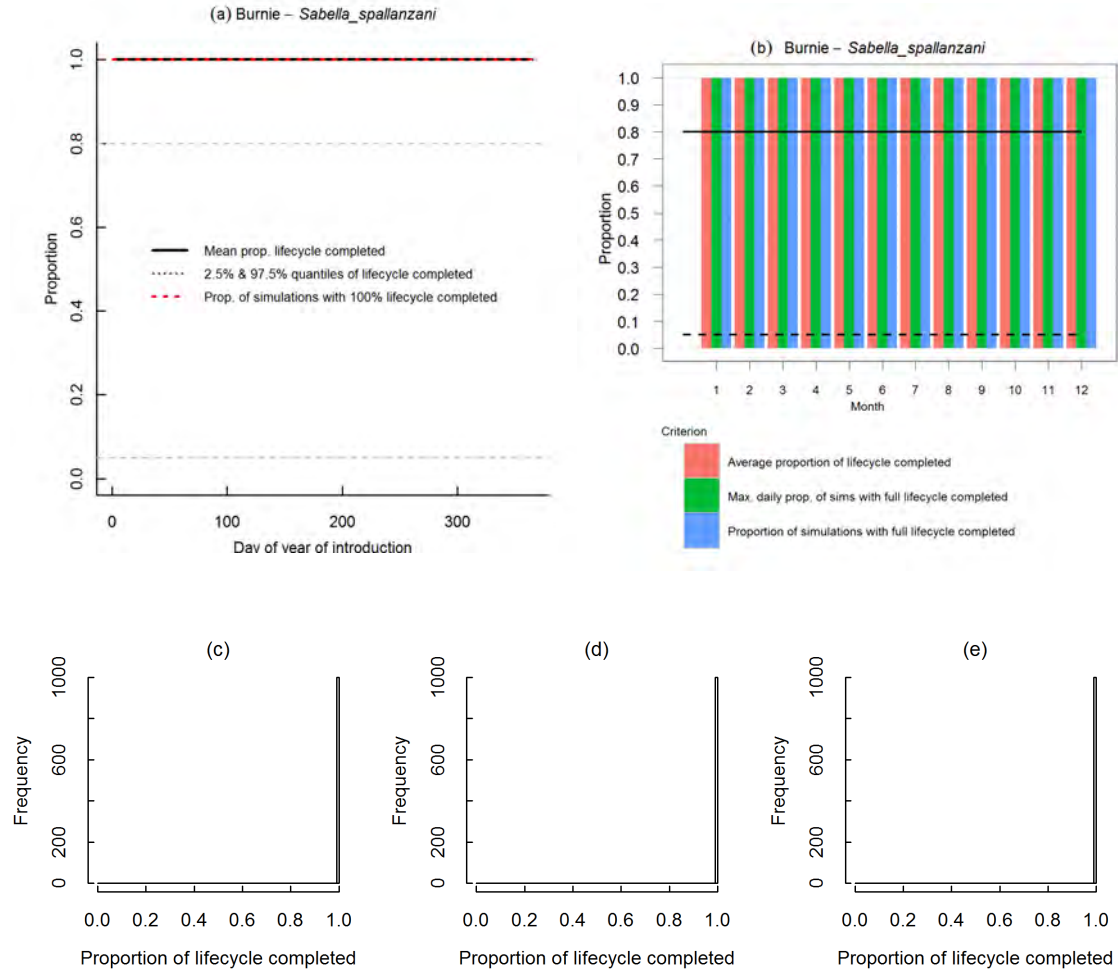

Figure B.51: Simulation results for lifecycle completion of *M. senhousia* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 330.

Thevenard

Under the old rule, *M. senhousia* would be considered a risk of establishing in Thevenard from day 289 to day 104 (months November – March), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 250 to day 136 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to September – May.
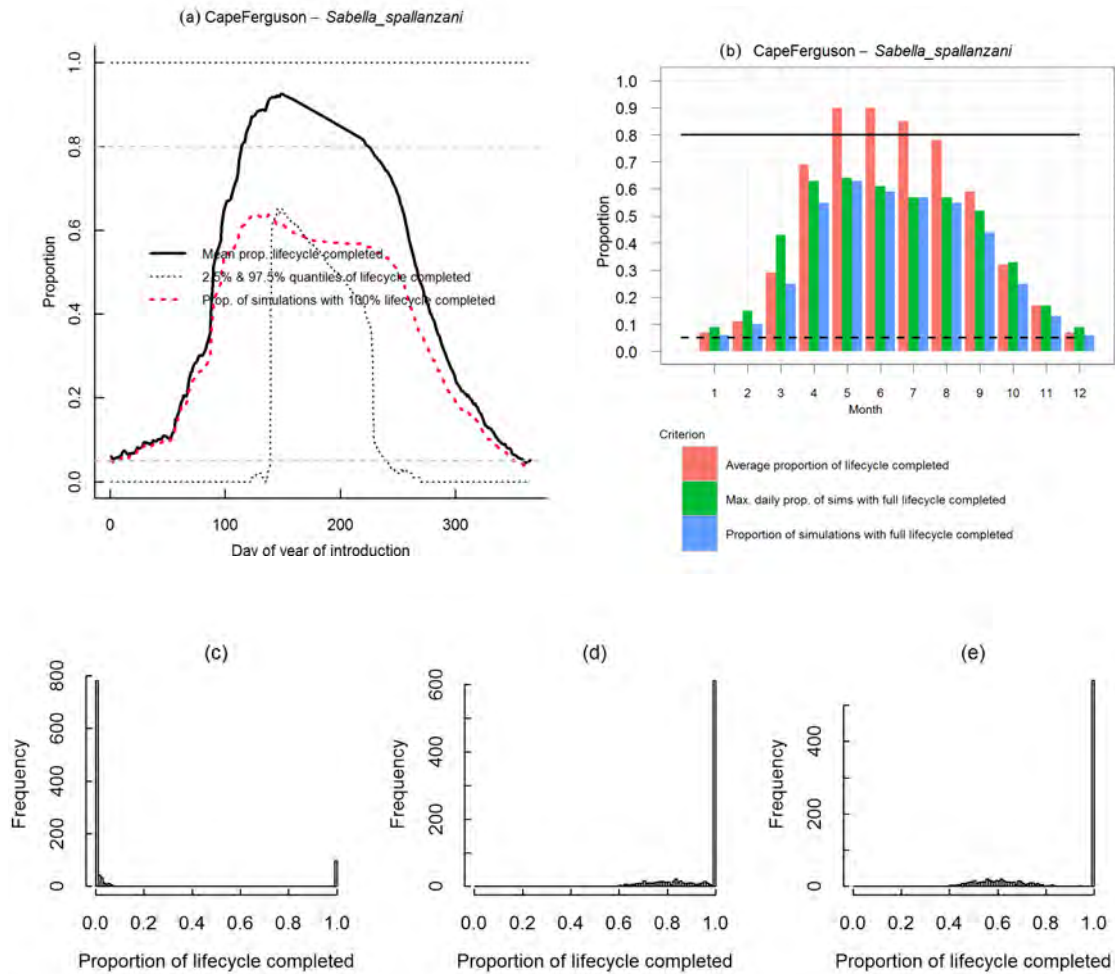

Figure B.52: Simulation results for lifecycle completion of *M. senhousia* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 260.

B.2.4 *Sabella spallanzani* - European Featherduster Worm

Broome

Under the old rule, *S. spallanzani* would never be considered a risk of establishing in Broome, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 106 to day 279 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to April – October. We also see that at day 160 a number of additional simulations also get close to 100% of the lifecycle completed.

Figure B.53: Simulation results for lifecycle completion of *S. spallanzani* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 80; (d) day 160; (e) day 250.

Burnie

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.
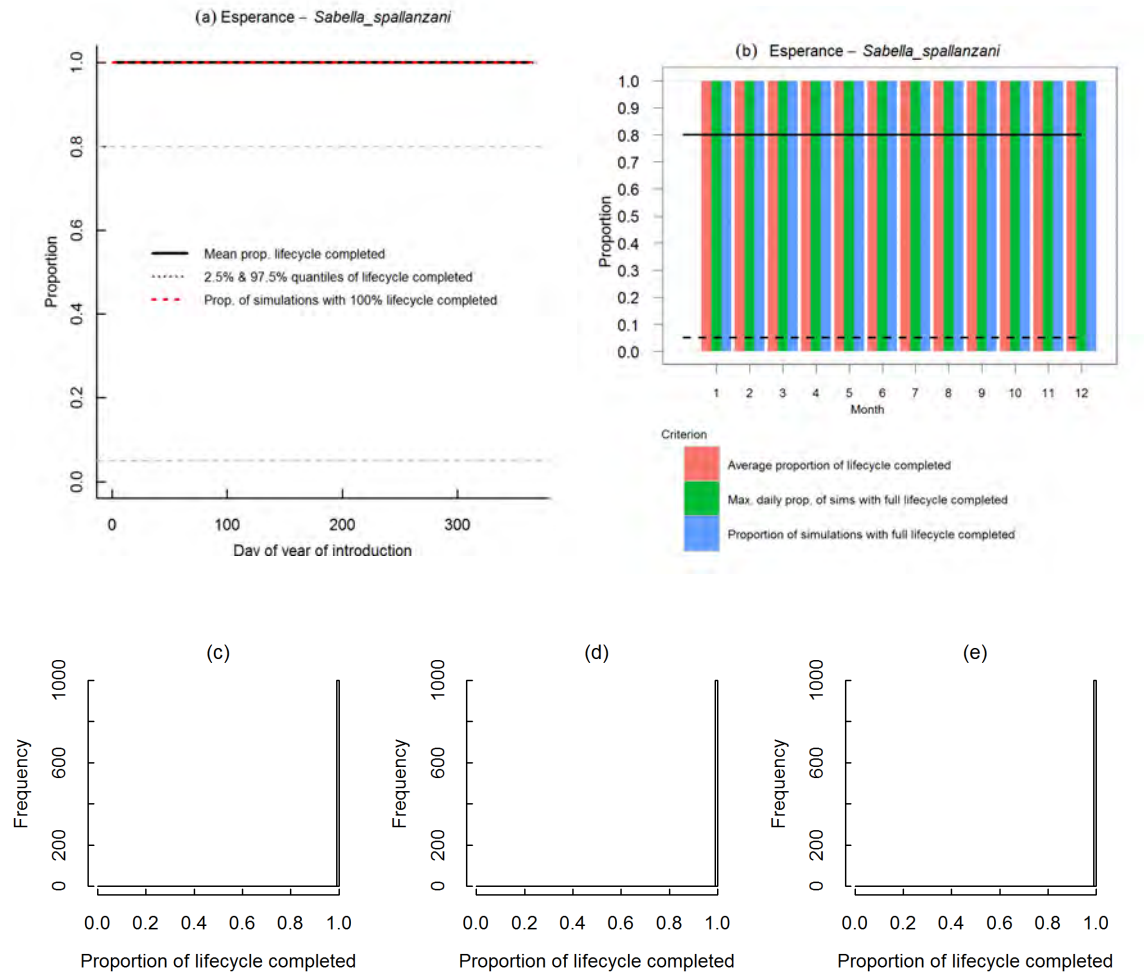

Figure B.54: Simulation results for lifecycle completion of *S. spallanzani* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 300.

Cape Ferguson

Under the old rule, *S. spallanzani* would be considered a risk of establishing in Cape Ferguson from day 115 to day 224 (months May – July), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 1 to day 350 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. This corresponds to the entire year for the new monthly rule.
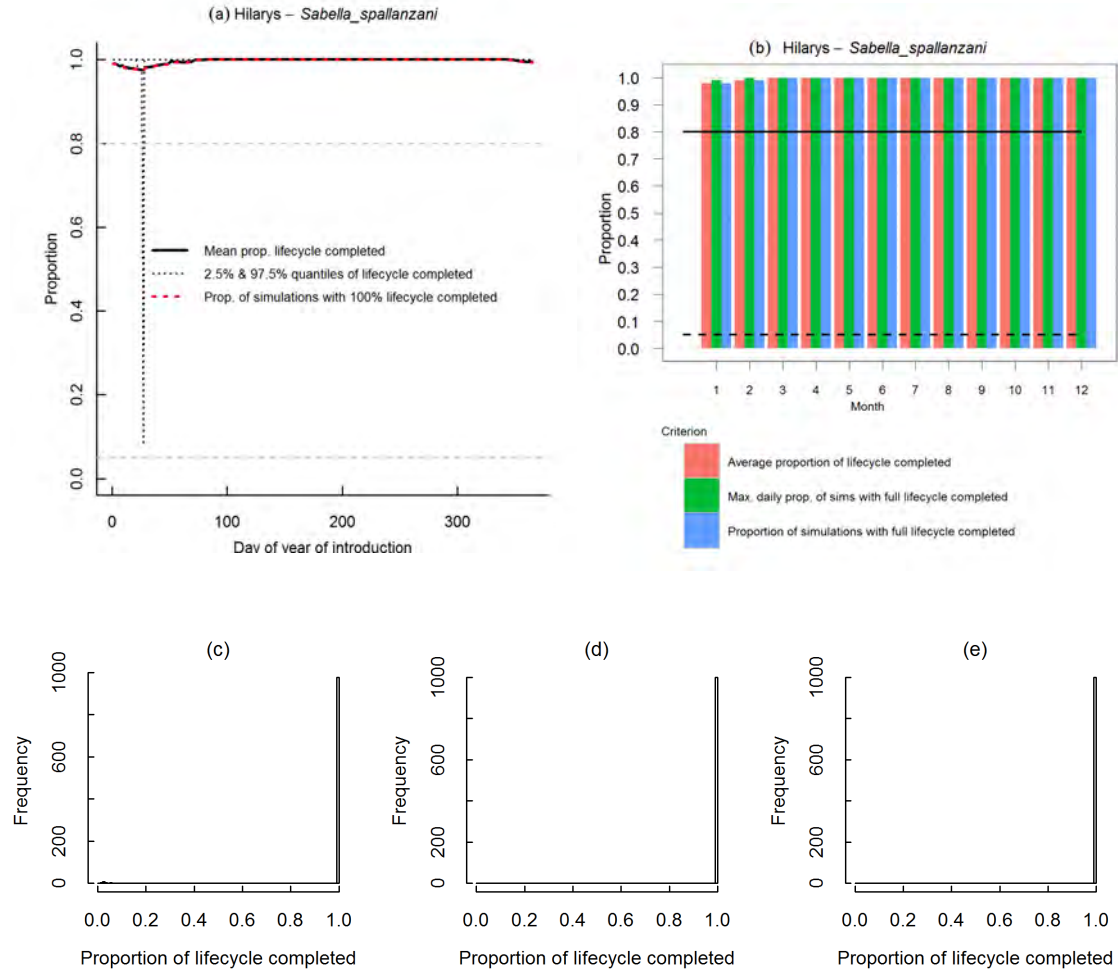

Figure B.55: Simulation results for lifecycle completion of *S. spallanzani* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 150; (e) day 210.

Darwin

Under the old rule, *S. spallanzani* would never be considered a risk of establishing in Darwin, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 149 to day 223 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to May – August.
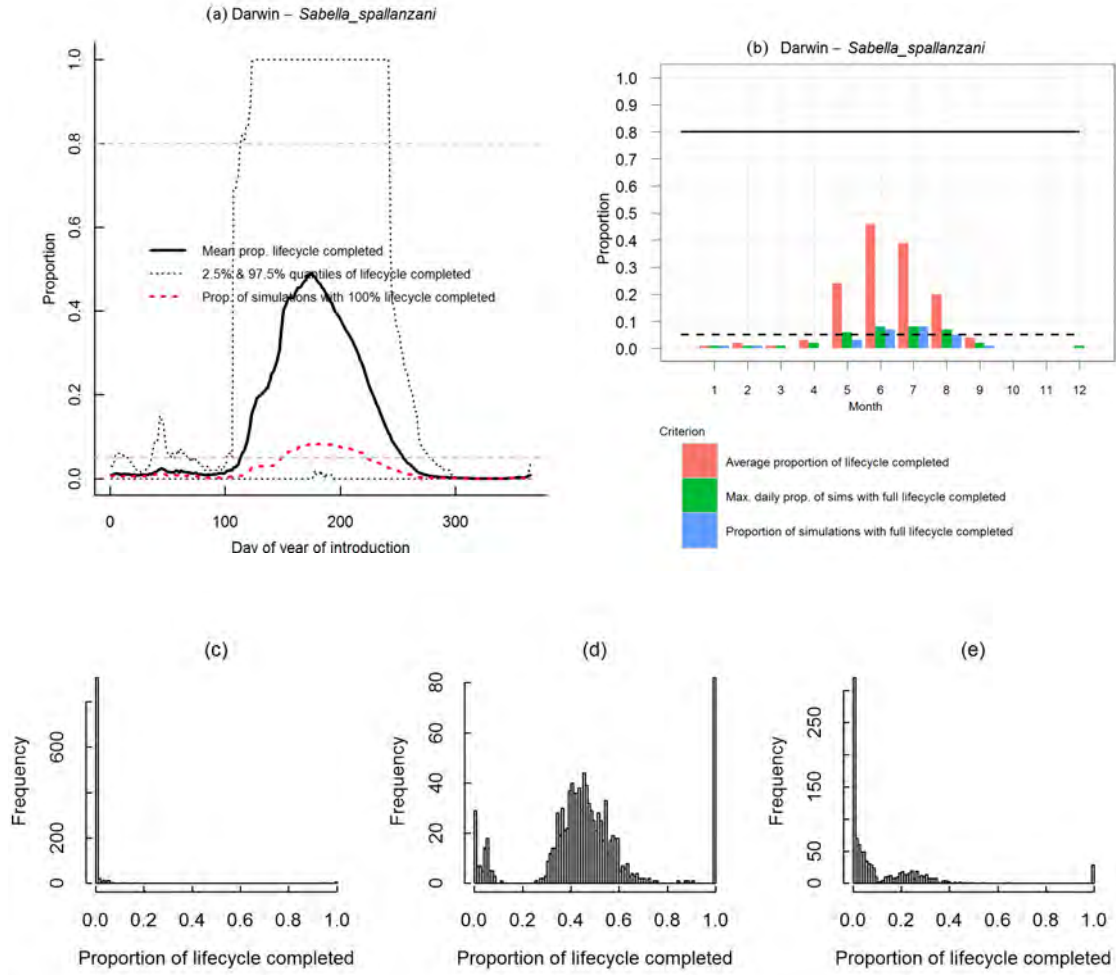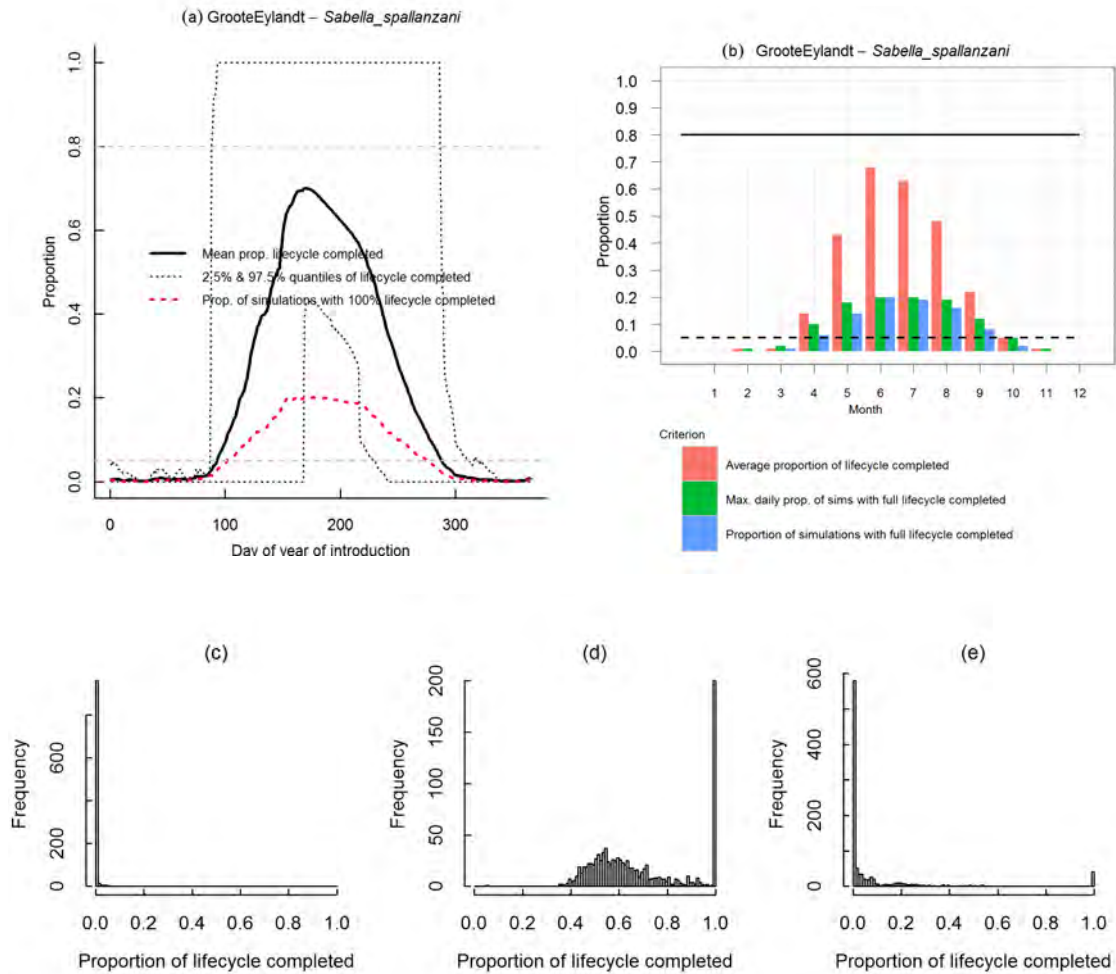

Figure B.56: Simulation results for lifecycle completion of *S. spallanzani* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 240.

Esperance

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.57: Simulation results for lifecycle completion of *S. spallanzani* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Hilarys

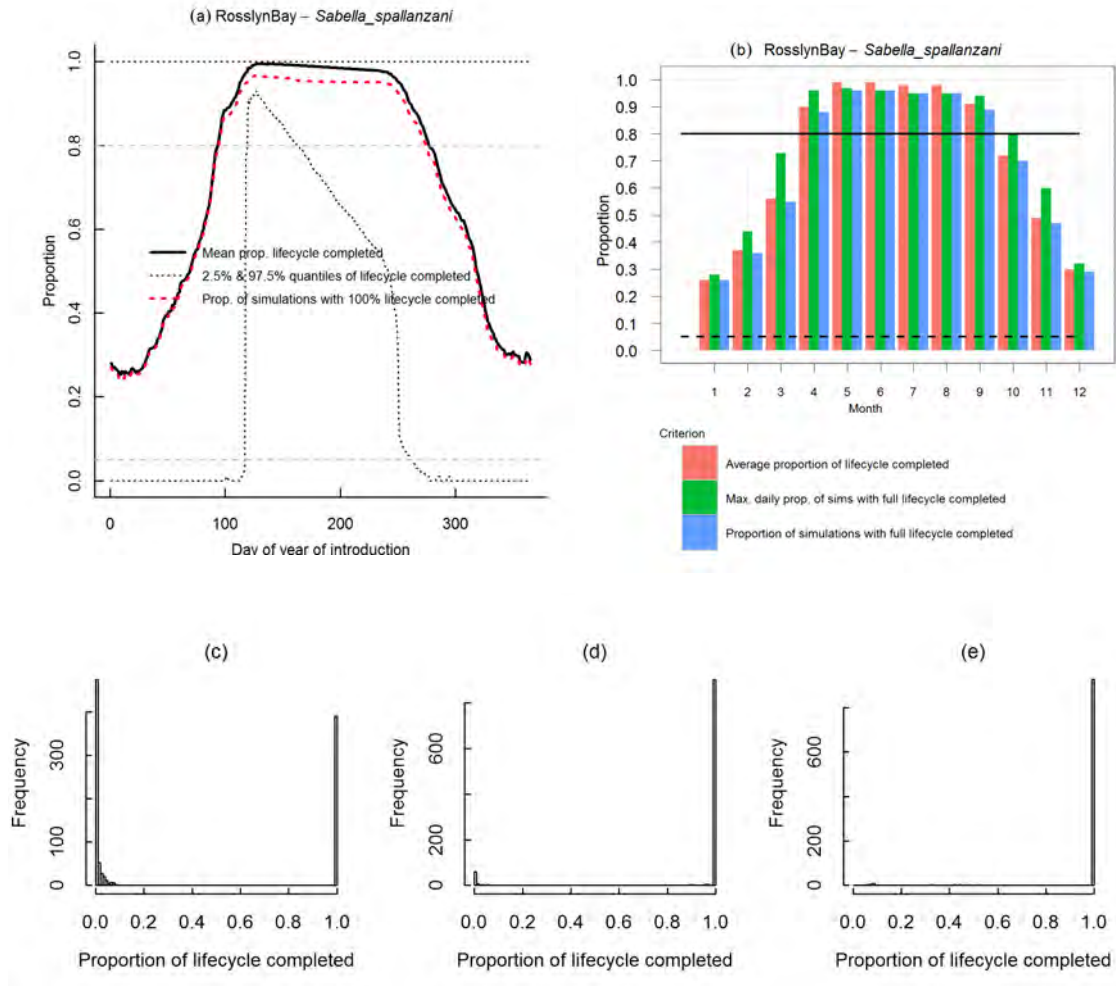In Hilarys establishment would be considered possible throughout the year under the old rule and the new rule.

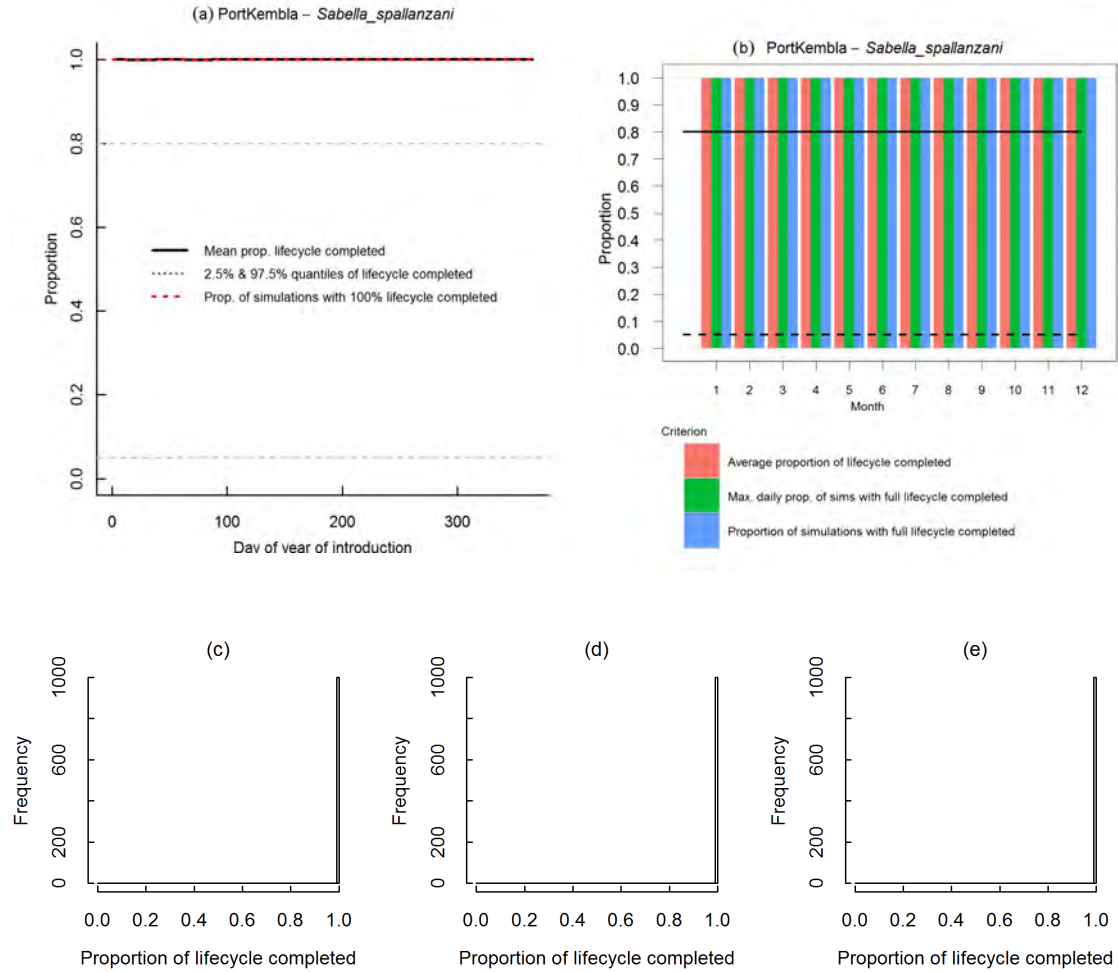**Figure B.58:** Simulation results for lifecycle completion of *S. spallanzani* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 340.

Groote Eylandt

Under the old rule, *S. spallanzani* would never be considered a risk of establishing in Groote Eylandt, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 102 to day 275 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to April – October. We also see that at day 180 a number of additional simulations also get close to 100% of the lifecycle completed.
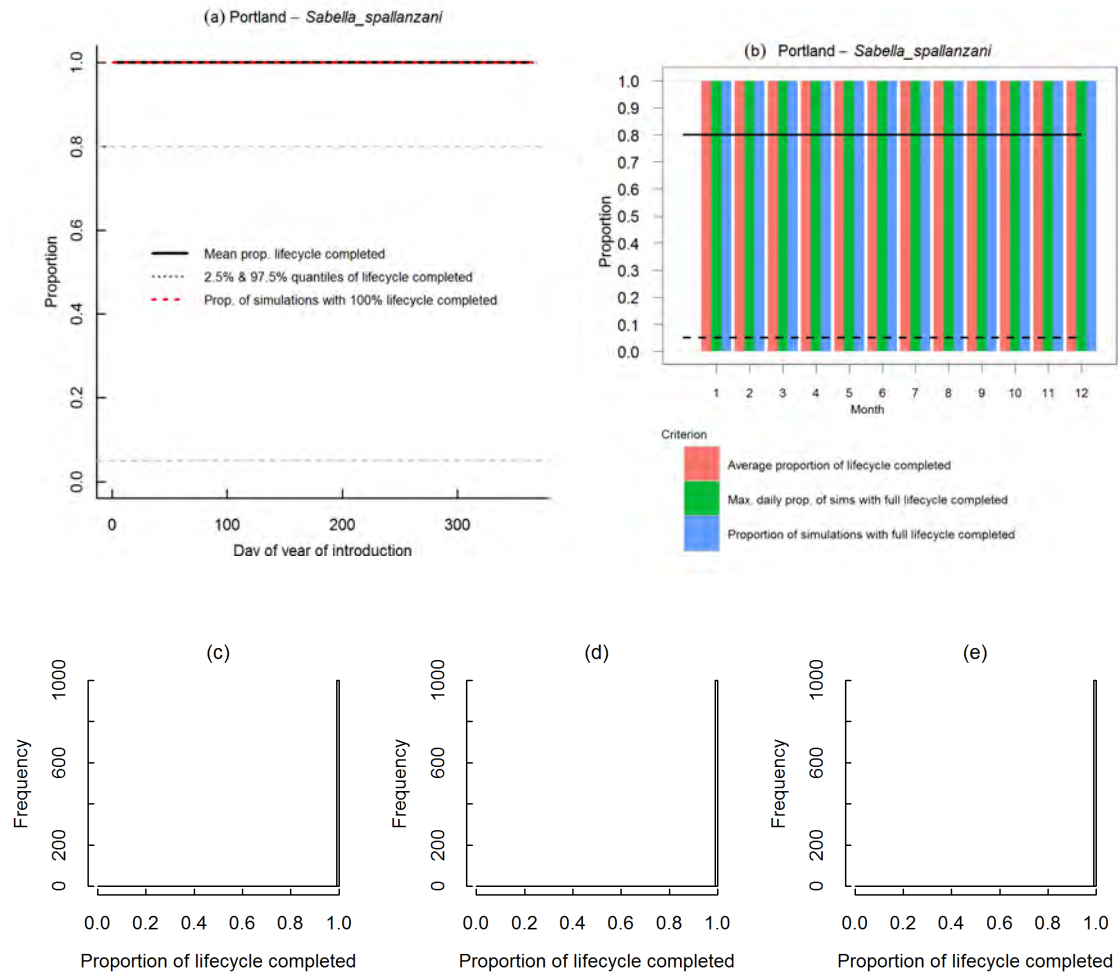

Figure B.59: Simulation results for lifecycle completion of *S. spallanzani* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 180; (e) day 280.

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Rosslyn Bay

Under the old rule, *S. spallanzani* would be considered a risk of establishing in Rosslyn Bay from day 94 to day 277 (months April – September), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
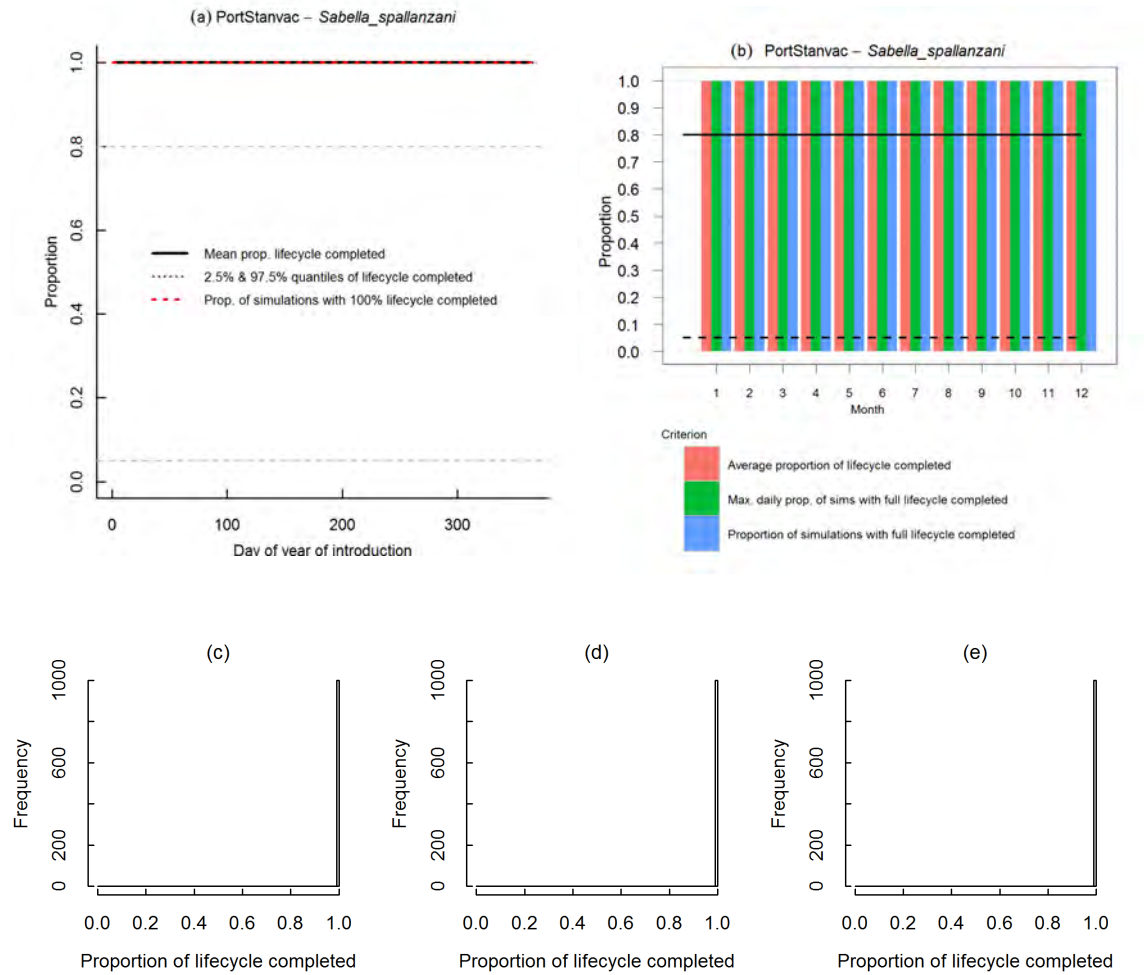

Figure B.60: Simulation results for lifecycle completion of *S. spallanzani* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 110; (e) day 250.

Port Kembla

In Port Kembla establishment would be considered possible throughout the year under the old rule and the new rule.
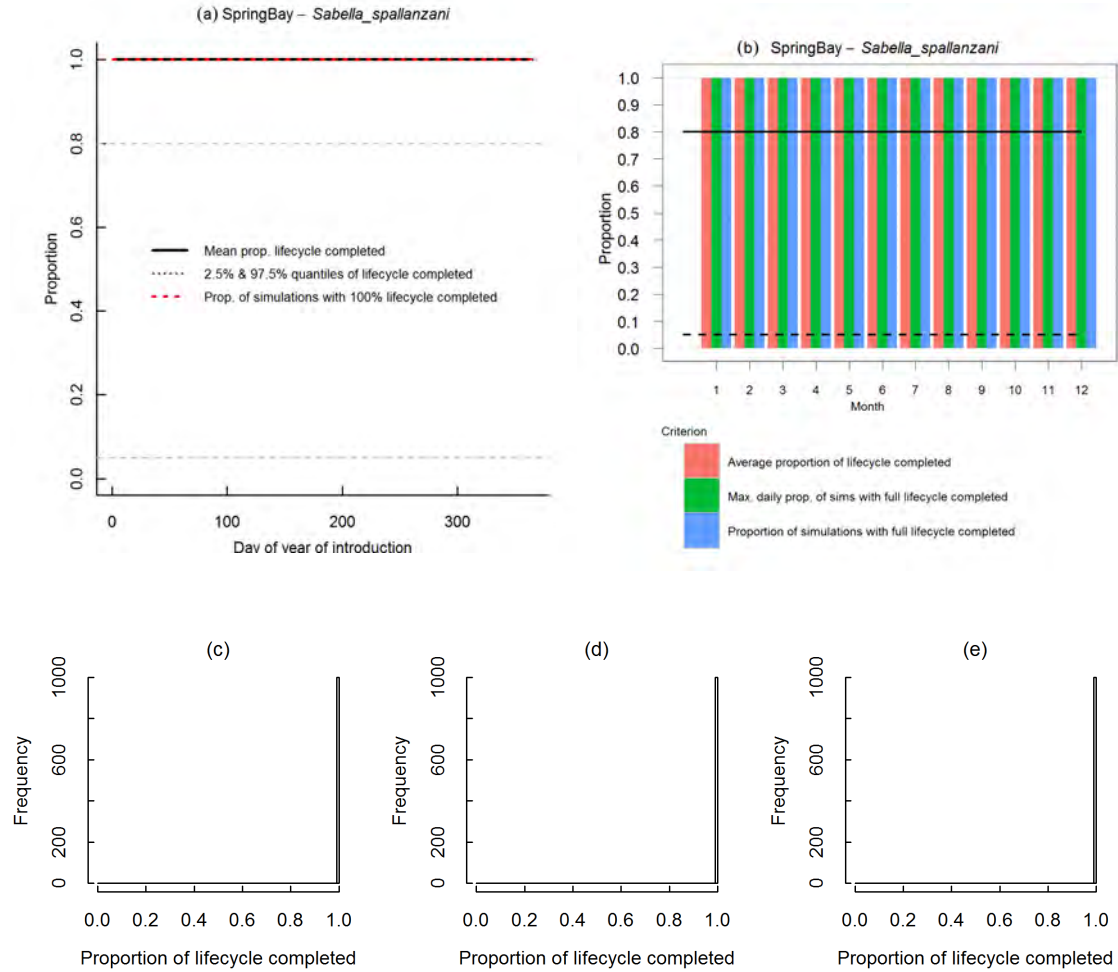

Figure B.61: Simulation results for lifecycle completion of *S. spallanzani* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Portland

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.
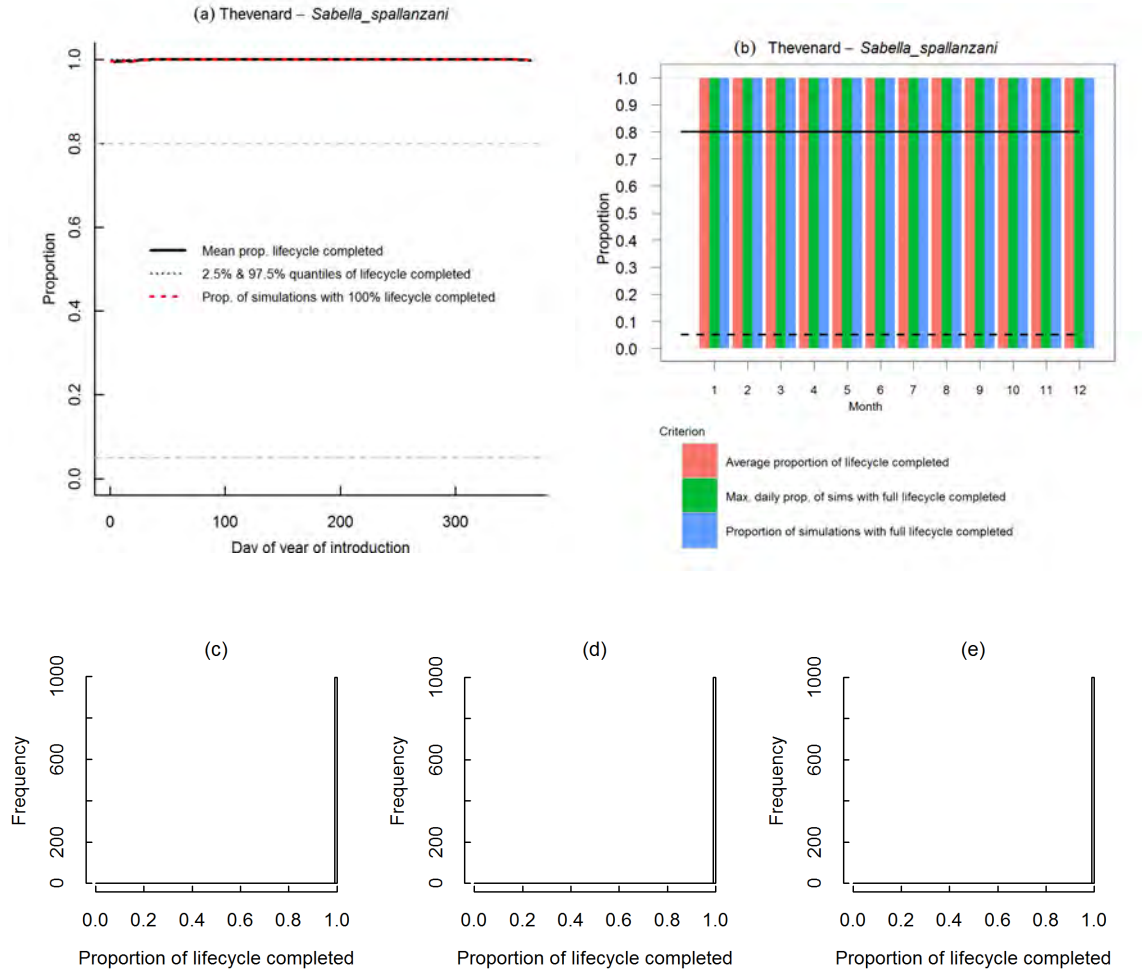

Figure B.62: Simulation results for lifecycle completion of *S. spallanzani* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Port Stanvac

In Port Stanvac establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.63: Simulation results for lifecycle completion of *S. spallanzani* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.
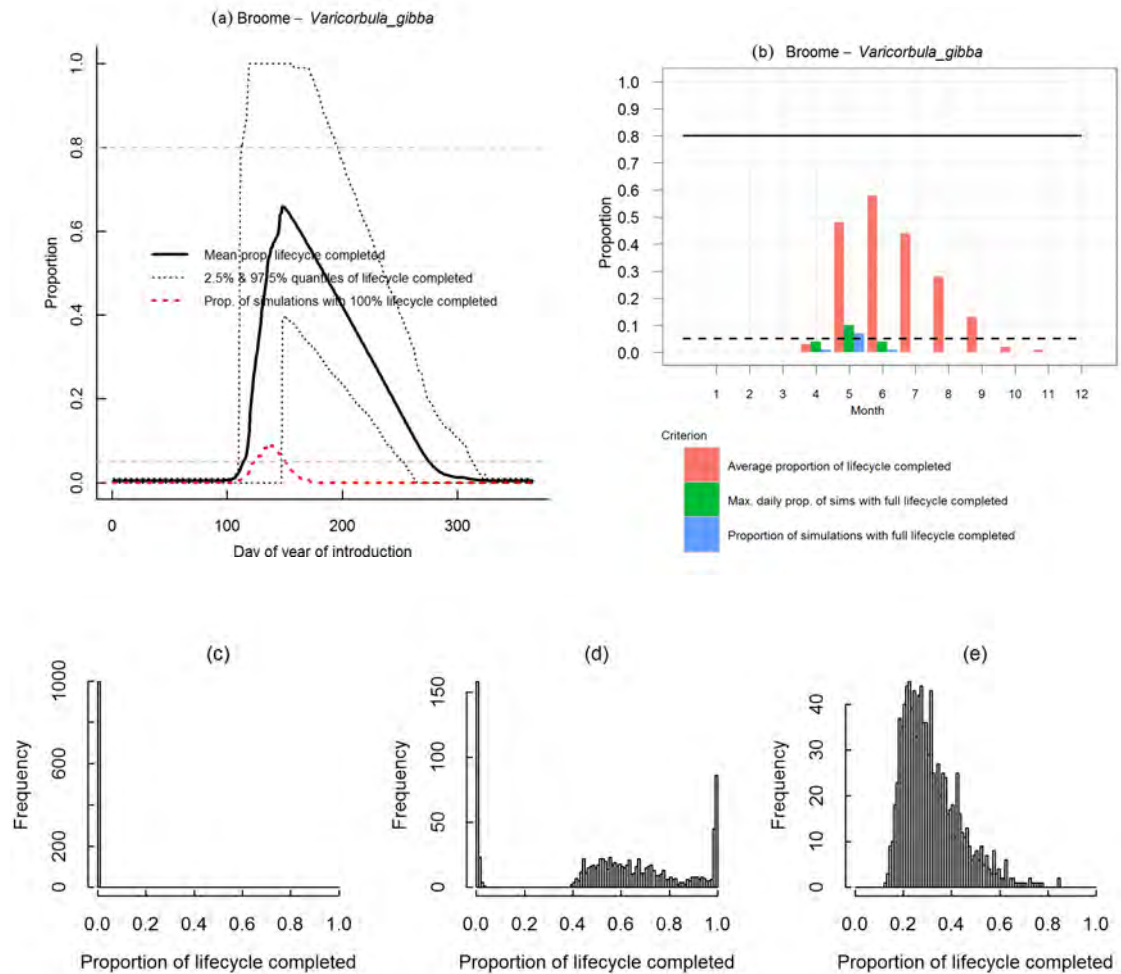

Figure B.64: Simulation results for lifecycle completion of *S. spallanzani* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Thevenard

In Thevenard establishment would be considered possible throughout the year under the old rule and the new rule.
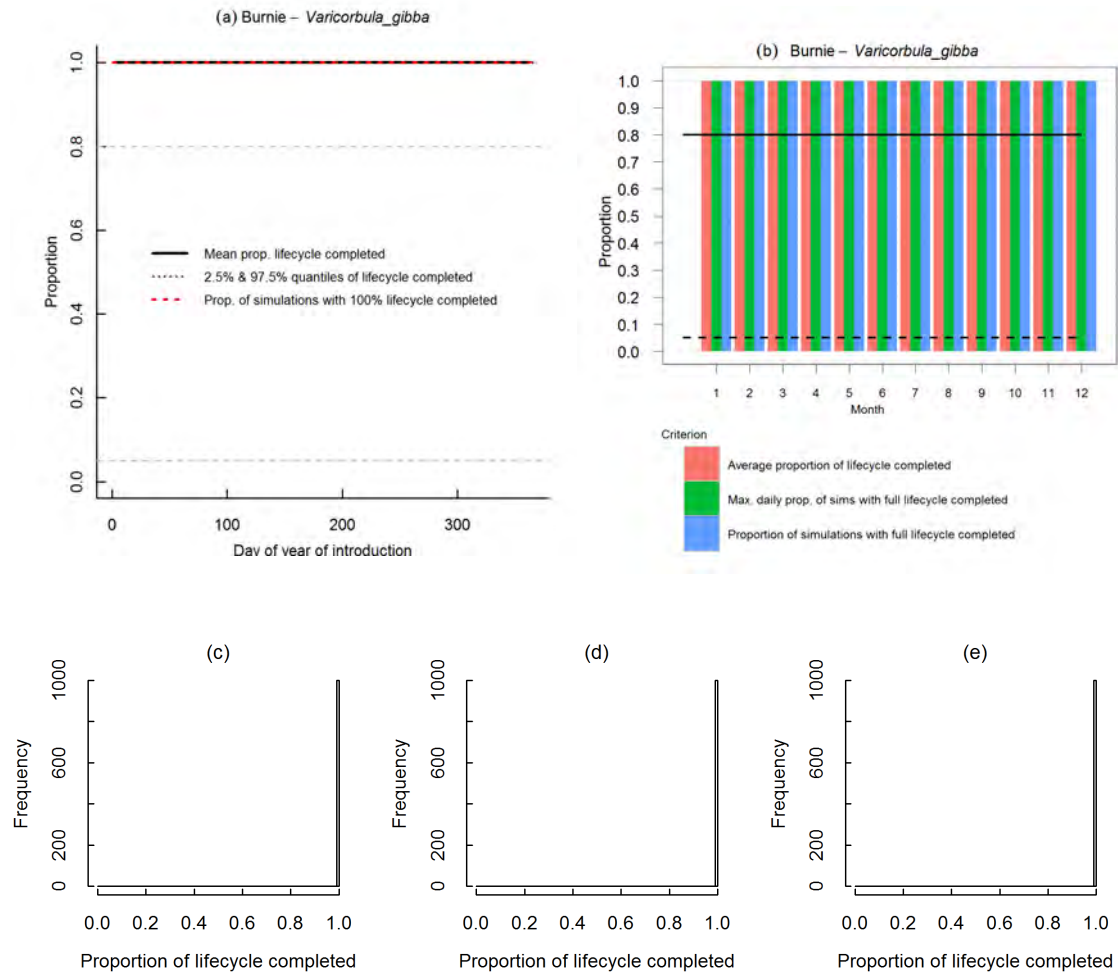

Figure B.65: Simulation results for lifecycle completion of *S. spallanzani* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 200; (e) day 300.

B.2.5 *Varicorbula gibba* - European Clam

Broome

Under the old rule, *V. gibba* would never be considered a risk of establishing in Broome, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 124 to day 150 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to May. We also see that at day 140 a number of additional simulations also get close to 100% of the lifecycle completed.
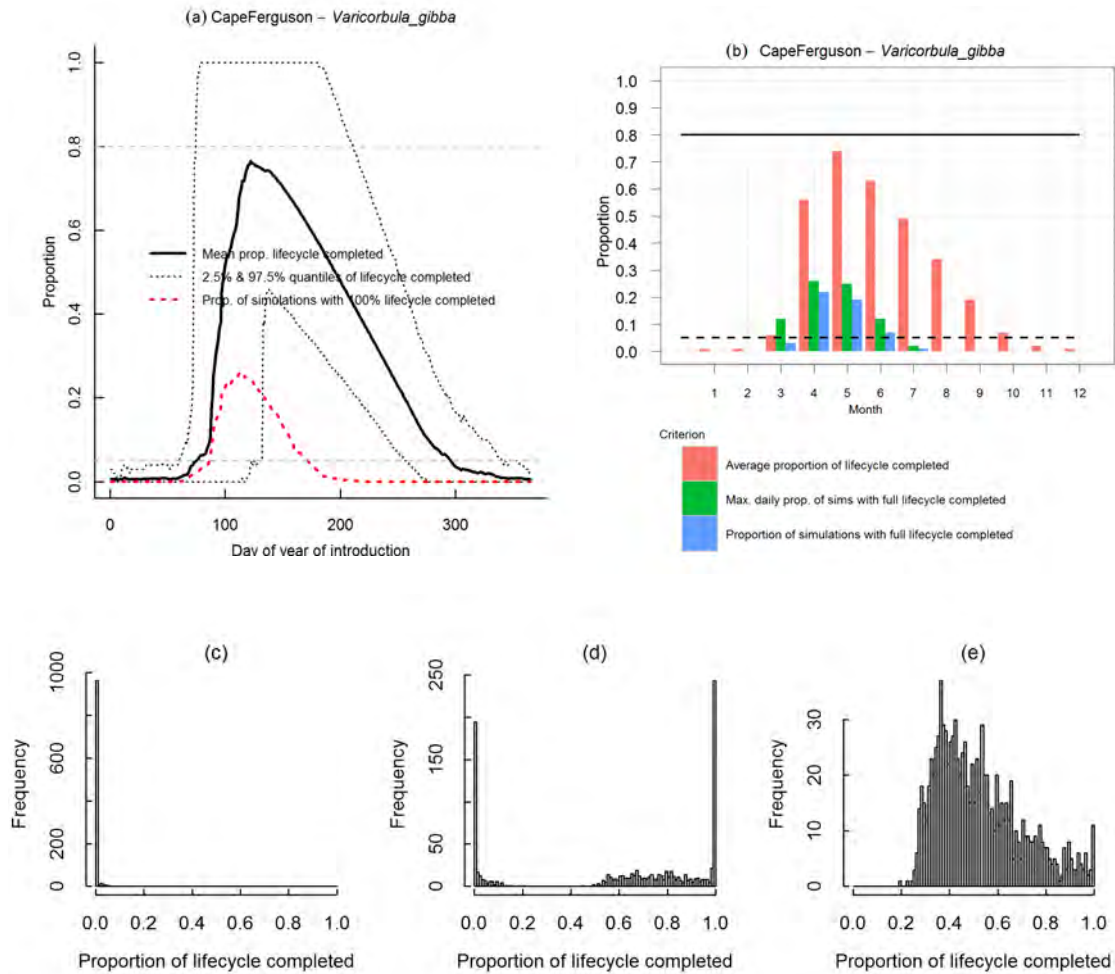

Figure B.66: Simulation results for lifecycle completion of *V. gibba* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 140; (e) day 220.

Burnie

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.
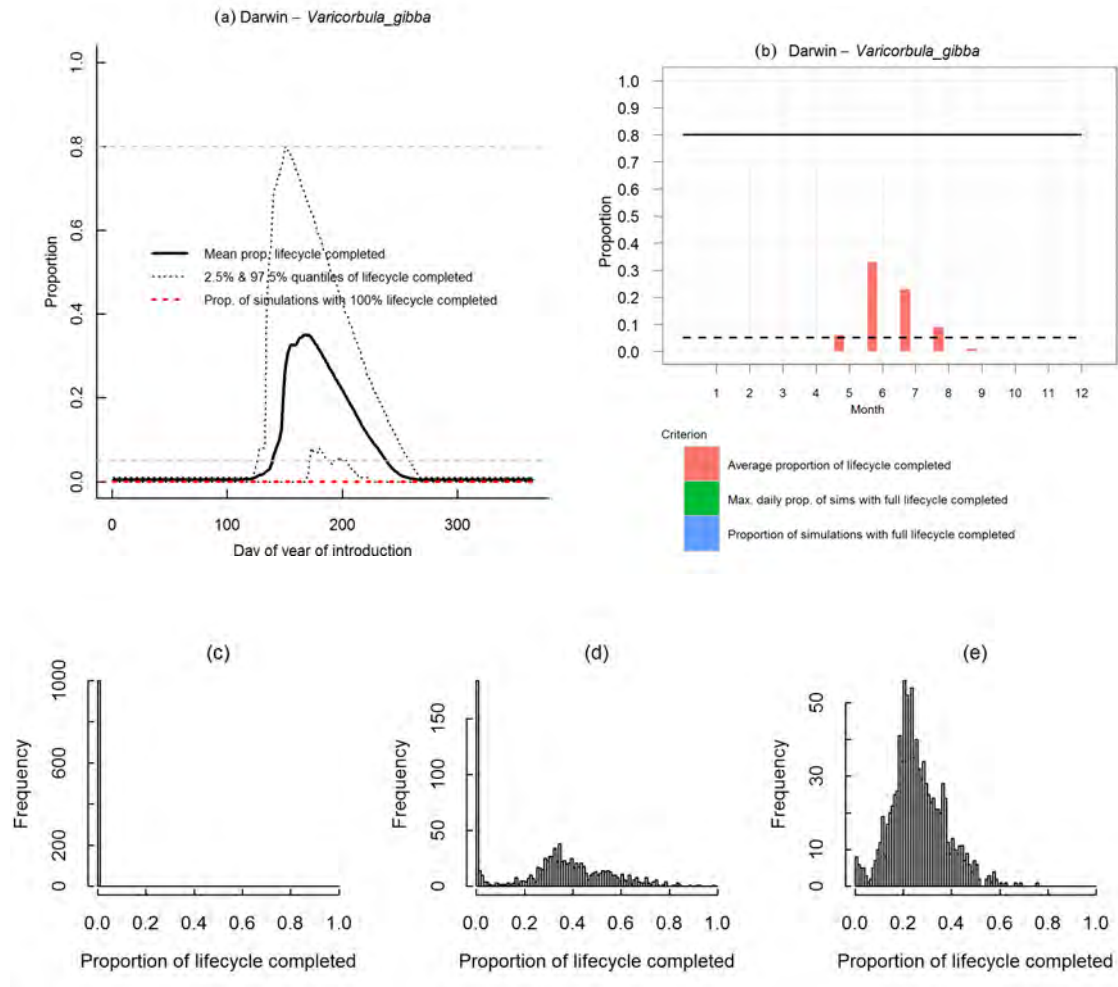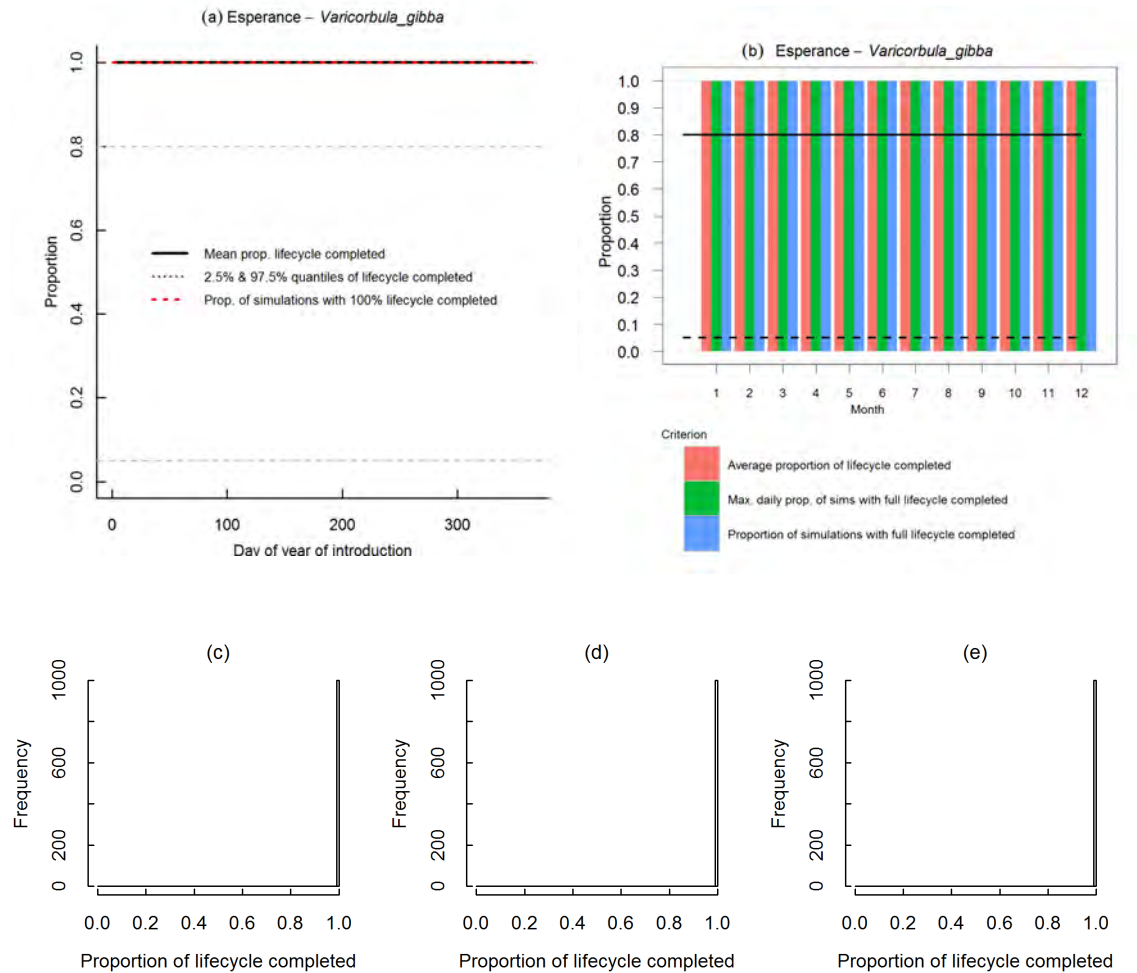

Figure B.67: Simulation results for lifecycle completion of *V. gibba* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 300.

Cape Ferguson

Under the old rule, *V. gibba* would never be considered a risk of establishing in Cape Ferguson, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 87 to day 171 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to March – June. We also see that at day 190, while the percentage of simulations completed is less than 5%, a number of simulations get close to 100% of the lifecycle completed.

Figure B.68: Simulation results for lifecycle completion of *V. gibba* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 110; (e) day 190.

Darwin

In Darwin establishment would be considered unlikely throughout the year under the old rule and the new rule.
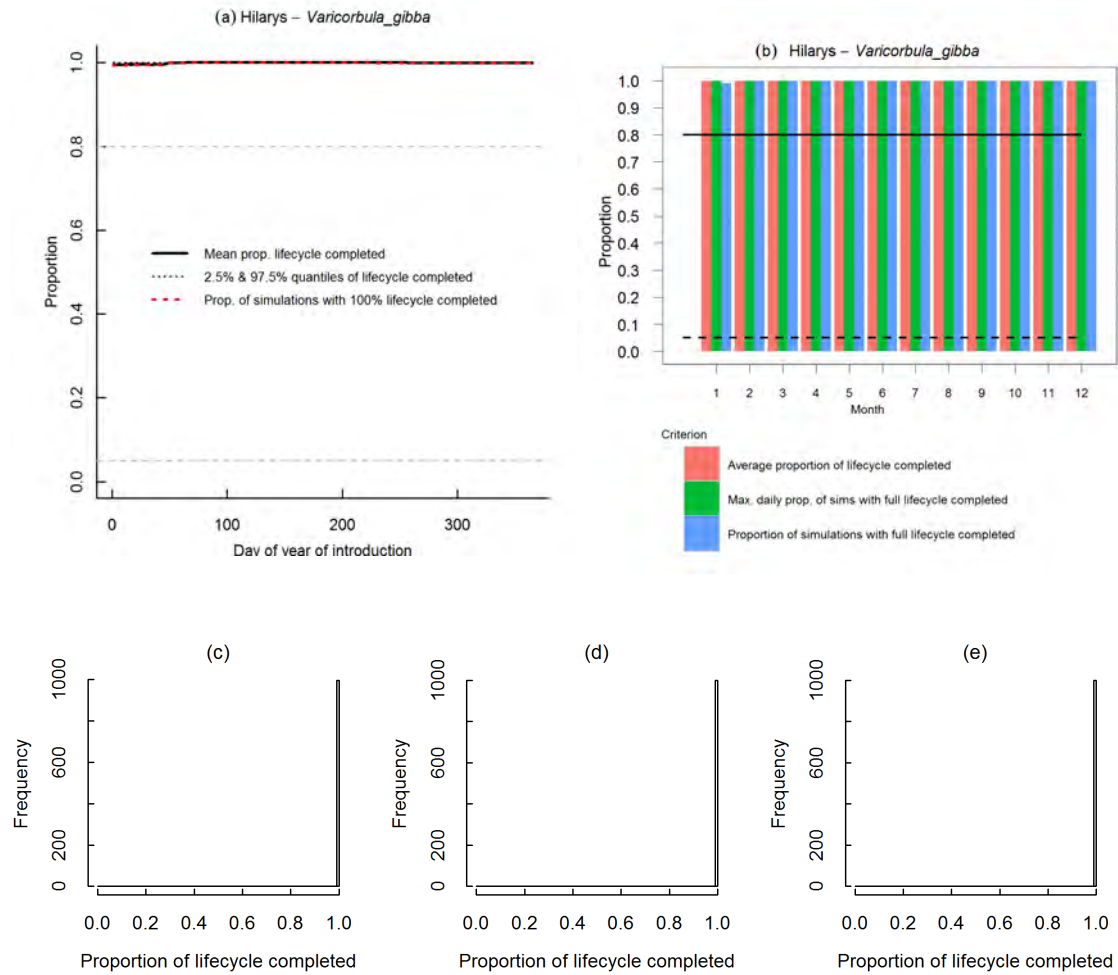

Figure B.69: Simulation results for lifecycle completion of *V. gibba* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 160; (e) day 190.

Esperance

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.

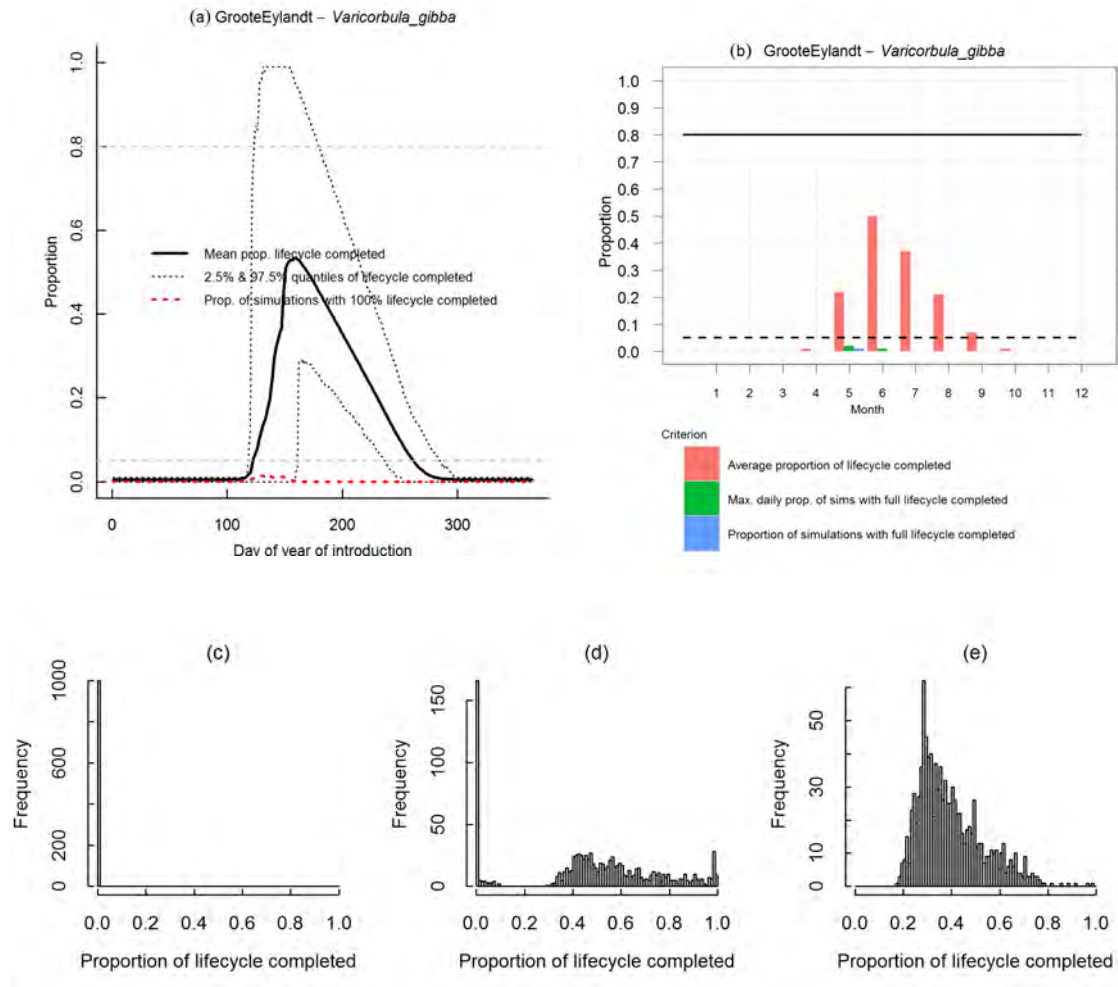**Figure B.70:** Simulation results for lifecycle completion of *V. gibba* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Hilarys

In Hilarys establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.71: Simulation results for lifecycle completion of *V. gibba* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 20; (d) day 200; (e) day 300.

Groote Eylandt

In Groote Eylandt establishment would be considered unlikely throughout the year under the old rule and the new rule.
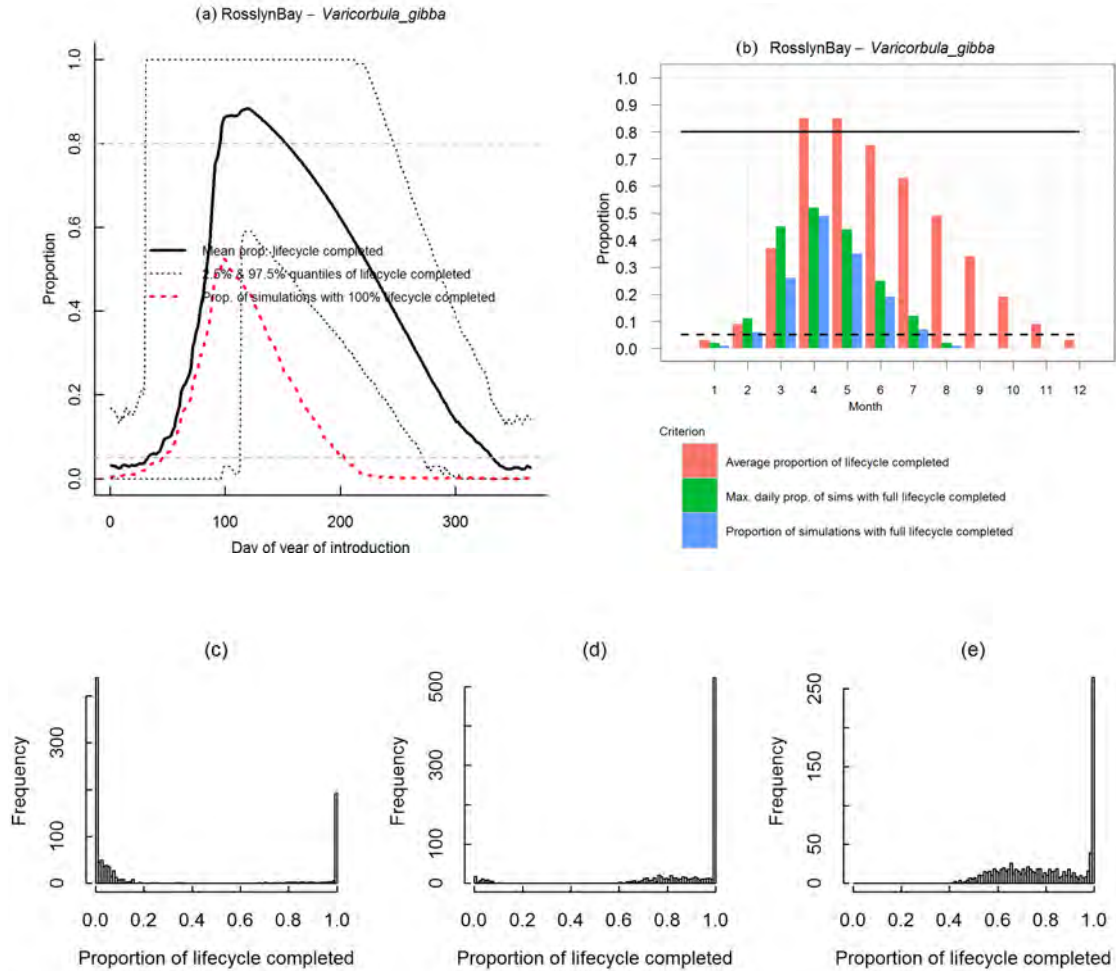

Figure B.72: Simulation results for lifecycle completion of *V. gibba* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 150; (e) day 190.

Rosslyn Bay

Under the old rule, *V. gibba* would be considered a risk of establishing in Rosslyn Bay from day 96 to day 152 (months April and May), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 46 to day 203 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to February – July.

Figure B.73: Simulation results for lifecycle completion of *V. gibba* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 70; (d) day 100; (e) day 150.

Port Kembla

In Port Kembla establishment would be considered possible throughout the year under the old rule and the new rule.
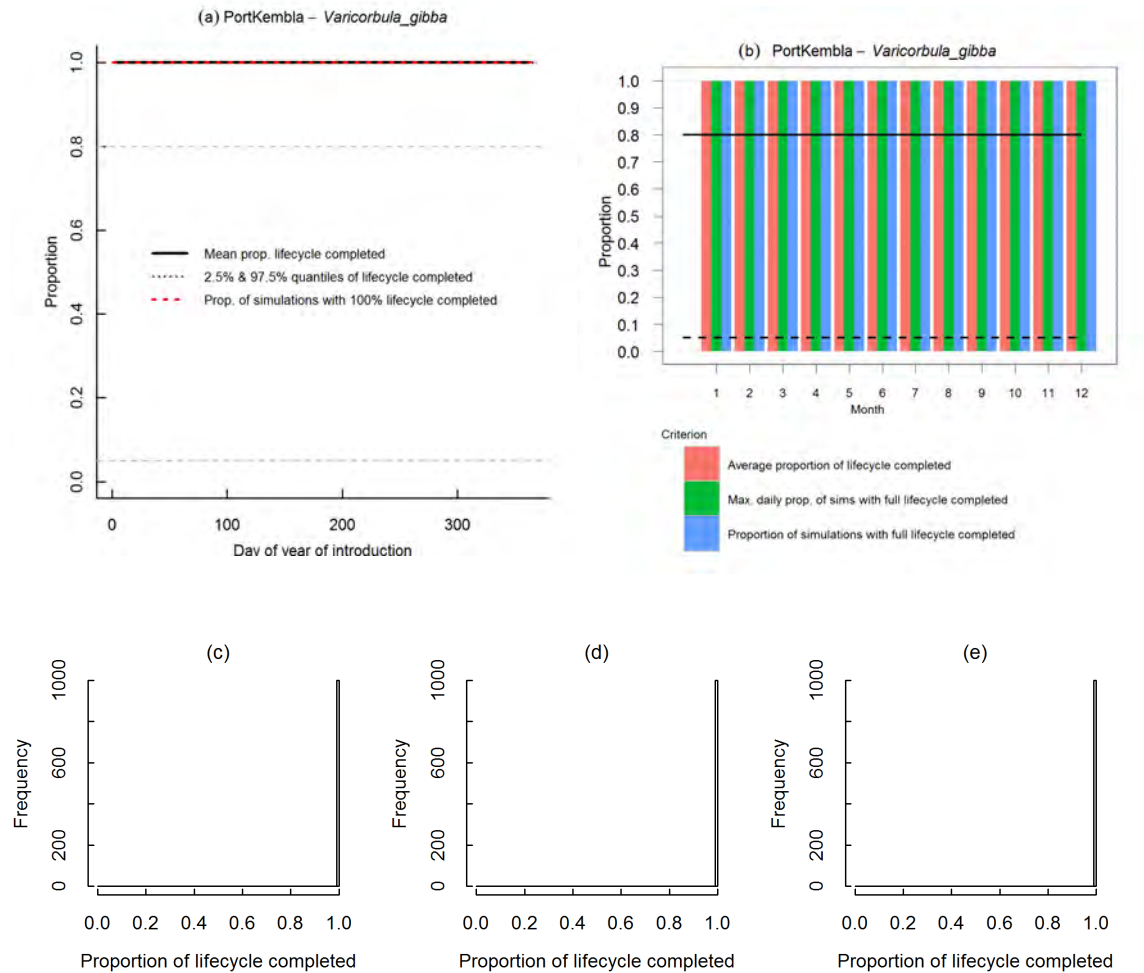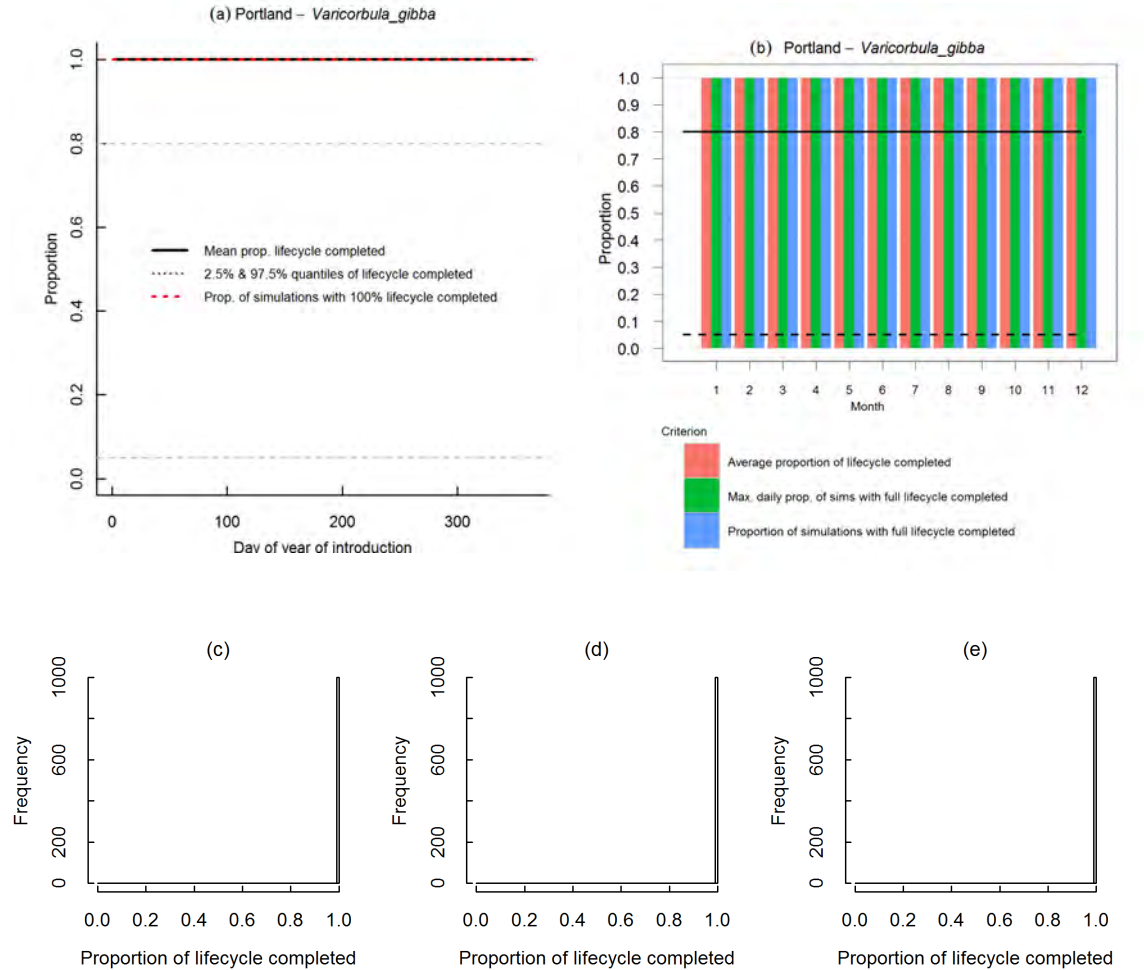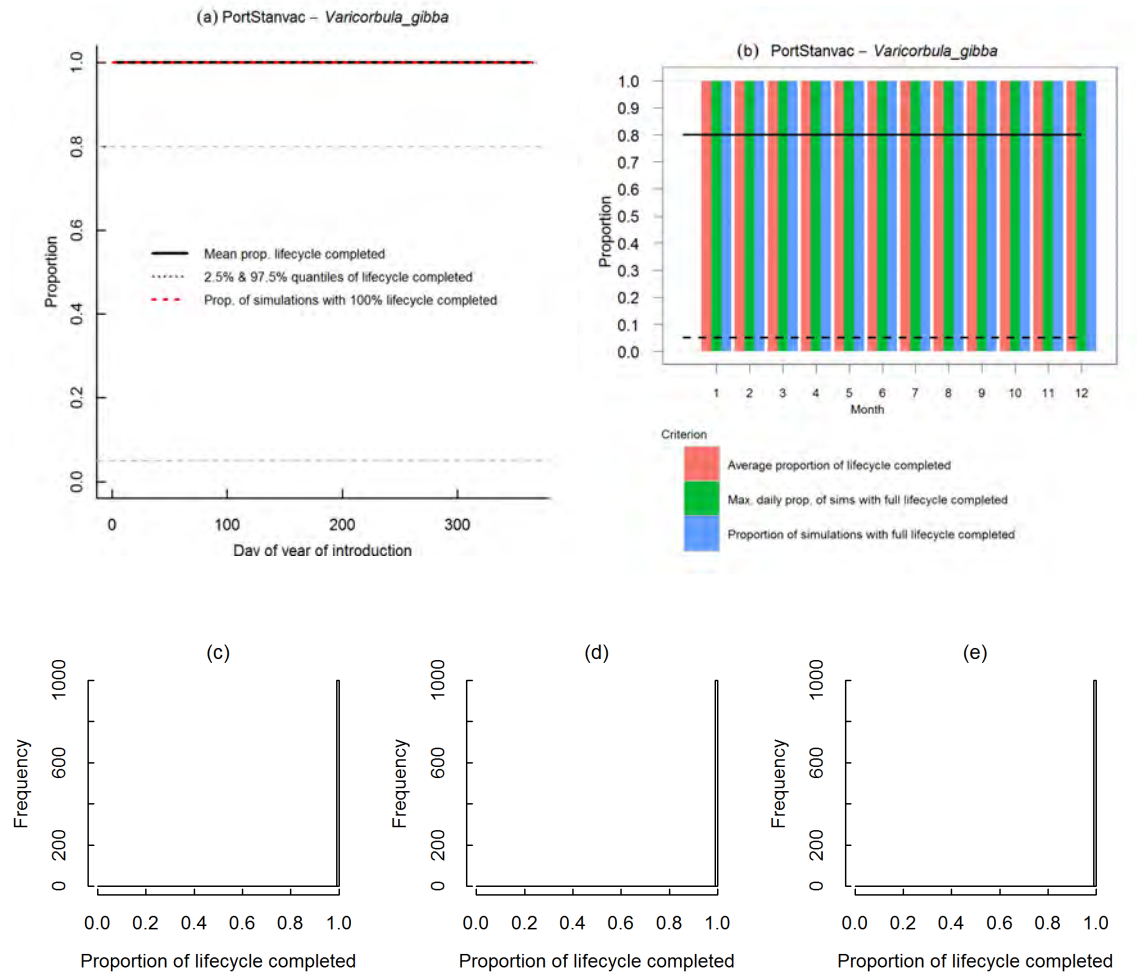

Figure B.74: Simulation results for lifecycle completion of *V. gibba* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Portland

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.75: Simulation results for lifecycle completion of *V. gibba* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

In Port Stanvac establishment would be considered possible throughout the year under the old rule and the new rule.
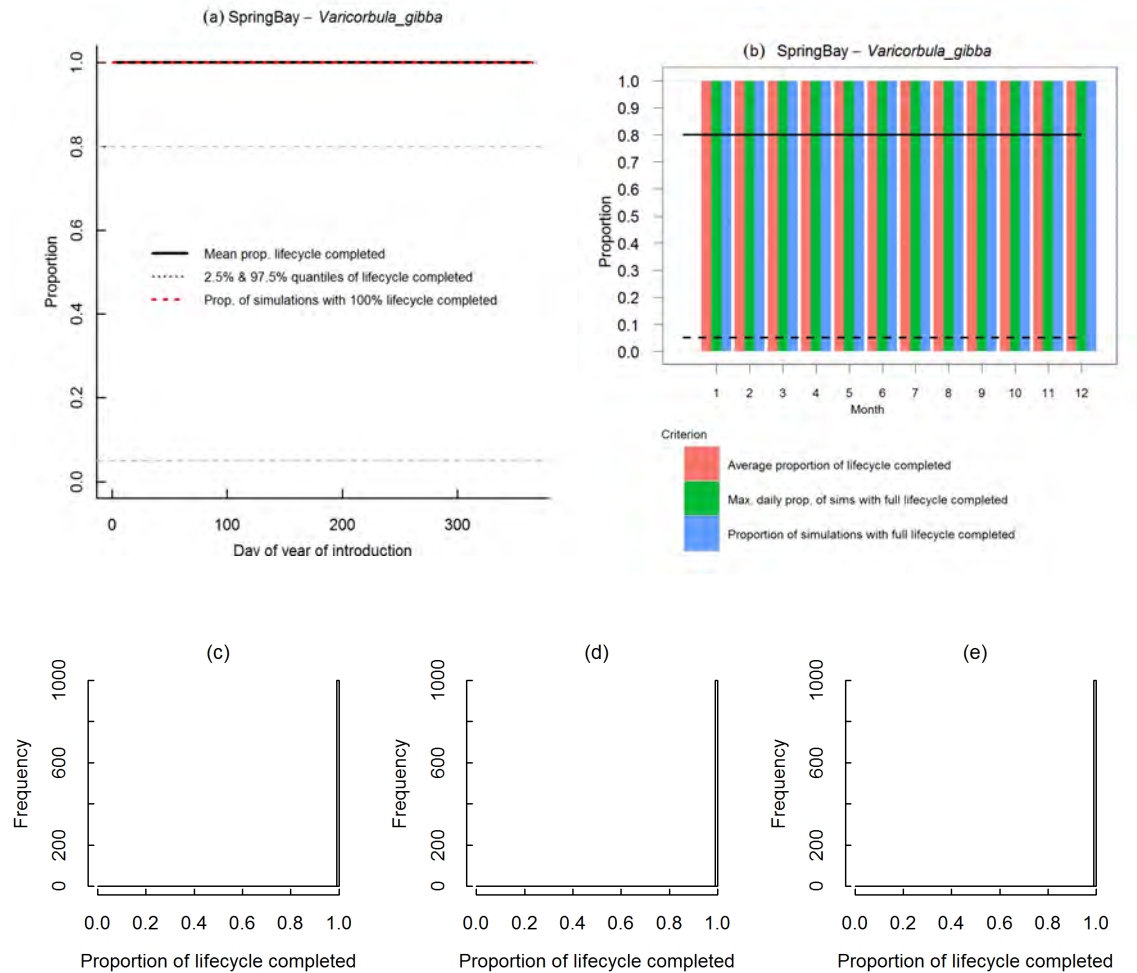

Figure B.76: Simulation results for lifecycle completion of *V. gibba* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.
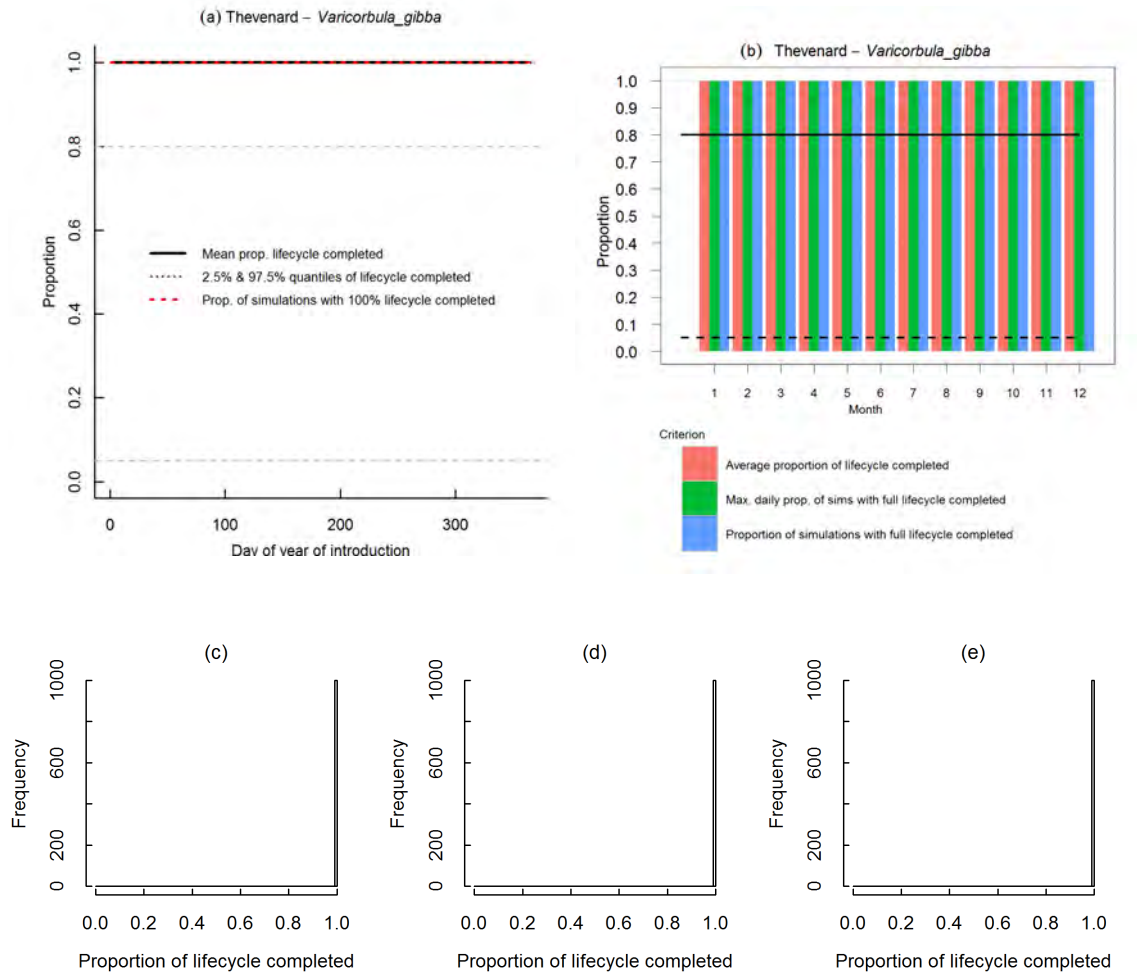

Figure B.77: Simulation results for lifecycle completion of *V. gibba* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Thevenard

In Thevenard establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.78: Simulation results for lifecycle completion of *V. gibba* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

B.3   Sub-tidal plants

B.3.1   *Undaria pinnatifida* - Japanese Seaweed or Wakame

Broome

Under the old rule, *U. pinnatifida* would never be considered a risk of establishing in Broome, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 148 to day 201 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to May – July). We also see that at day 200 a number of additional simulations also get close to 100% of the lifecycle completed.
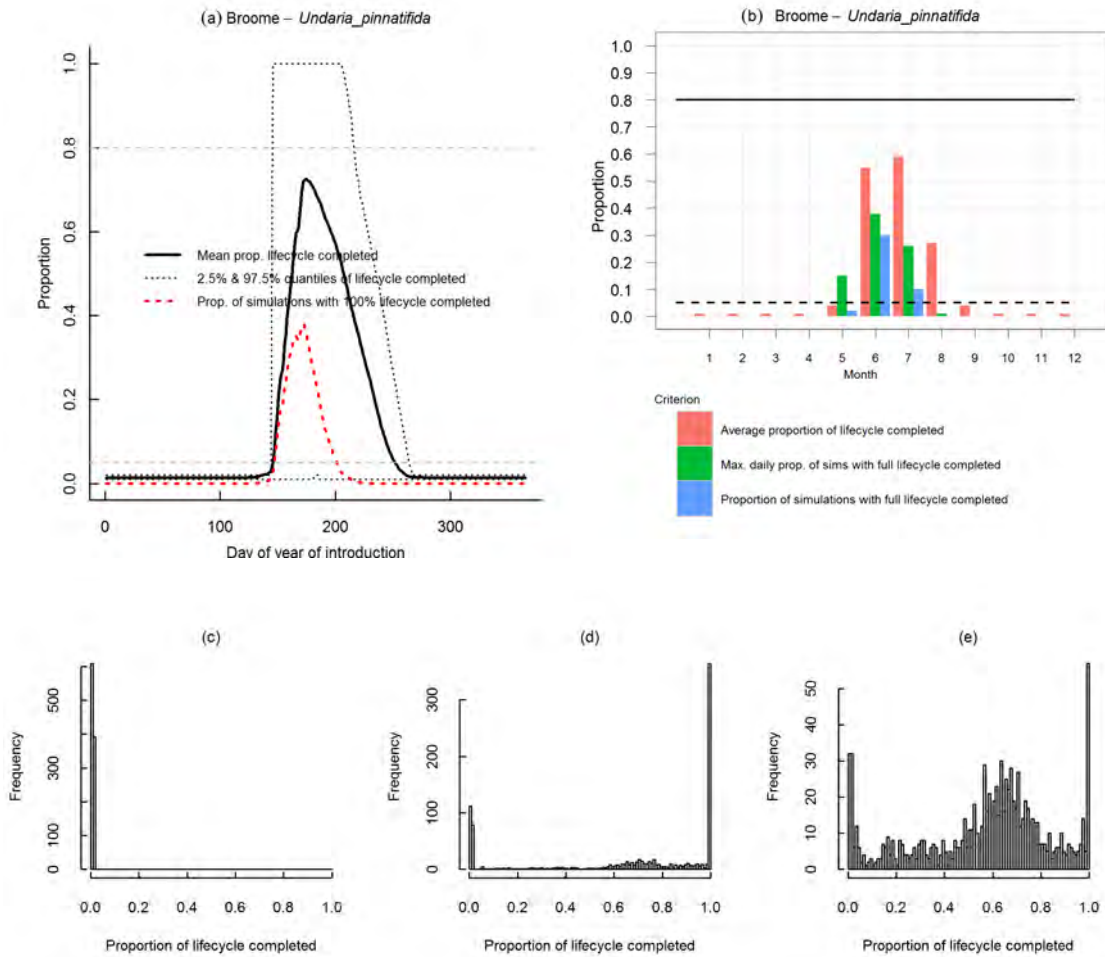

Figure B.79: Simulation results for lifecycle completion of *U. pinnatifida* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (d) day 50; (e) day 170; (e) day 200.

Burnie

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.
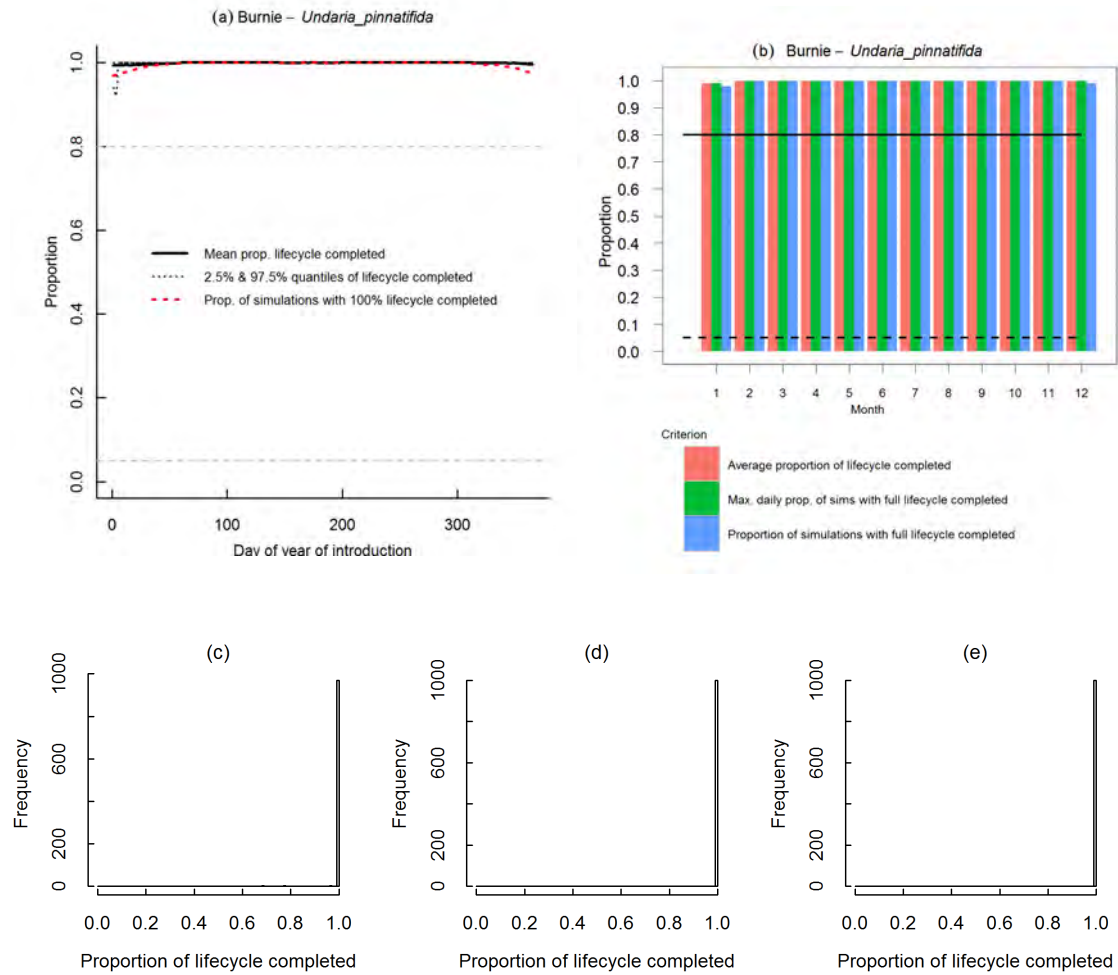

Figure B.80: Simulation results for lifecycle completion of *U. pinnatifida* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 200; (e) day 300.

Cape Ferguson

Under the old rule, *U. pinnatifida* would never be considered a risk of establishing in Cape Ferguson, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 140 to day 196 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to May – July.
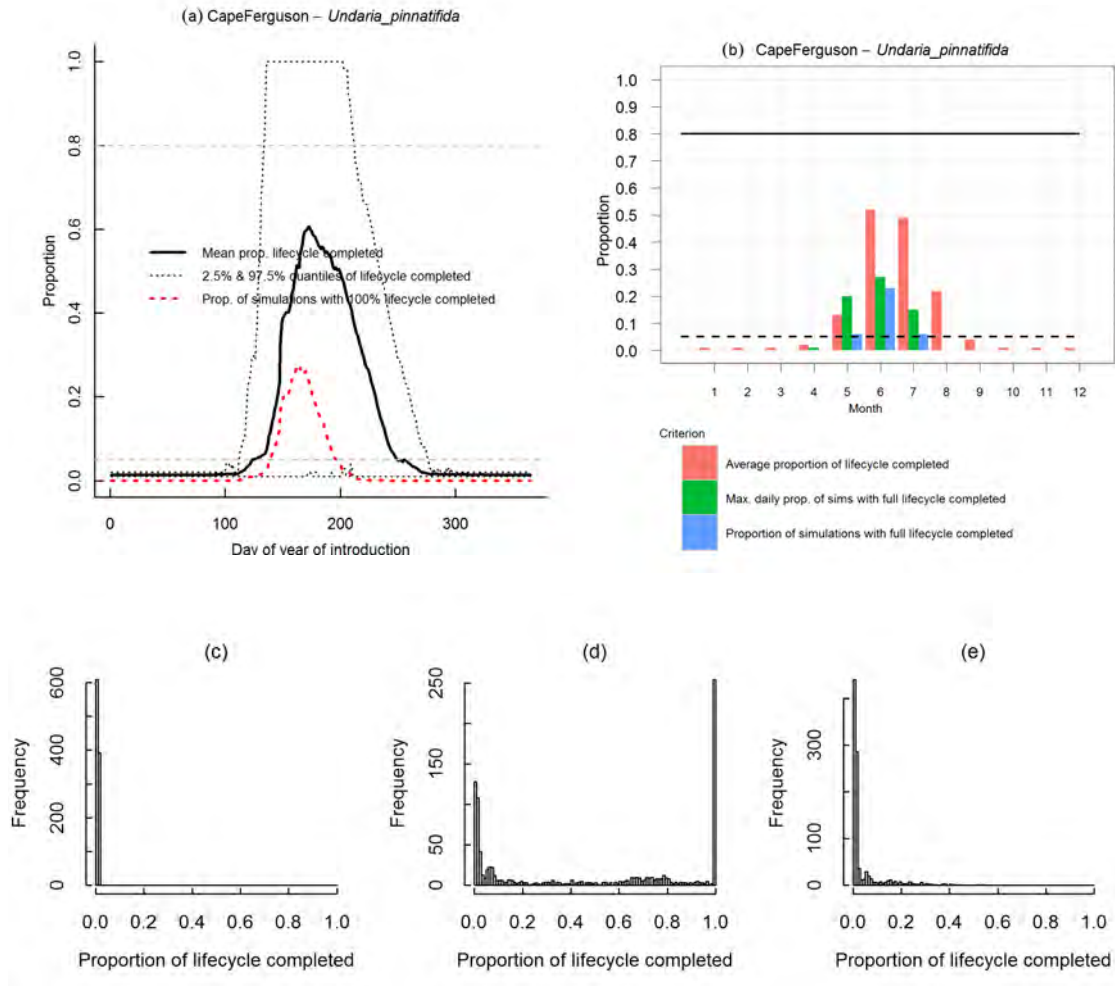

Figure B.81: Simulation results for lifecycle completion of *U. pinnatifida* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 160; (e) day 250.

Darwin

In Darwin establishment would be considered unlikely throughout the year under the old rule and the new rule.
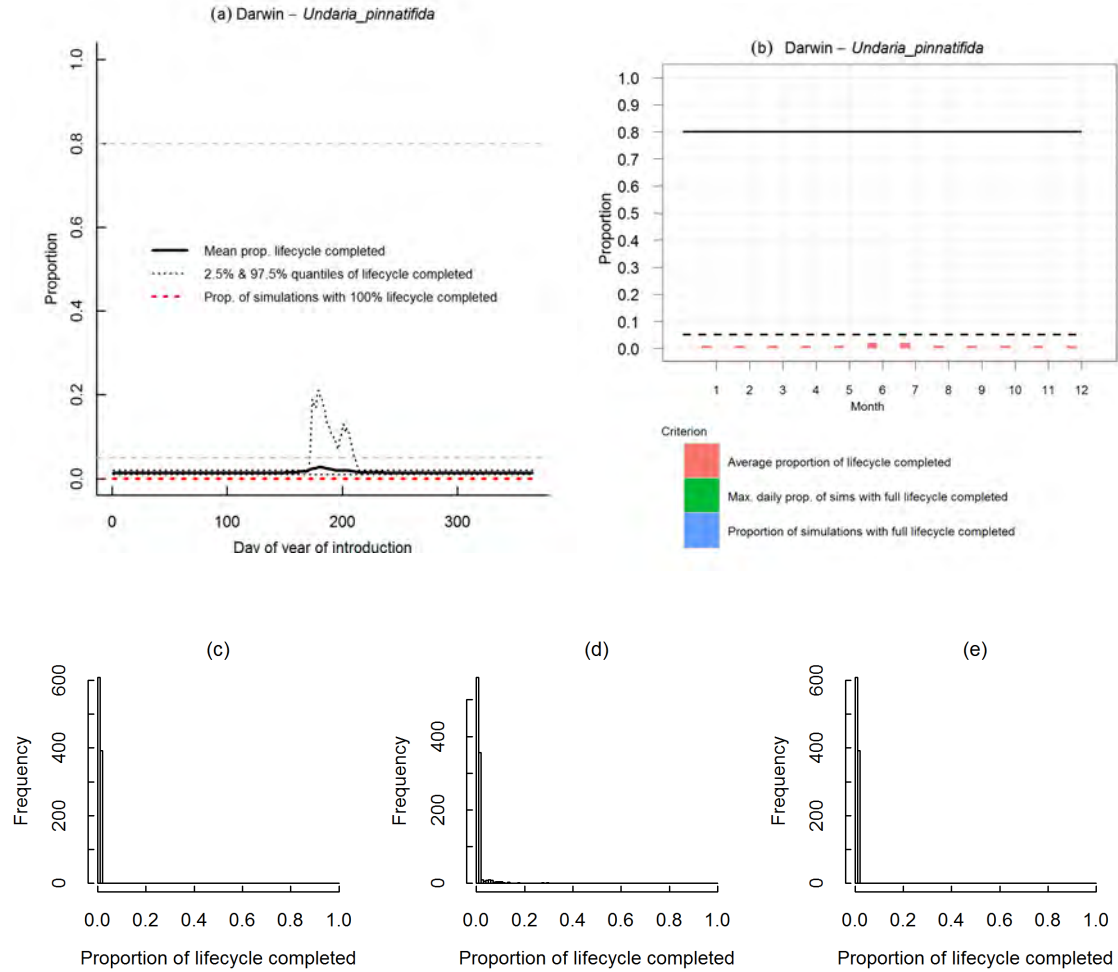

Figure B.82: Simulation results for lifecycle completion of *U. pinnatifida* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 190; (e) day 300.

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.

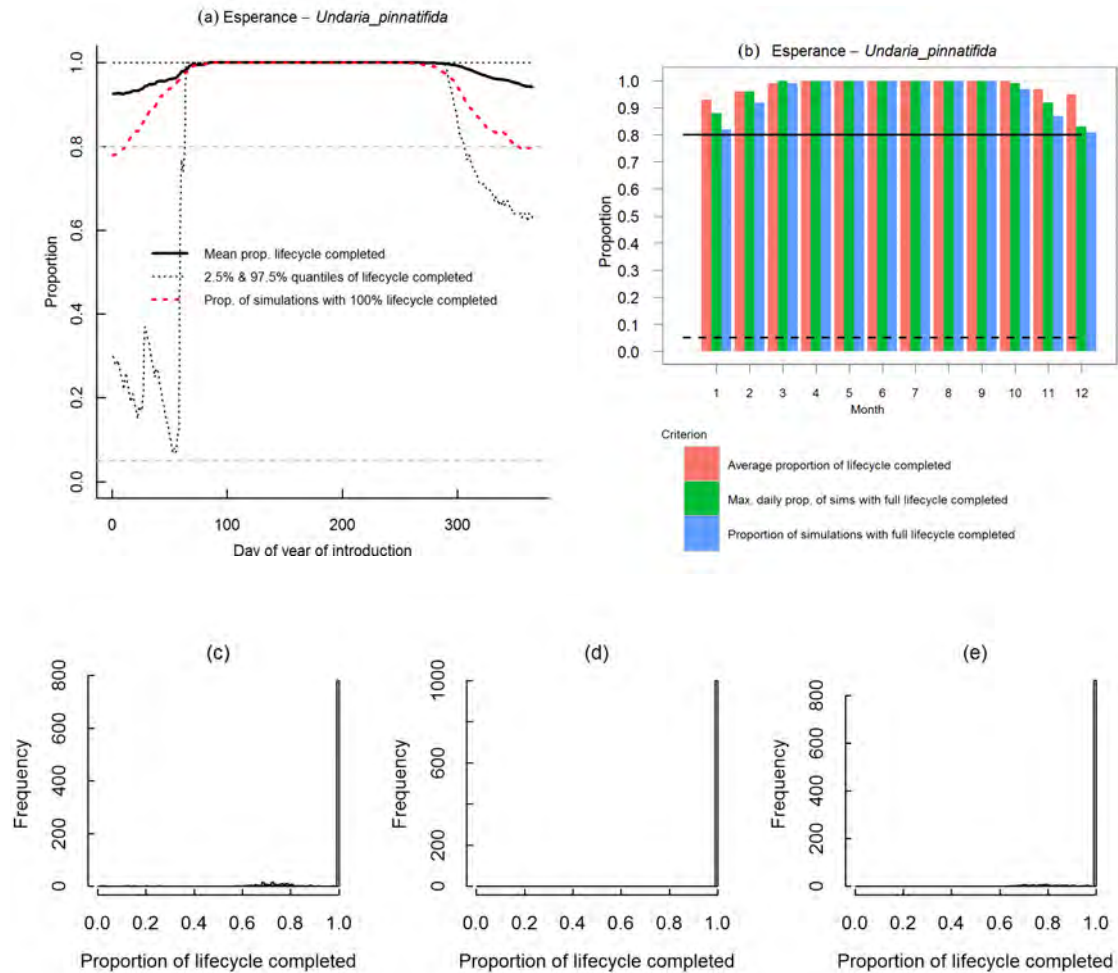**Figure B.83:** Simulation results for lifecycle completion of *U. pinnatifida* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 200; (e) day 320.

Hilarys

Under the old rule, *U. pinnatifida* would be considered a risk of establishing in Hilarys from day 88 to day 291 (months April – October), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 40 to day 326 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to February – November.
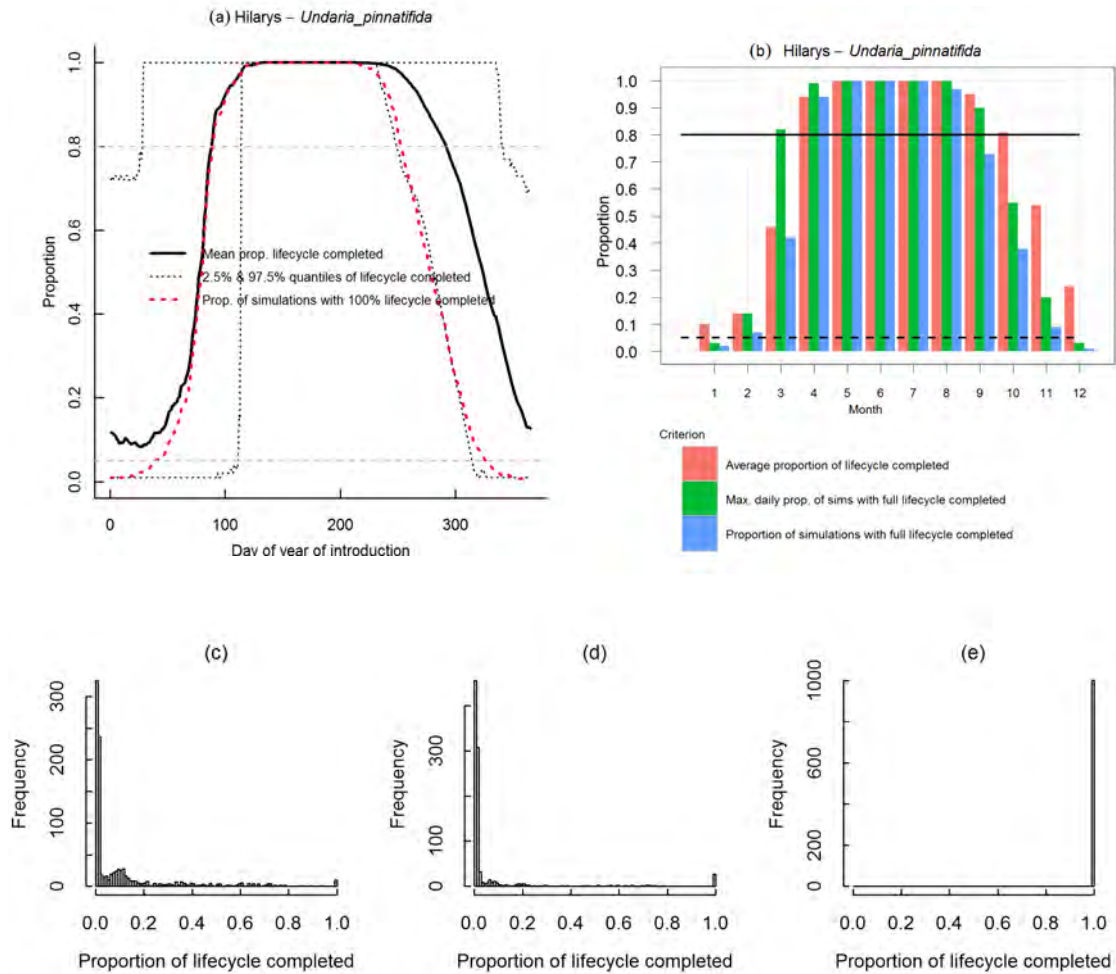

Figure B.84: Simulation results for lifecycle completion of *U. pinnatifida* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 30; (e) day 200.

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Groote Eylandt

In Groote Eylandt establishment would be considered unlikely throughout the year under the old rule and the new rule.
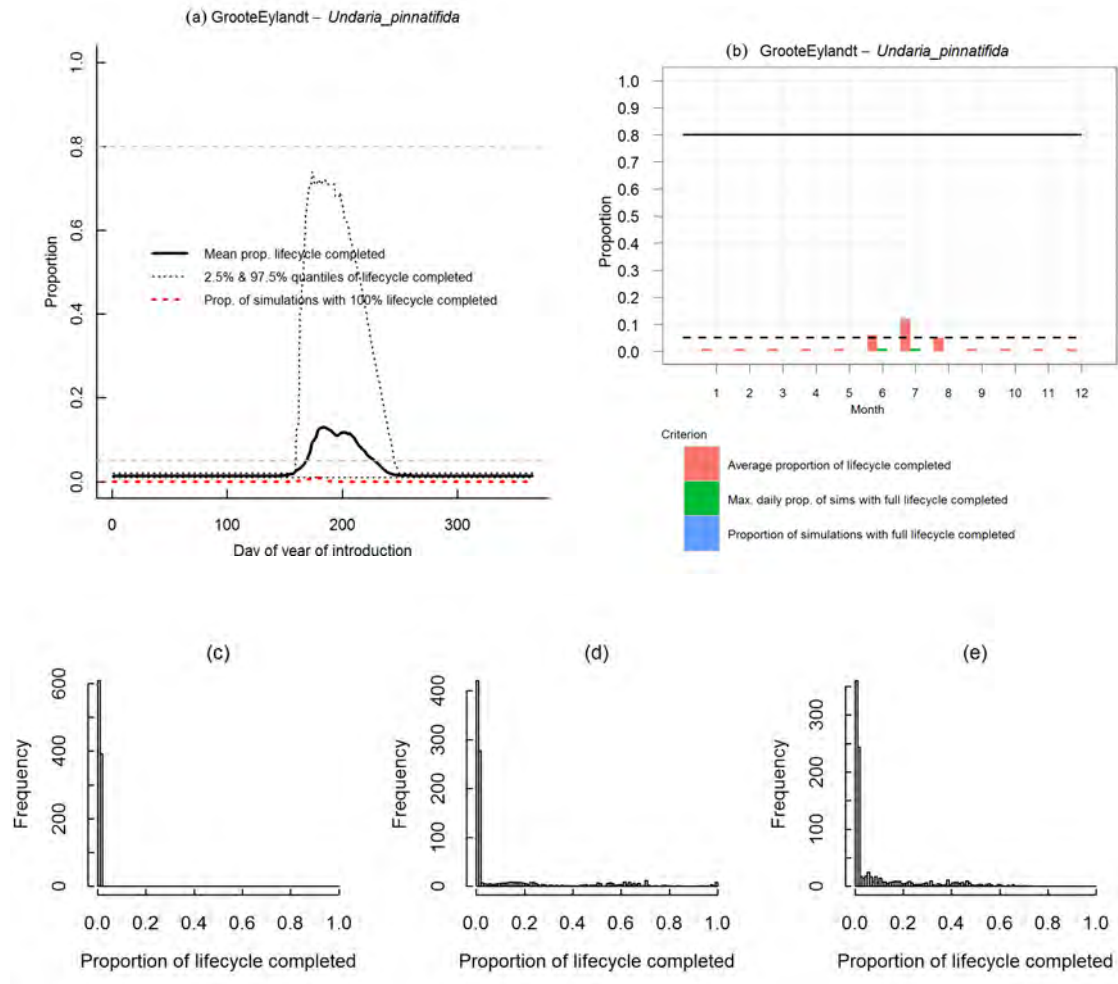

Figure B.85: Simulation results for lifecycle completion of *U. pinnatifida* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 180; (e) day 210.

Rosslyn Bay

Under the old rule, *U. pinnatifida* would be considered a risk of establishing in Rosslyn Bay from day 148 to day 200 (months June and July), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 114 to day 216 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to April – August.
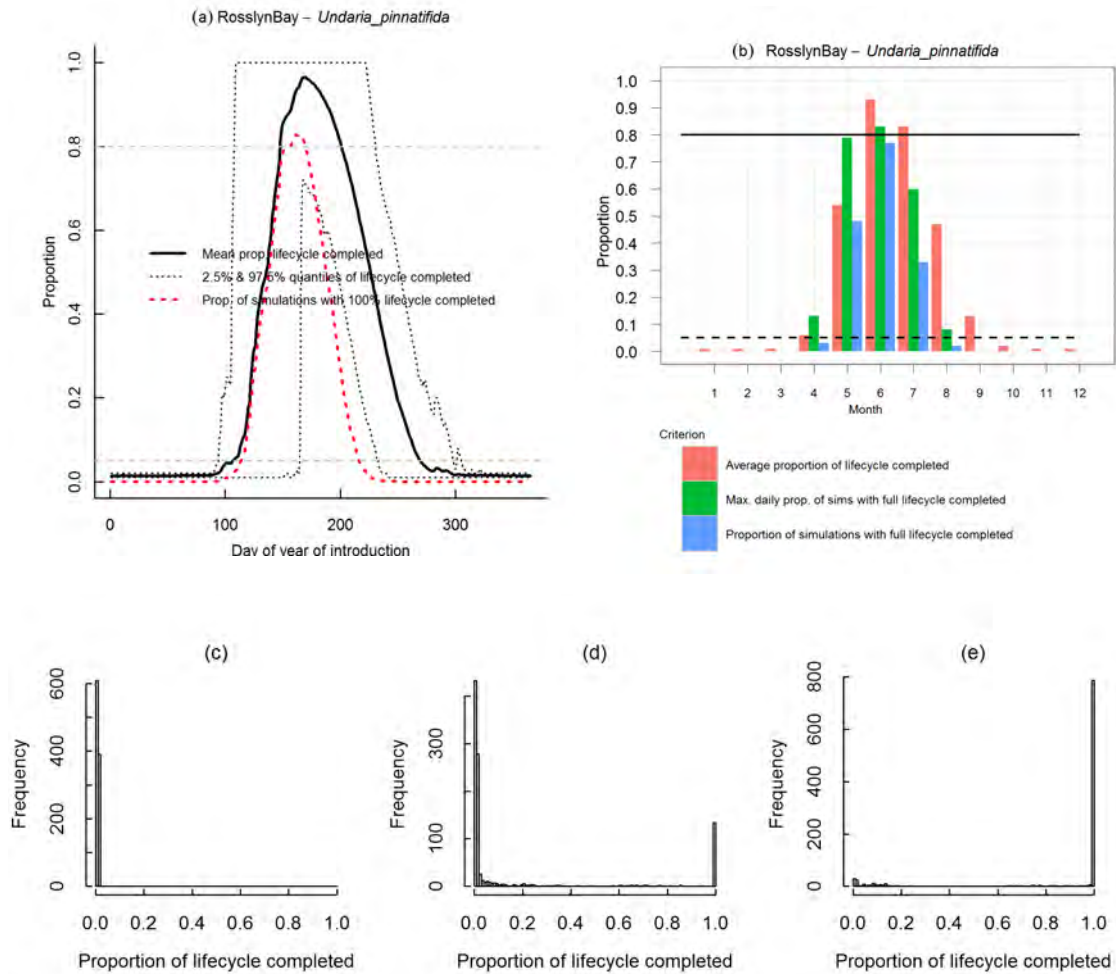

Figure B.86: Simulation results for lifecycle completion of *U. pinnatifida* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 70; (d) day 120; (e) day 150.

Port Kembla

Under the old rule, *U. pinnatifida* would be considered a risk of establishing in Port Kembla from day 88 to day 331 (months April – November), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
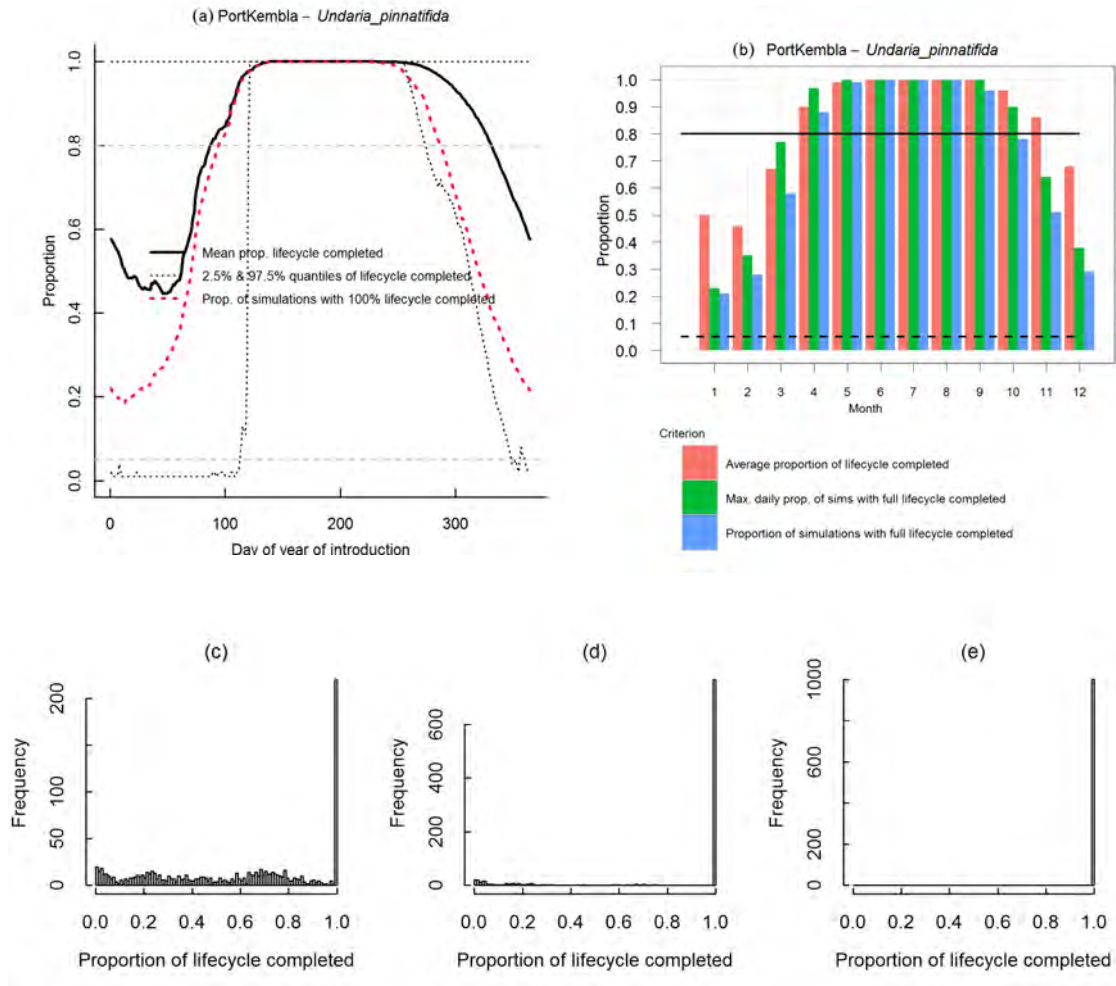

Figure B.87: Simulation results for lifecycle completion of *U. pinnatifida* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 90; (e) day 200.

Portland

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.
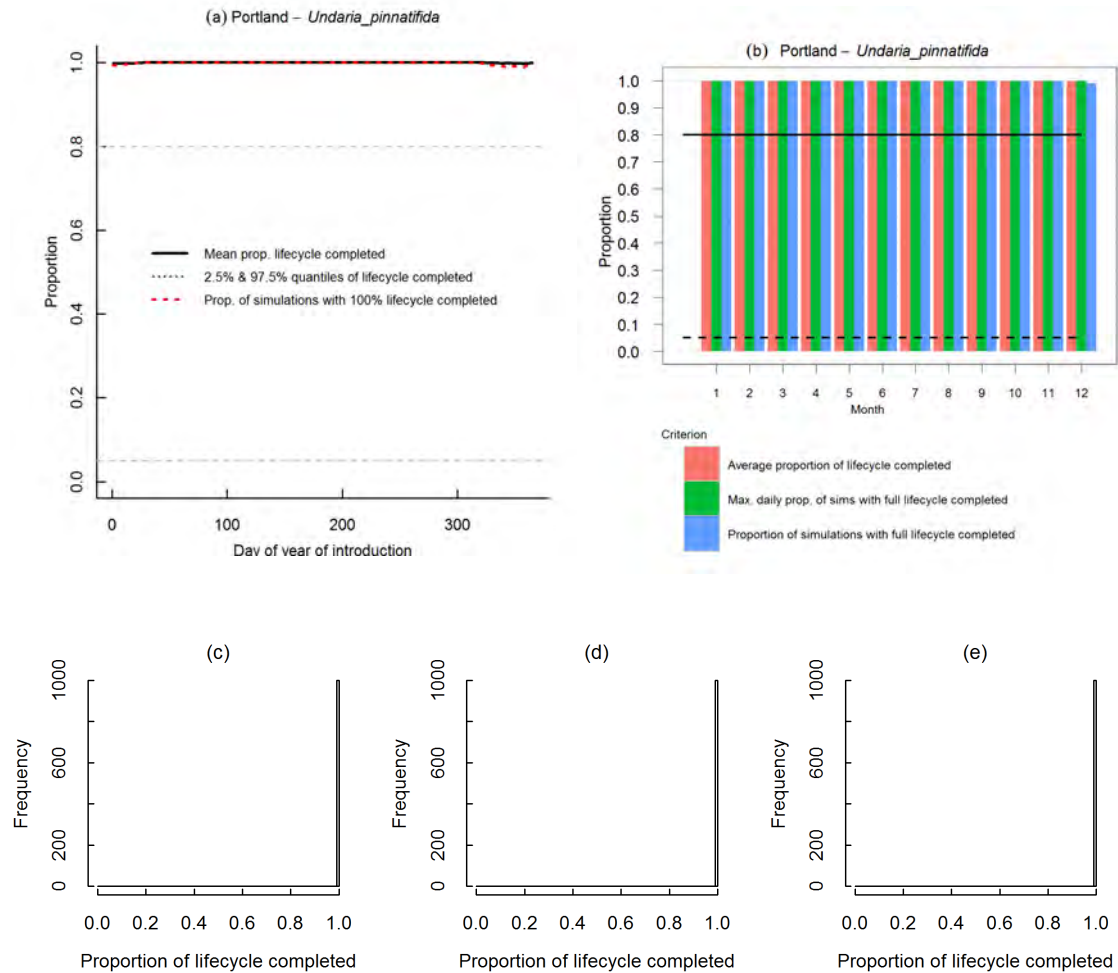

Figure B.88: Simulation results for lifecycle completion of *U. pinnatifida* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Port Stanvac

Under the old rule, *U. pinnatifida* would be considered a risk of establishing in Port Stanvac from day 73 to day 341 (months March – November), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
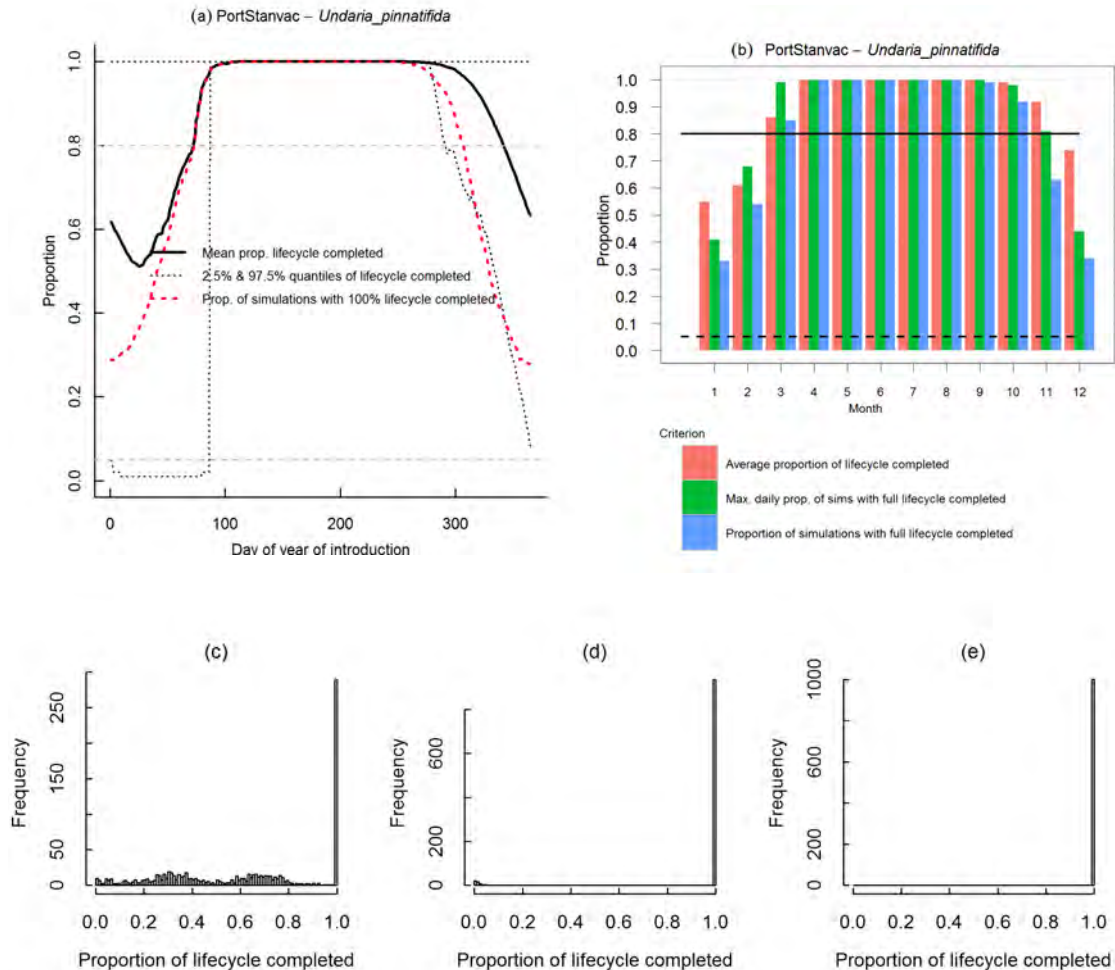

Figure B.89: Simulation results for lifecycle completion of *U. pinnatifida* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 80; (e) day 200.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.
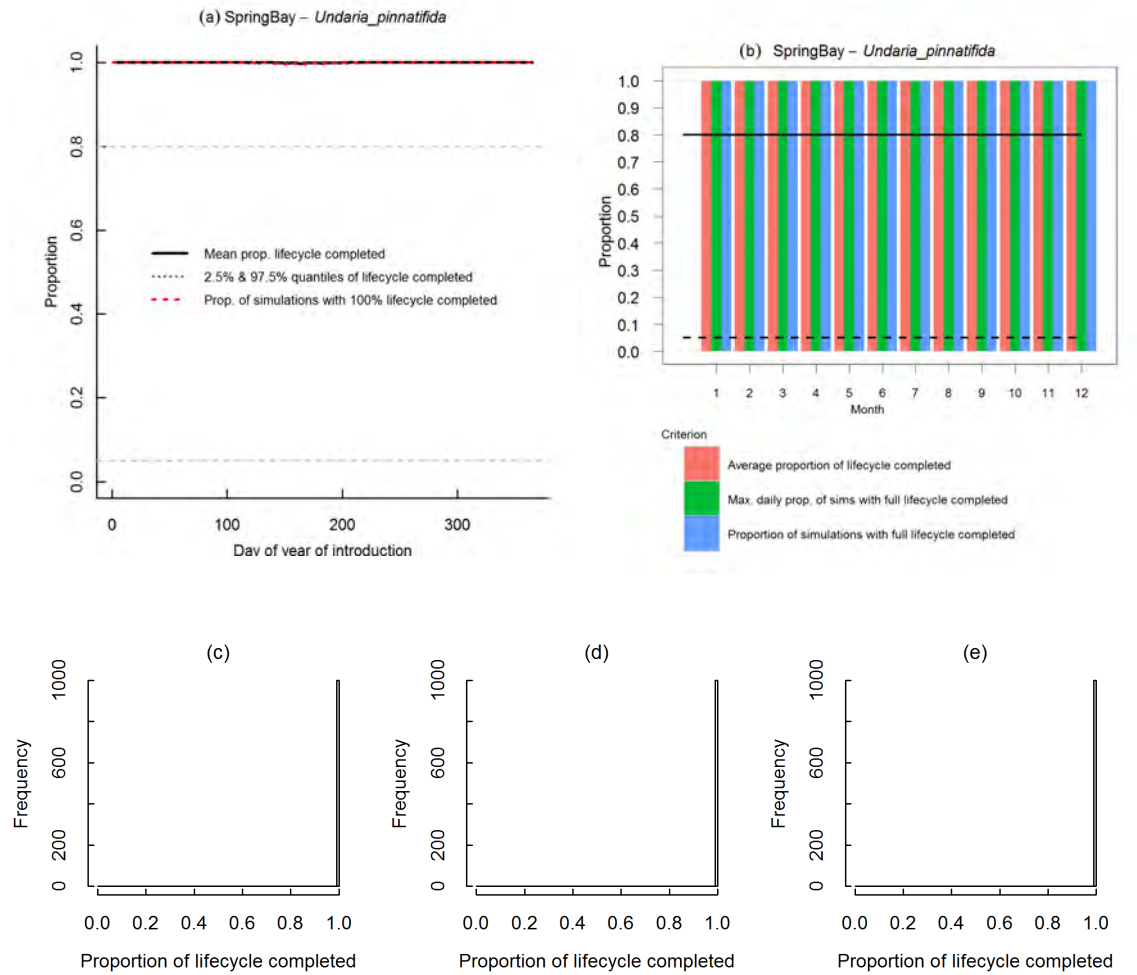

Figure B.90: Simulation results for lifecycle completion of *U. pinnatifida* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Thevenard

Under the old rule, *U. pinnatifida* would be considered a risk of establishing in Thevenard from day 68 to day 299 (months March – October), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
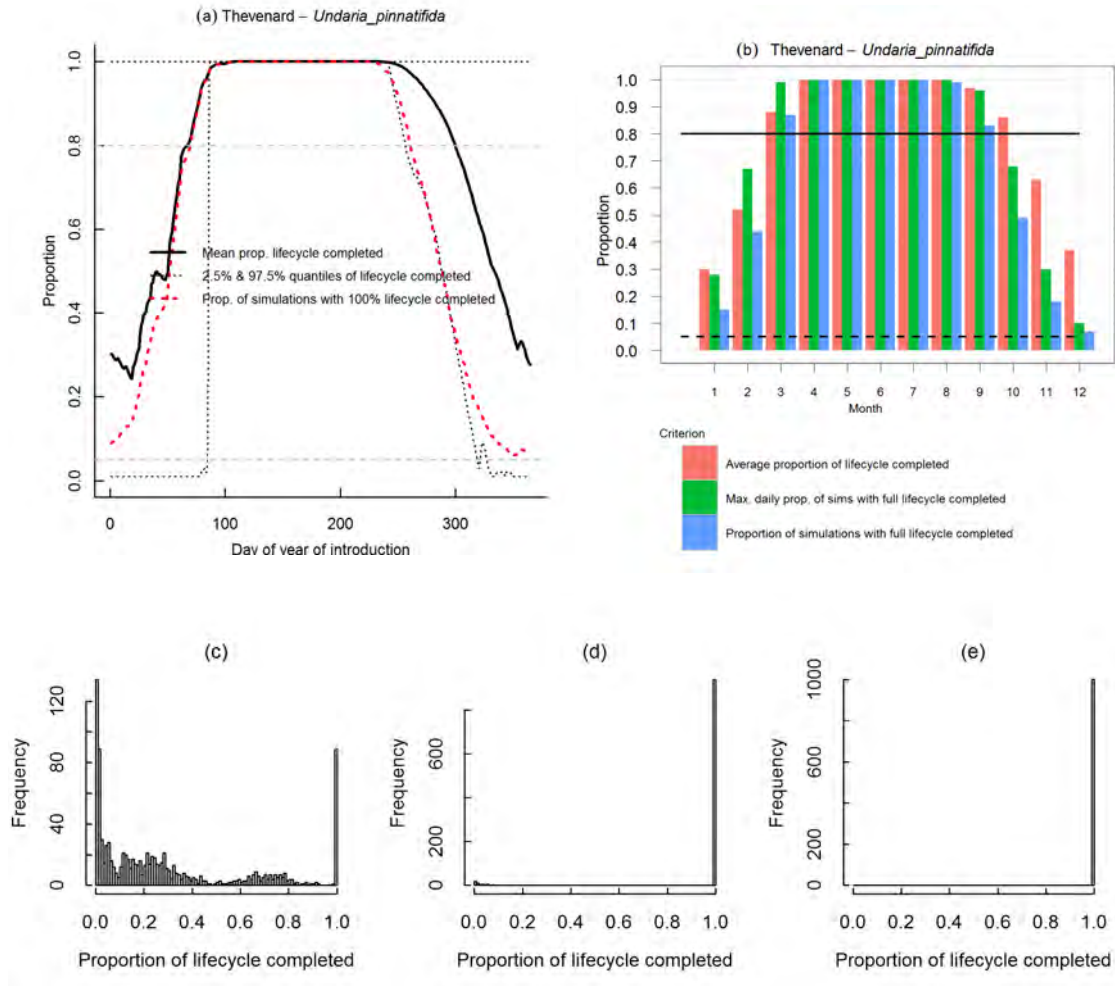

Figure B.91: Simulation results for lifecycle completion of *U. pinnatifida* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 1; (d) day 80; (e) day 200.

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B.4 Species not currently part of the BWRA

B.4.1 *Mytilopsis sallei* - Black-striped Mussel

Broome

In Broome establishment would be considered likely throughout the year under the old rule. Under the new rule we see that from day 7 to day 323 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to all month except December. When *M. sallei* doesn't complete its lifecycle, in many simulations it gets very close to completing it.
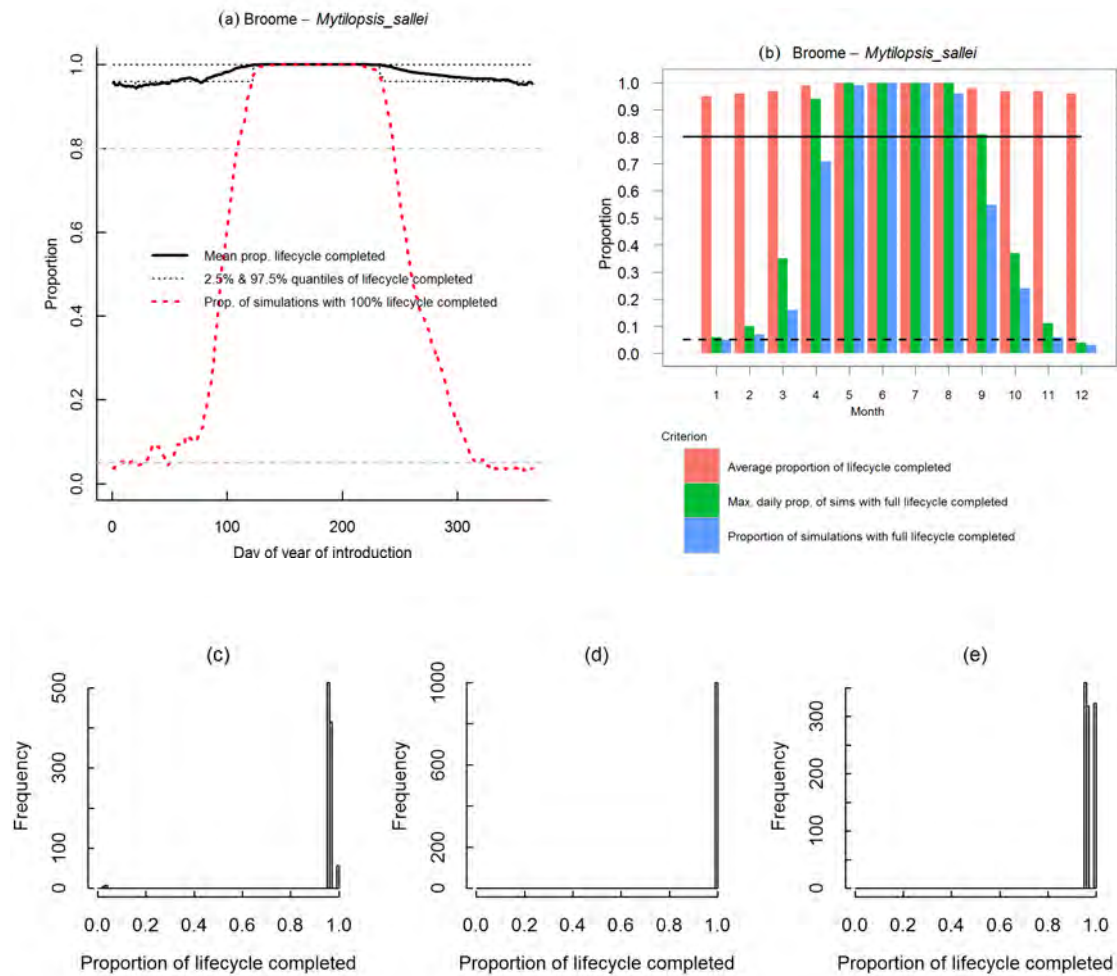

Figure B.92: Simulation results for lifecycle completion of *M. sallei* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 30; (d) day 200; (e) day 280.

Burnie

In Burnie establishment would be considered possible throughout the year under the old rule and the new rule.
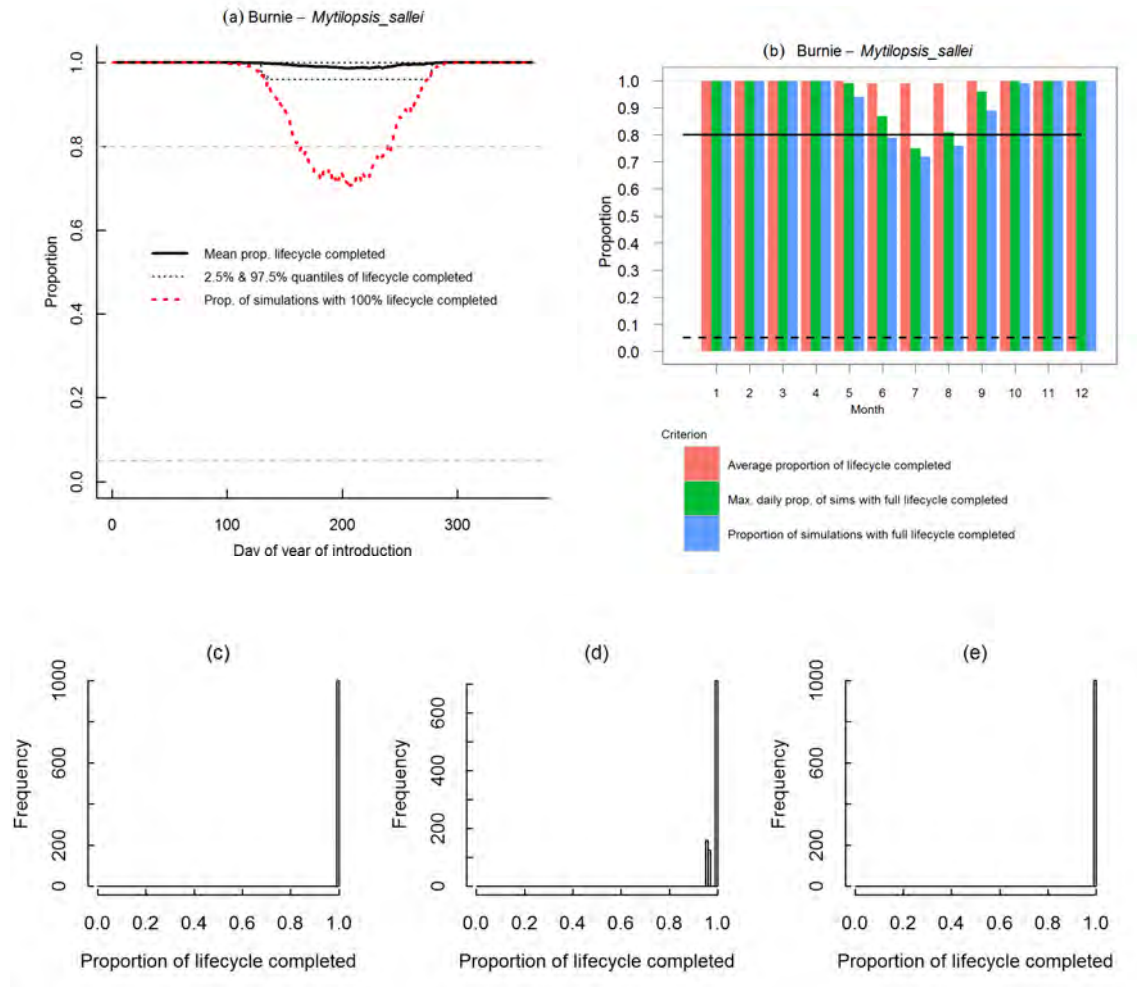

Figure B.93: Simulation results for lifecycle completion of *M. sallei* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 210; (e) day 300.

Cape Ferguson

In Cape Ferguson establishment would be considered possible throughout the year under the old rule and the new rule.
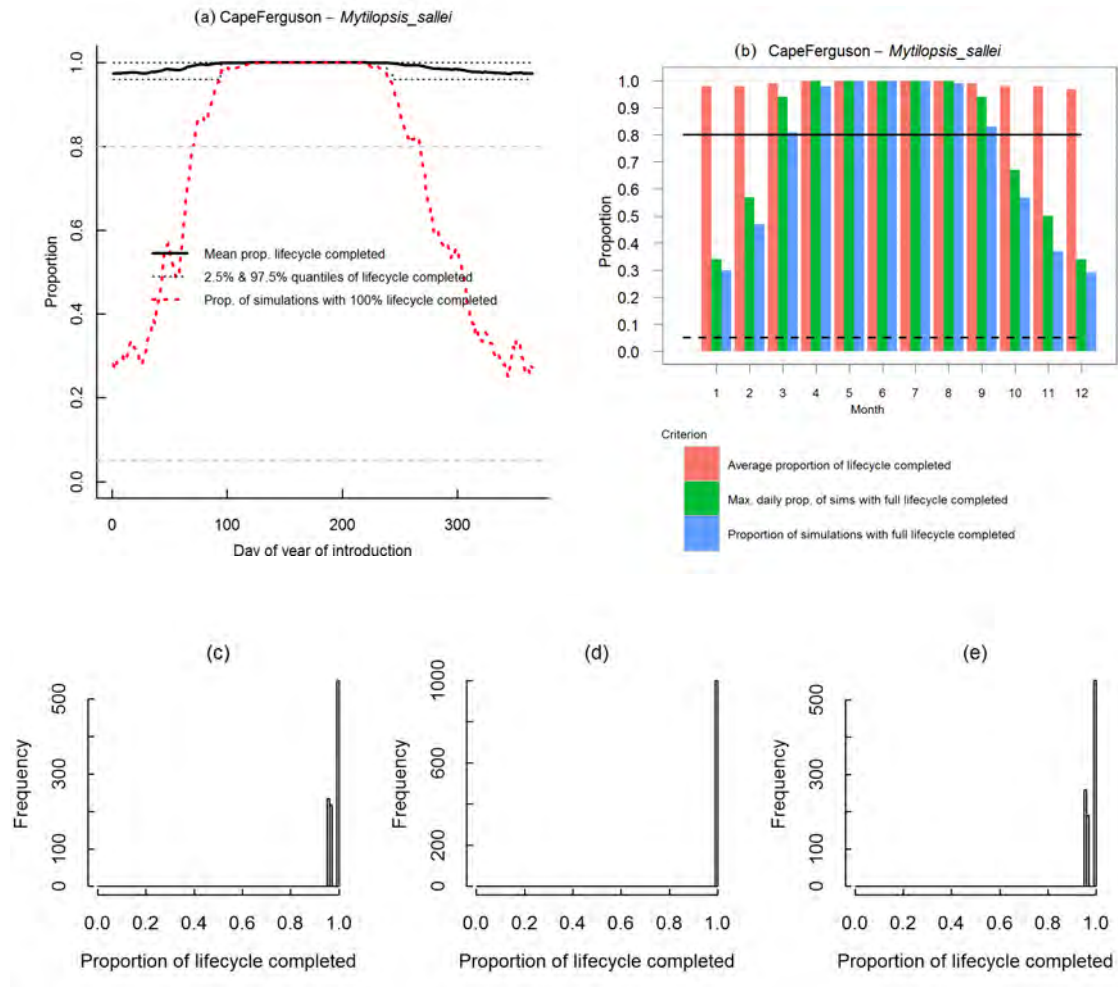

Figure B.94: Simulation results for lifecycle completion of *M. sallei* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Darwin

In Darwin establishment would be considered possible throughout the year under the old rule. Under the new rule we see that establishment would be considered possible over much of the year. For the new monthly rule this corresponds to December – September. When *M. sallei* doesn't complete its lifecycle, in many simulations it gets very close to completing it.
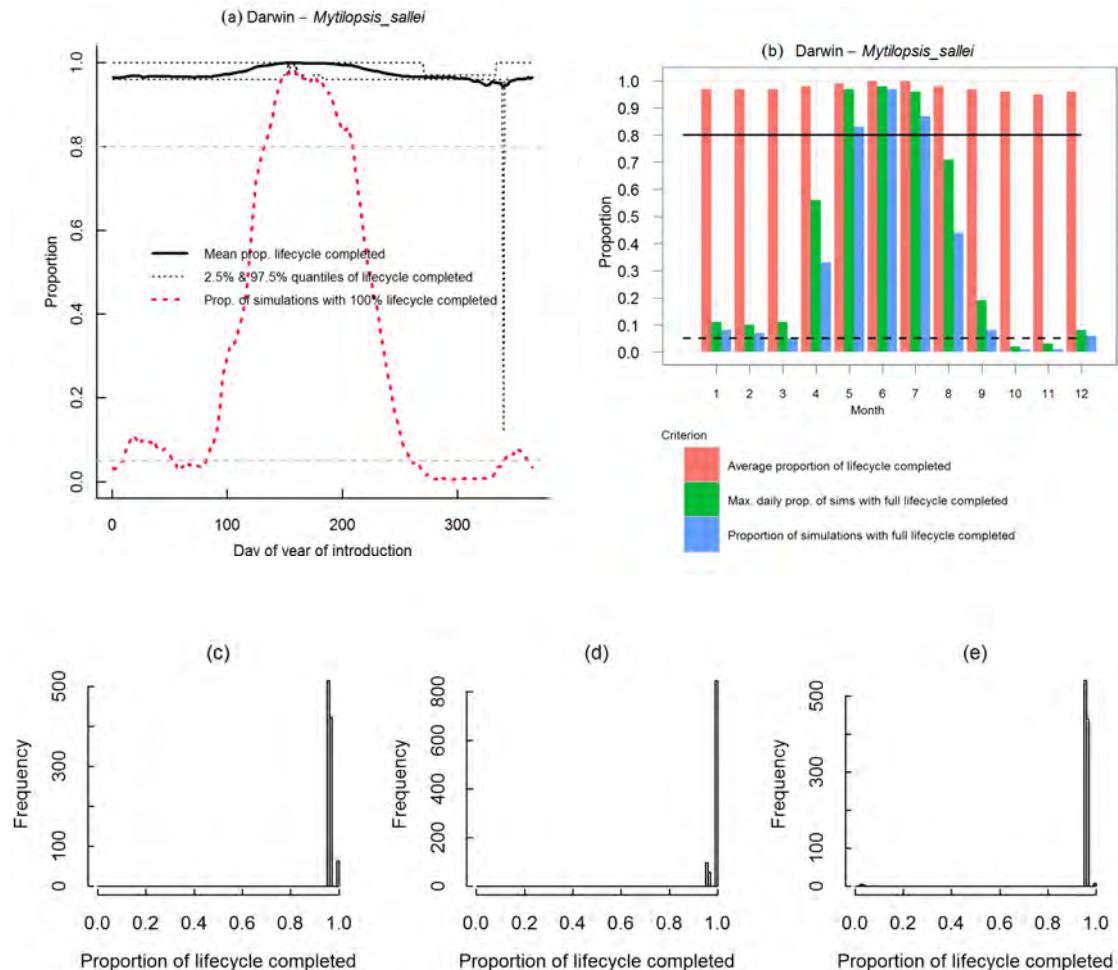

Figure B.95: Simulation results for lifecycle completion of *M. sallei* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 320.

Esperance

In Esperance establishment would be considered possible throughout the year under the old rule and the new rule.
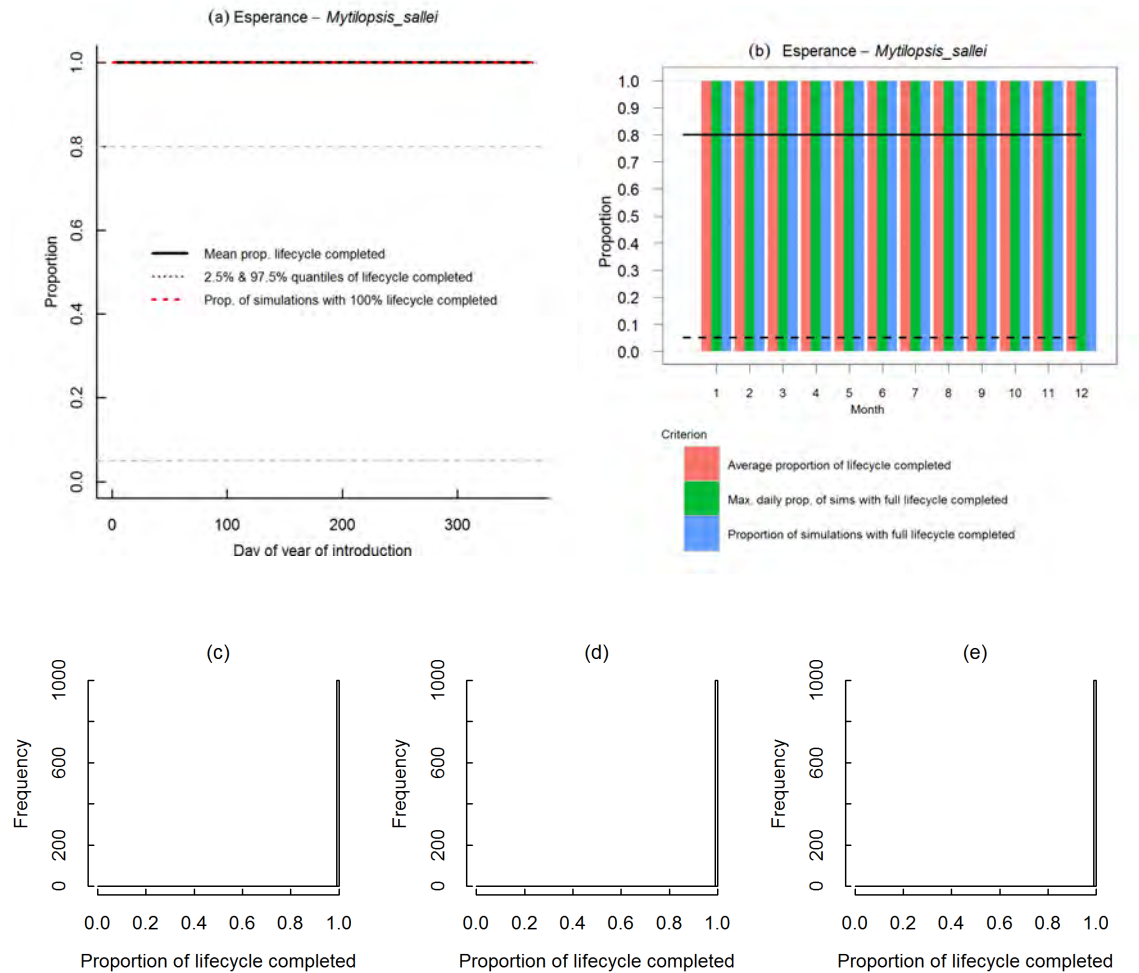

Figure B.96: Simulation results for lifecycle completion of *M. sallei* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Hilarys

In Hilarys establishment would be considered possible throughout the year under the old rule and the new rule.
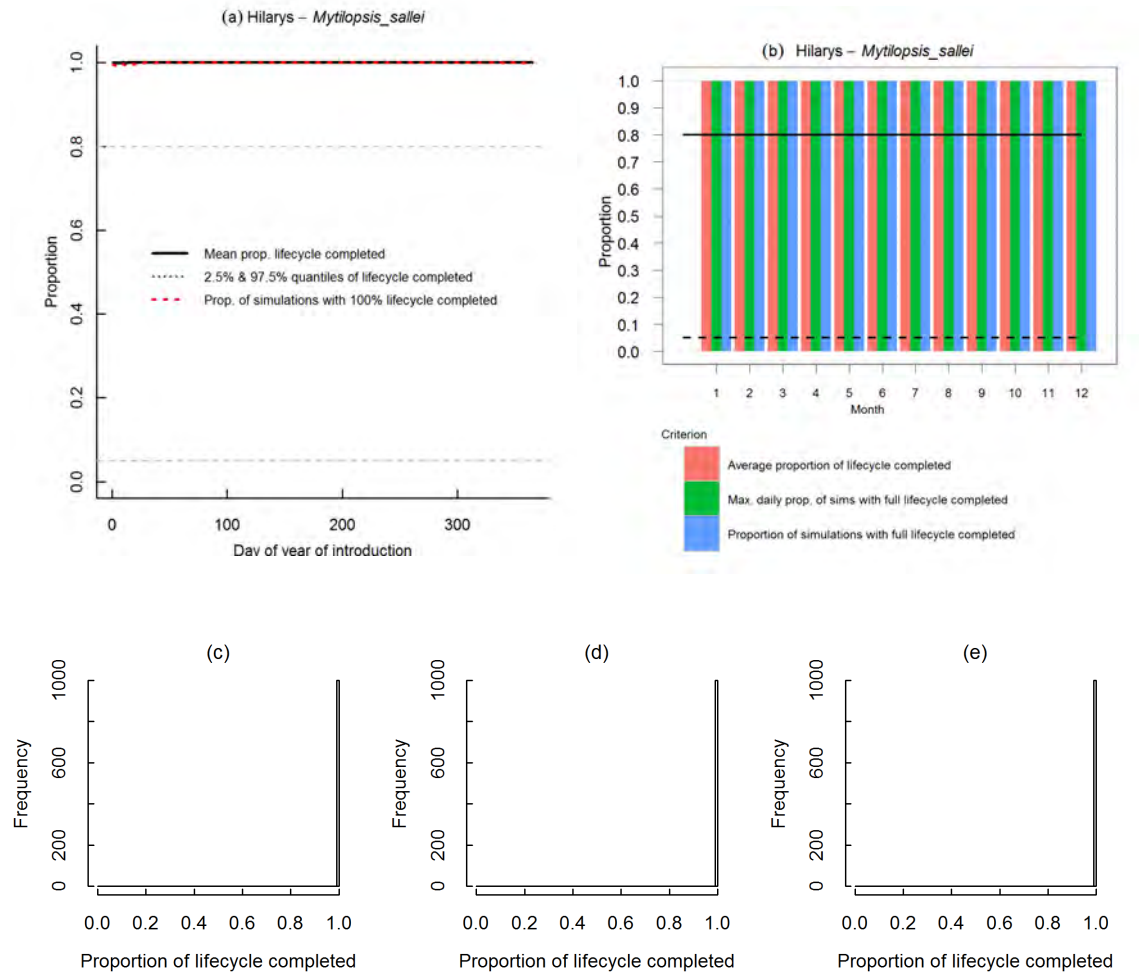

Figure B.97: Simulation results for lifecycle completion of *M. sallei* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Groote Eylandt

In Groote Eylandt establishment would be considered possible throughout the year under the old rule. Under the new rule we see would be considered possible over much of the year. For the new monthly rule this corresponds to March – October plus December. When *M. sallei* doesn't complete its lifecycle, in many simulations it gets very close to completing it.
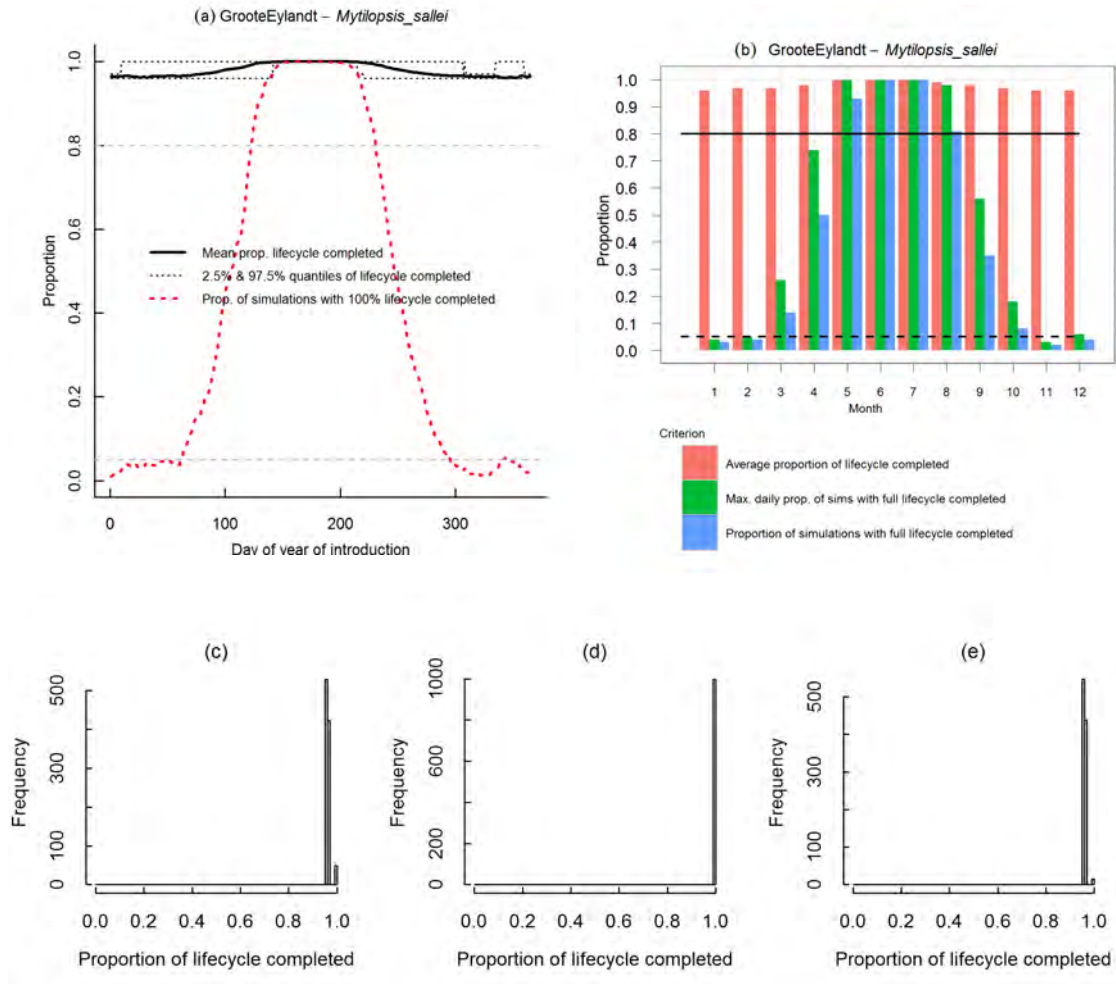

Figure B.98: Simulation results for lifecycle completion of *M. sallei* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 330.

Rosslyn Bay

In Rosslyn Bay establishment would be considered possible throughout the year under the old rule and the new rule.
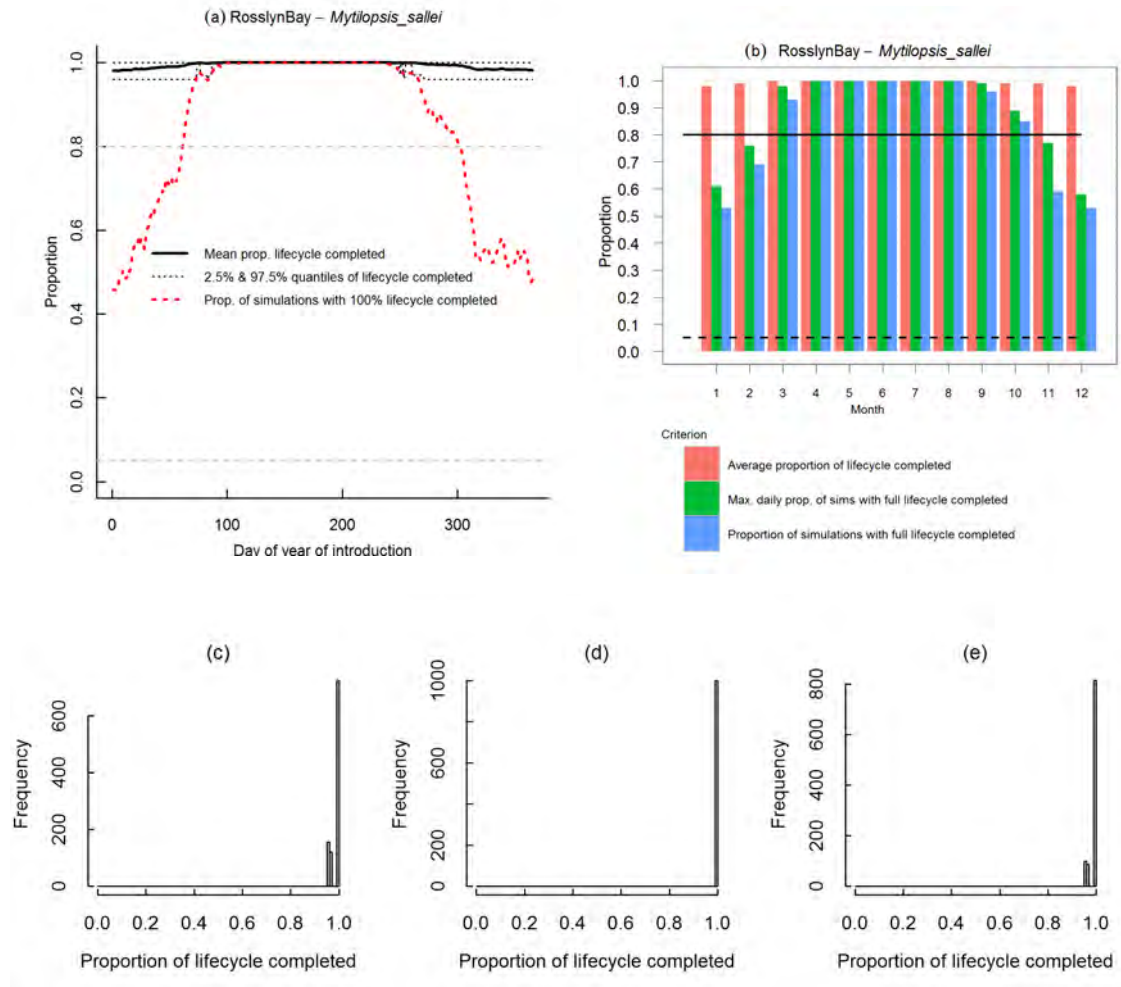

Figure B.99: Simulation results for lifecycle completion of *M. sallei* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Port Kembla

In Port Kembla establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.100: Simulation results for lifecycle completion of *M. sallei* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Portland

In Portland establishment would be considered possible throughout the year under the old rule and the new rule.
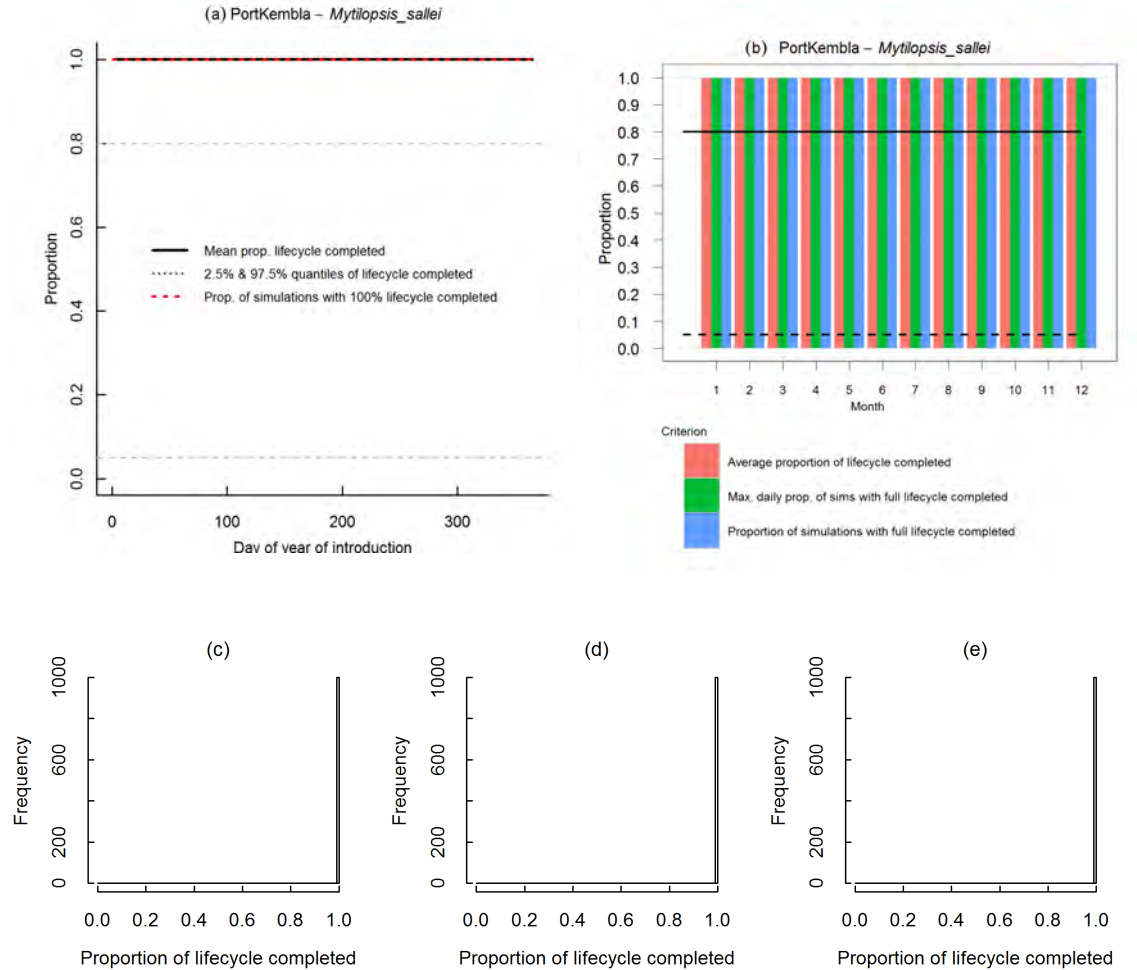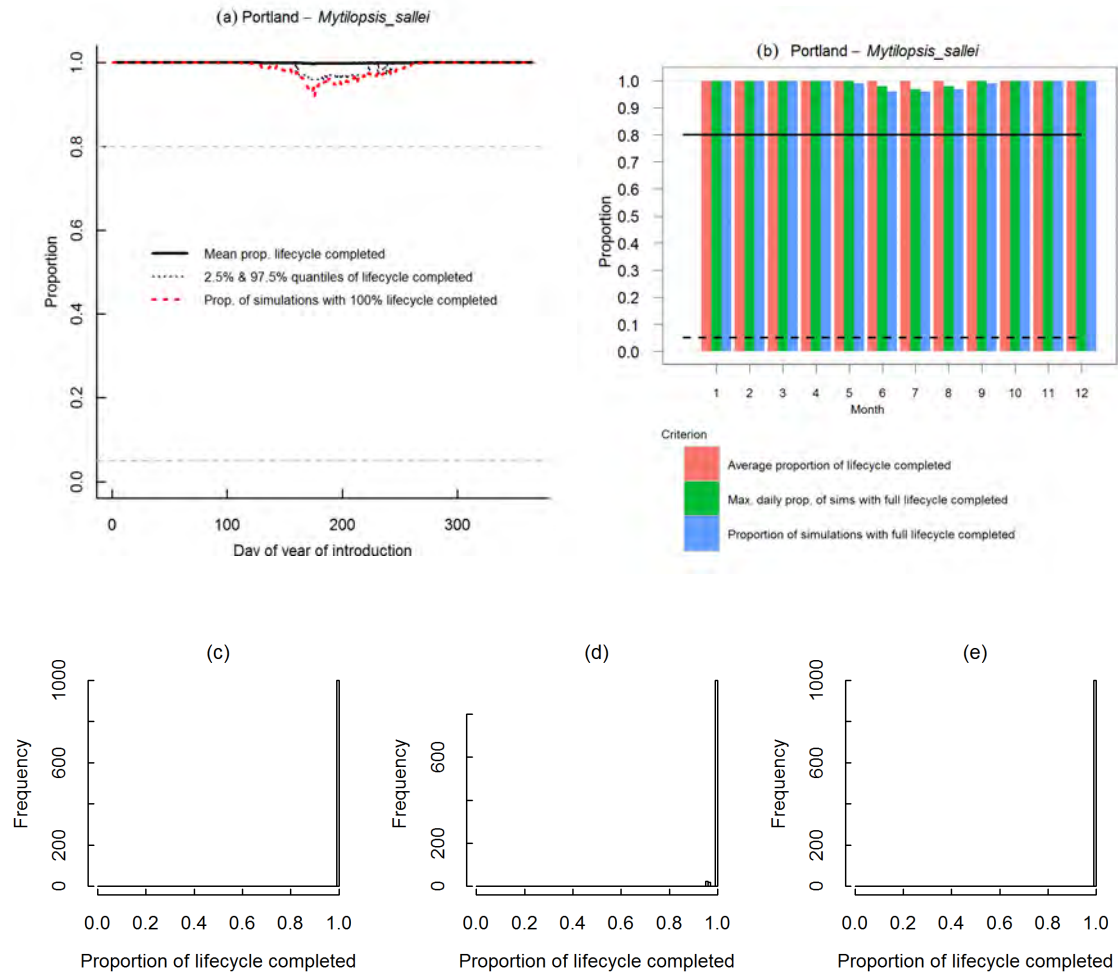

Figure B.101: Simulation results for lifecycle completion of *M. sallei* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Port Stanvac

In Port Stanvac establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.102: Simulation results for lifecycle completion of *M. sallei* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

Spring Bay

In Spring Bay establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.103: Simulation results for lifecycle completion of *M. sallei* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 190; (e) day 300.

Thevenard

In Thevenard establishment would be considered possible throughout the year under the old rule and the new rule.
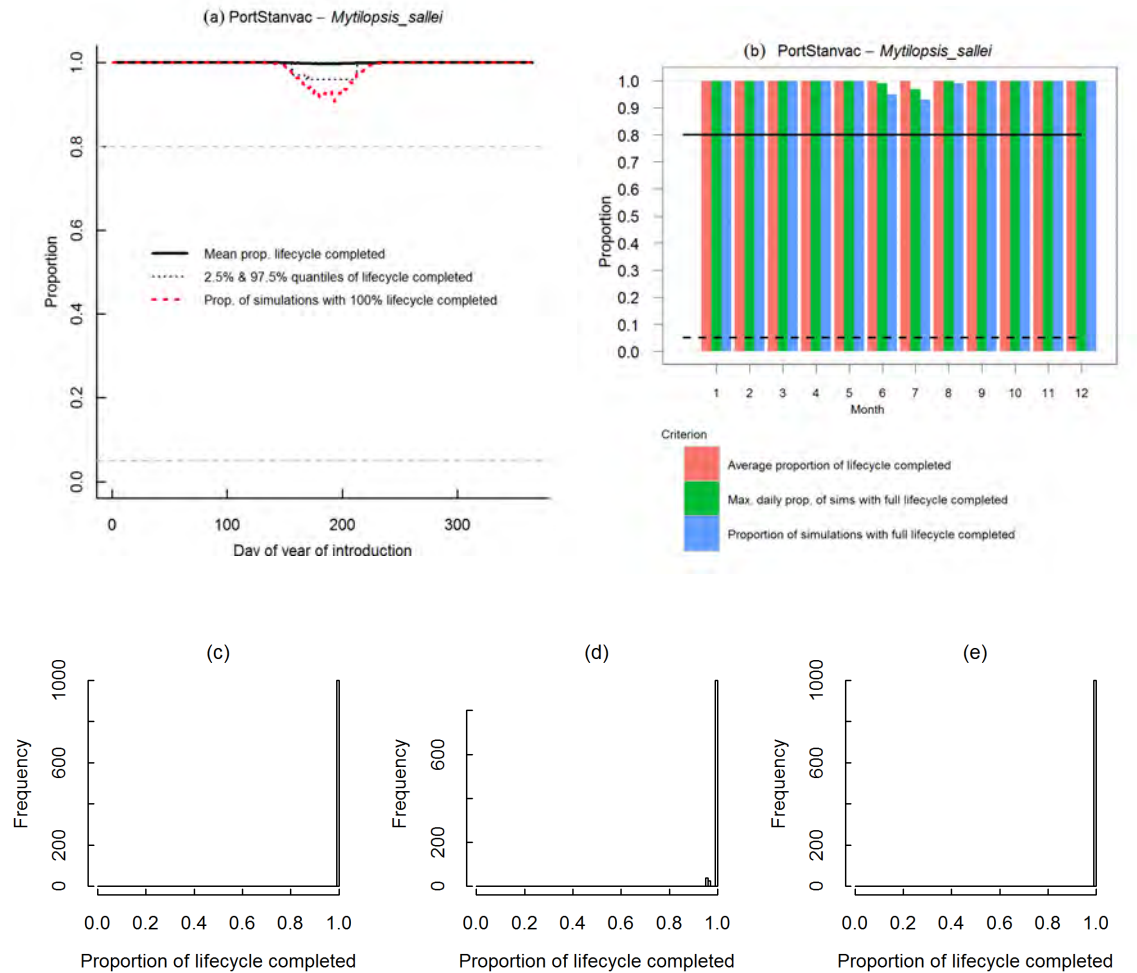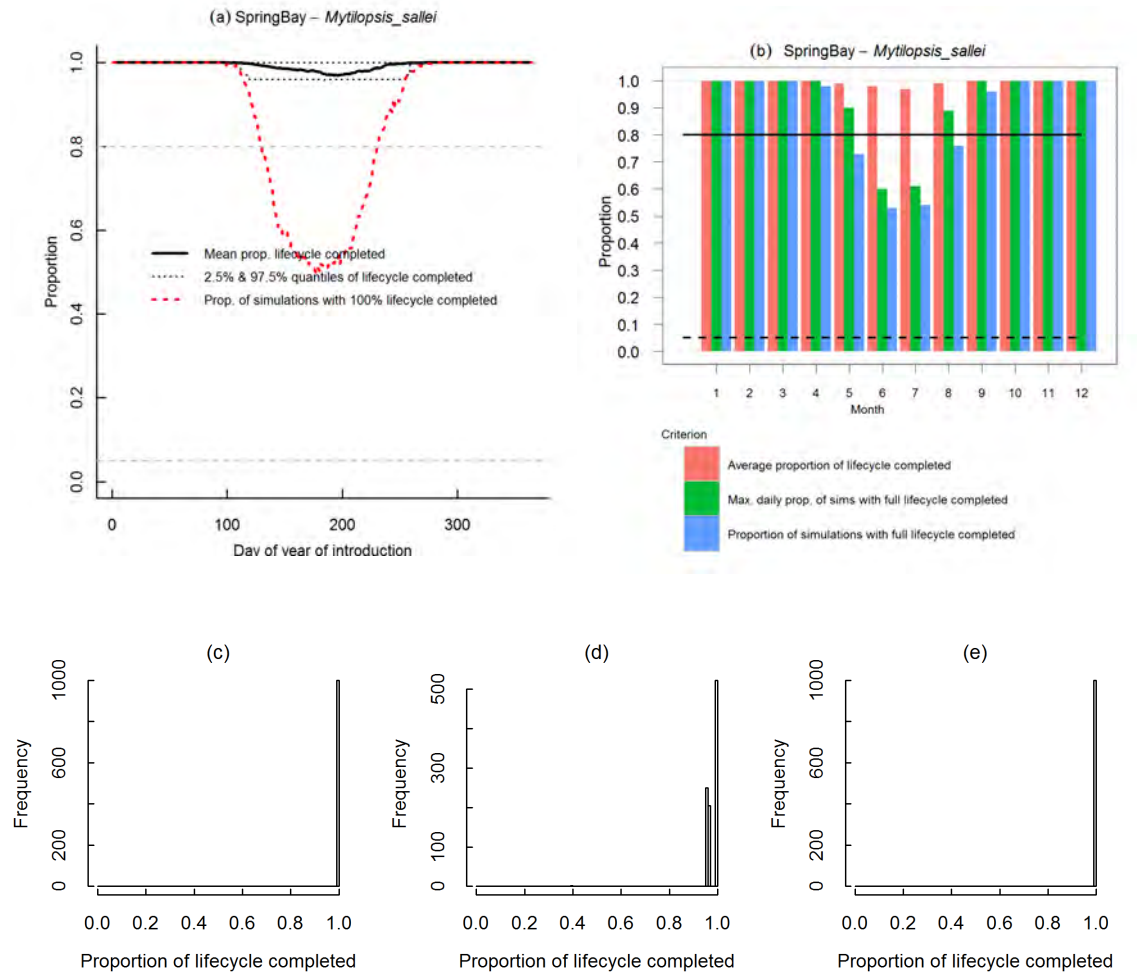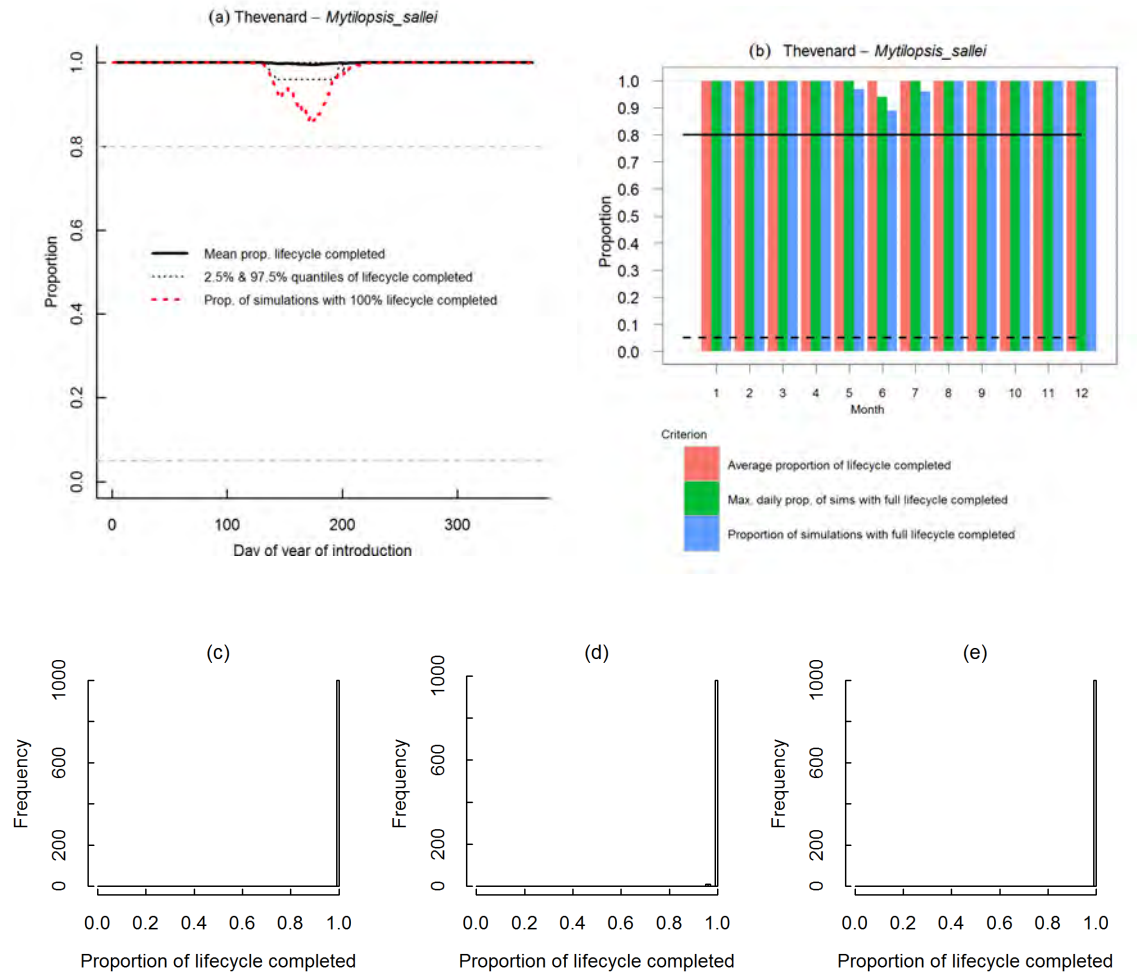

Figure B.104: Simulation results for lifecycle completion of *M. sallei* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 300.

B.4.2 *Perna viridis* - Asian Green Mussel

Broome

Under the old rule, *P. viridis* would be considered a risk of establishing in Broome from day 240 to day 139 (months September – May), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.

Figure B.105: Simulation results for lifecycle completion of *P. viridis* in Broome. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 100; (d) day 180; (e) day 300.

Burnie

In Burnie establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.106: Simulation results for lifecycle completion of *P. viridis* in Burnie. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 40; (d) day 60; (e) day 300.

Cape Ferguson

Under the old rule, *P. viridis* would be considered a risk of establishing in Cape Ferguson from day 242 to day 121 (months September – April), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that over the entire year the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over the entire year.
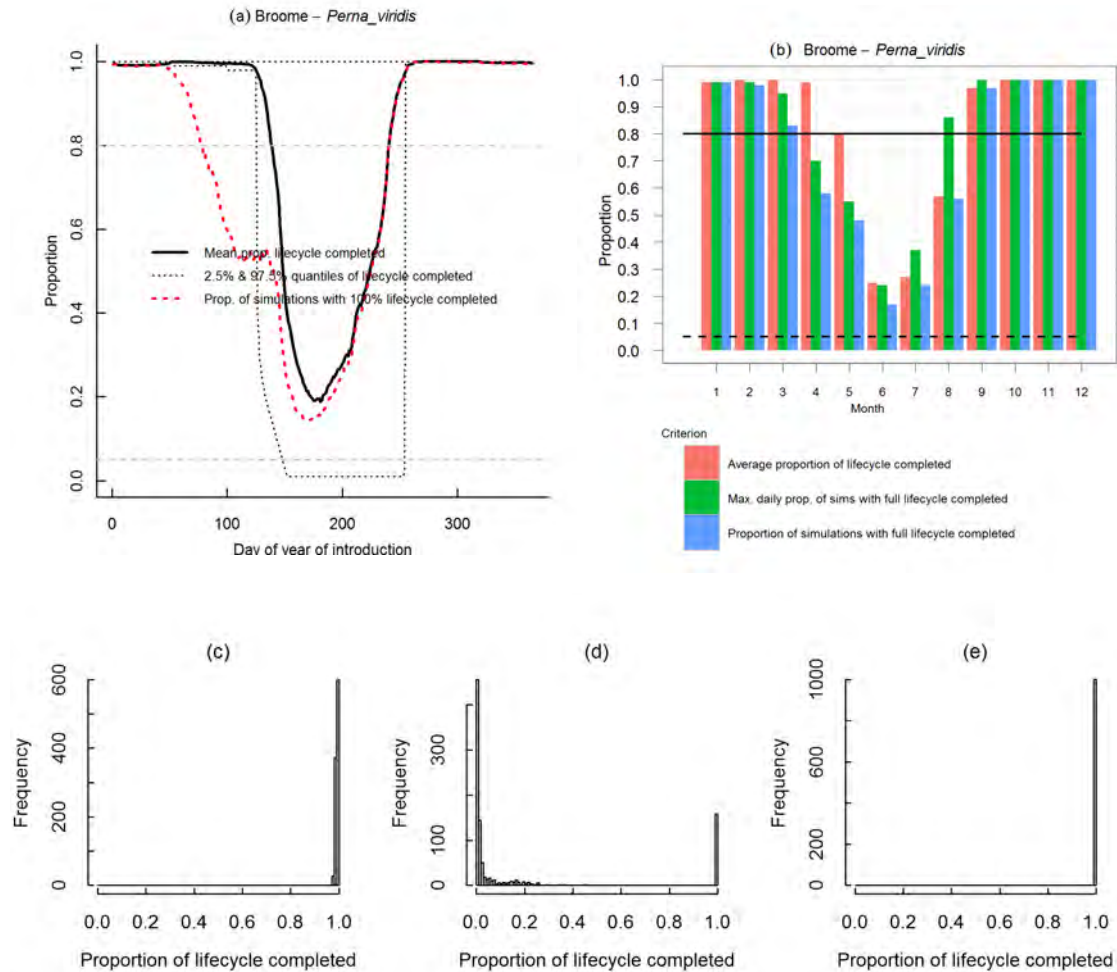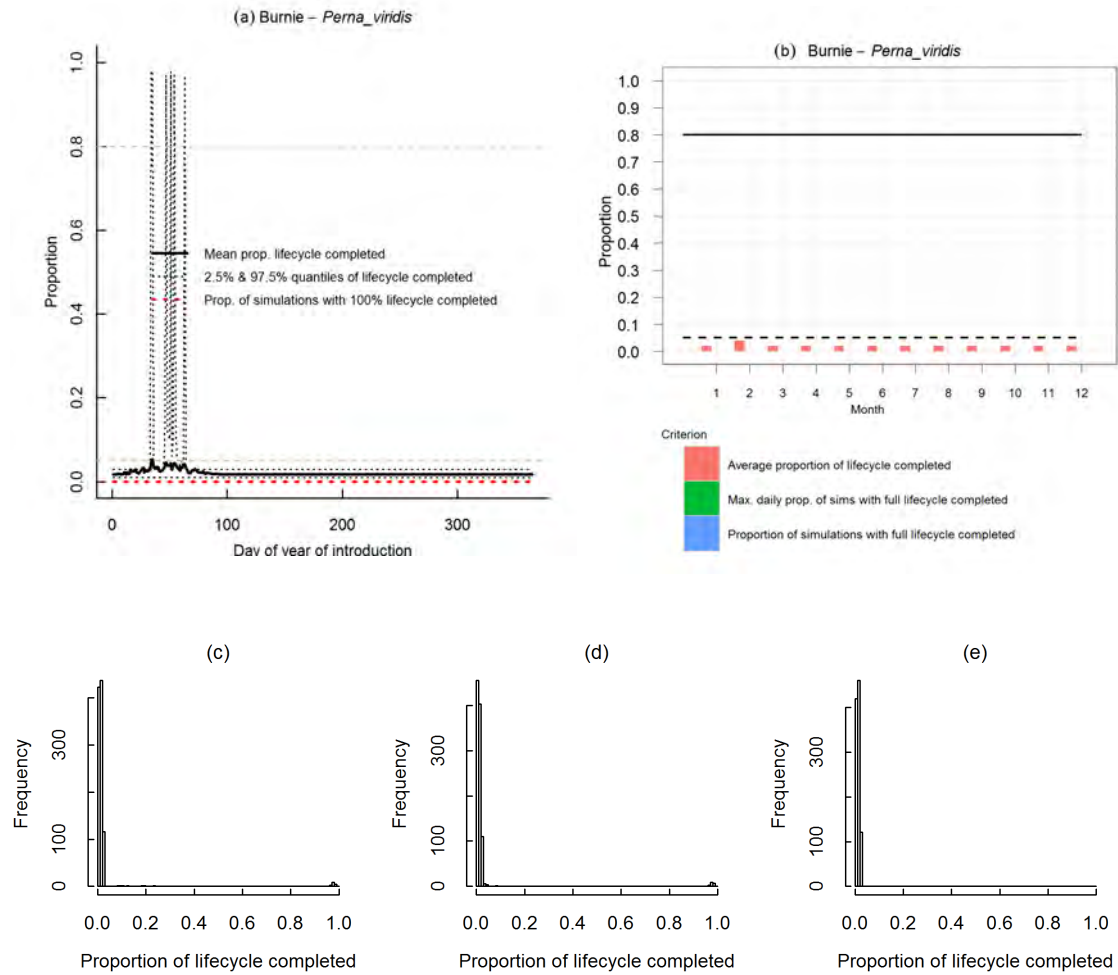

Figure B.107: Simulation results for lifecycle completion of *P. viridis* in Cape Ferguson. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 100; (d) day 160; (e) day 300.

Darwin

In Darwin establishment would be considered possible throughout the year under the old rule and the new rule.

Figure B.108: Simulation results for lifecycle completion of *P. viridis* in Darwin. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 320.

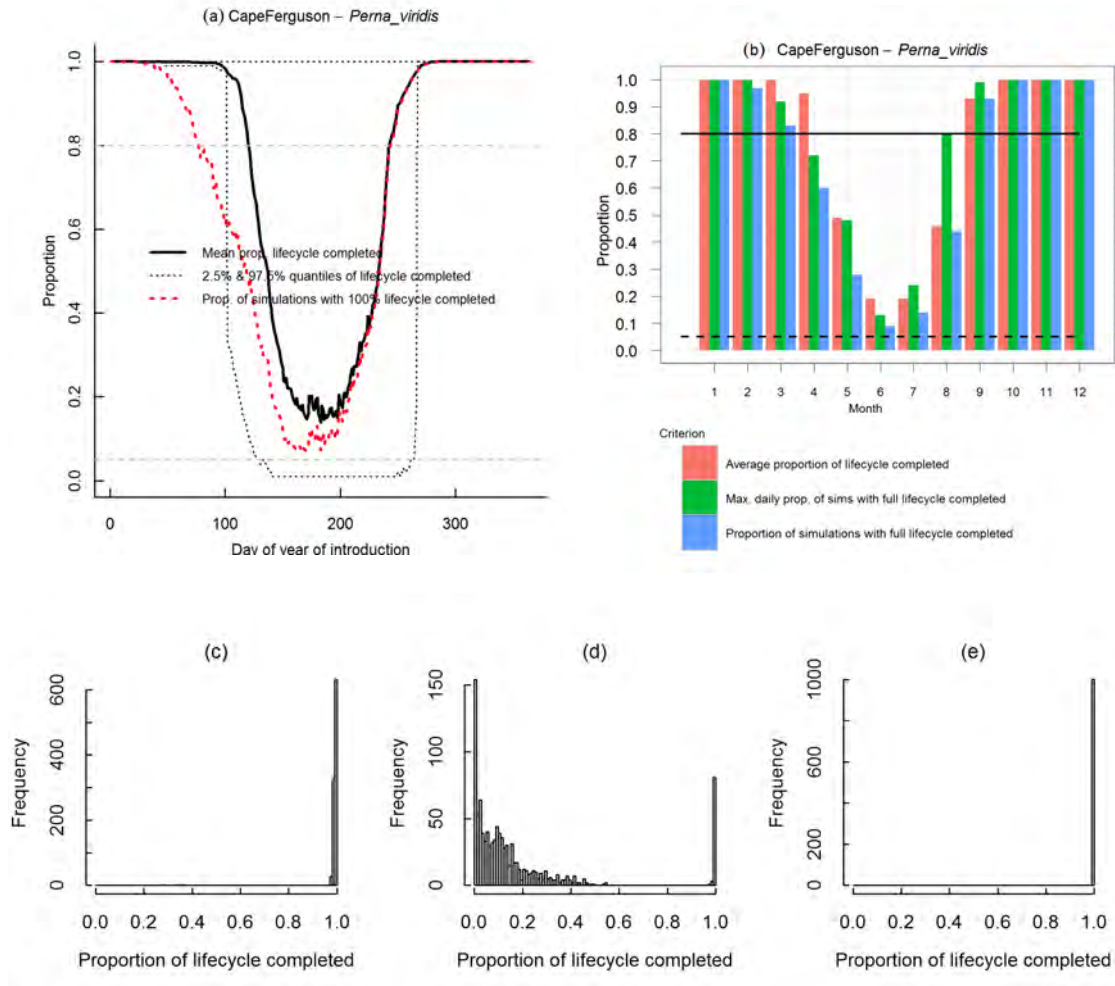In Esperance establishment would be considered unlikely throughout the year under the old rule and the new rule.

Figure B.109: Simulation results for lifecycle completion of *P. viridis* in Esperance. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 60; (e) day 300.

Hilarys

Under the old rule, *P. viridis* would be considered a risk of establishing in Hilarys from day 360 to day 38 (January), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 310 to day 39 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to November – February.
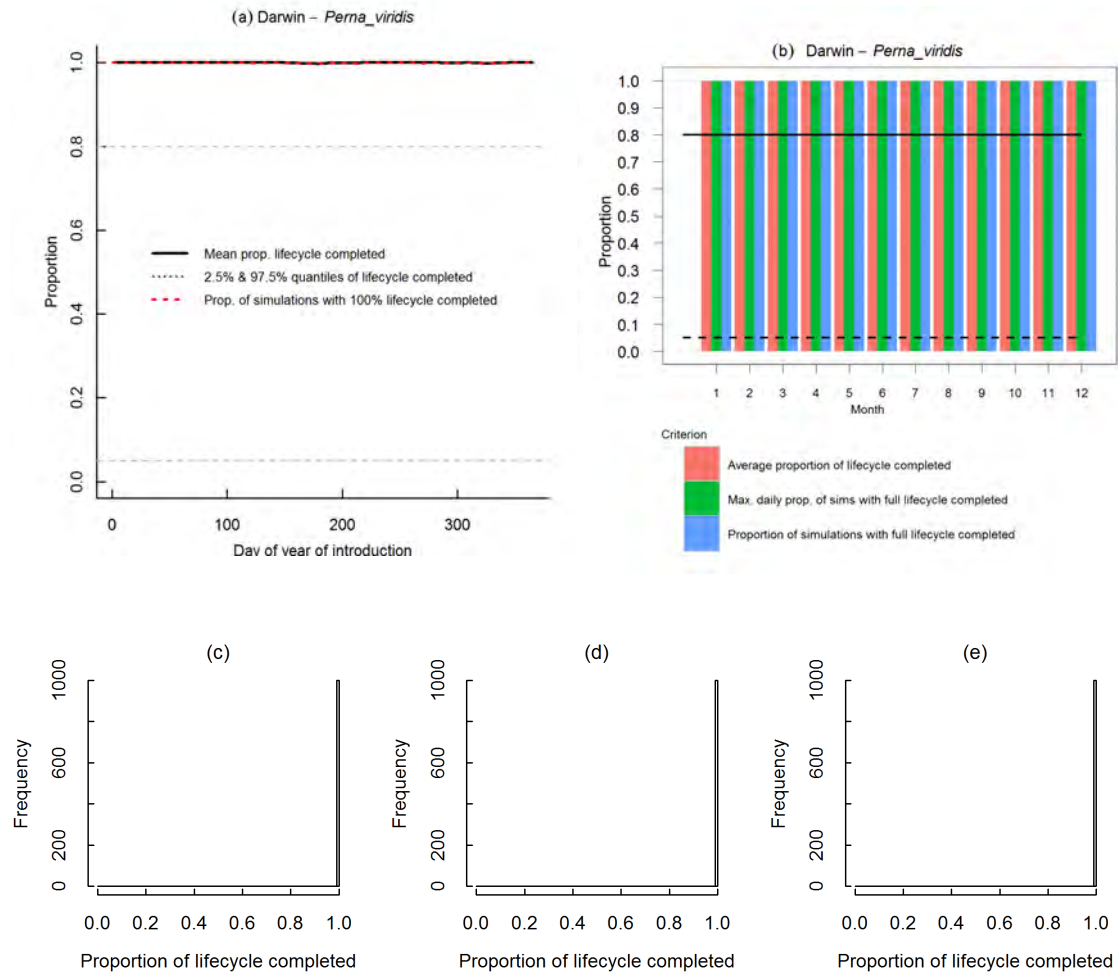

Figure B.110: Simulation results for lifecycle completion of *P. viridis* in Hilarys. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 200; (e) day 320.

Groote Eylandt

In Groote Eylandt establishment would be considered possible throughout the year under the old rule and the new rule.
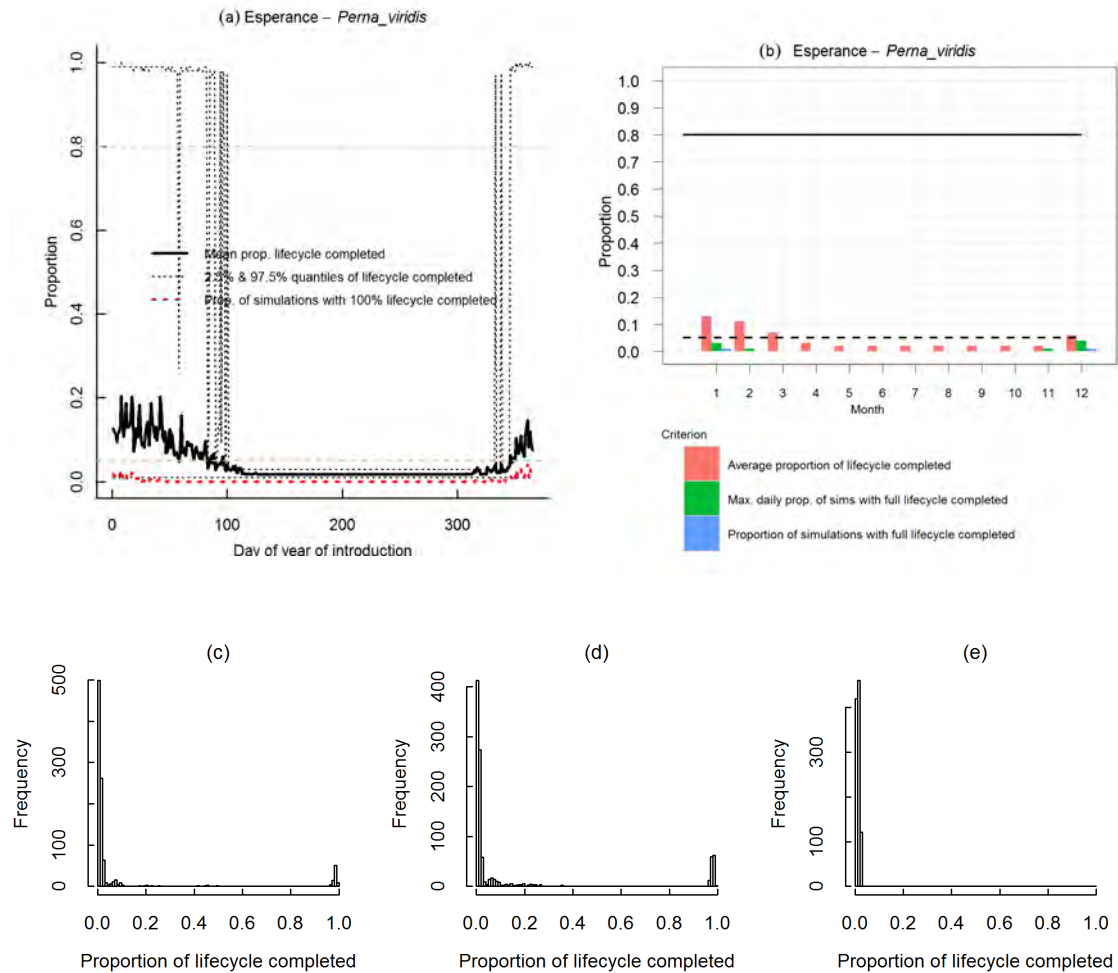

Figure B.111: Simulation results for lifecycle completion of *P. viridis* in Groote Eylandt. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 330.

Rosslyn Bay

Under the old rule, *P. viridis* would be considered a risk of establishing in Rosslyn Bay from day 263 to day 98 (months October – March), with the average proportion of lifecycle completed over that period greater than 0.8. Under the new rule, we see that from day 224 to day 109 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to August – April.

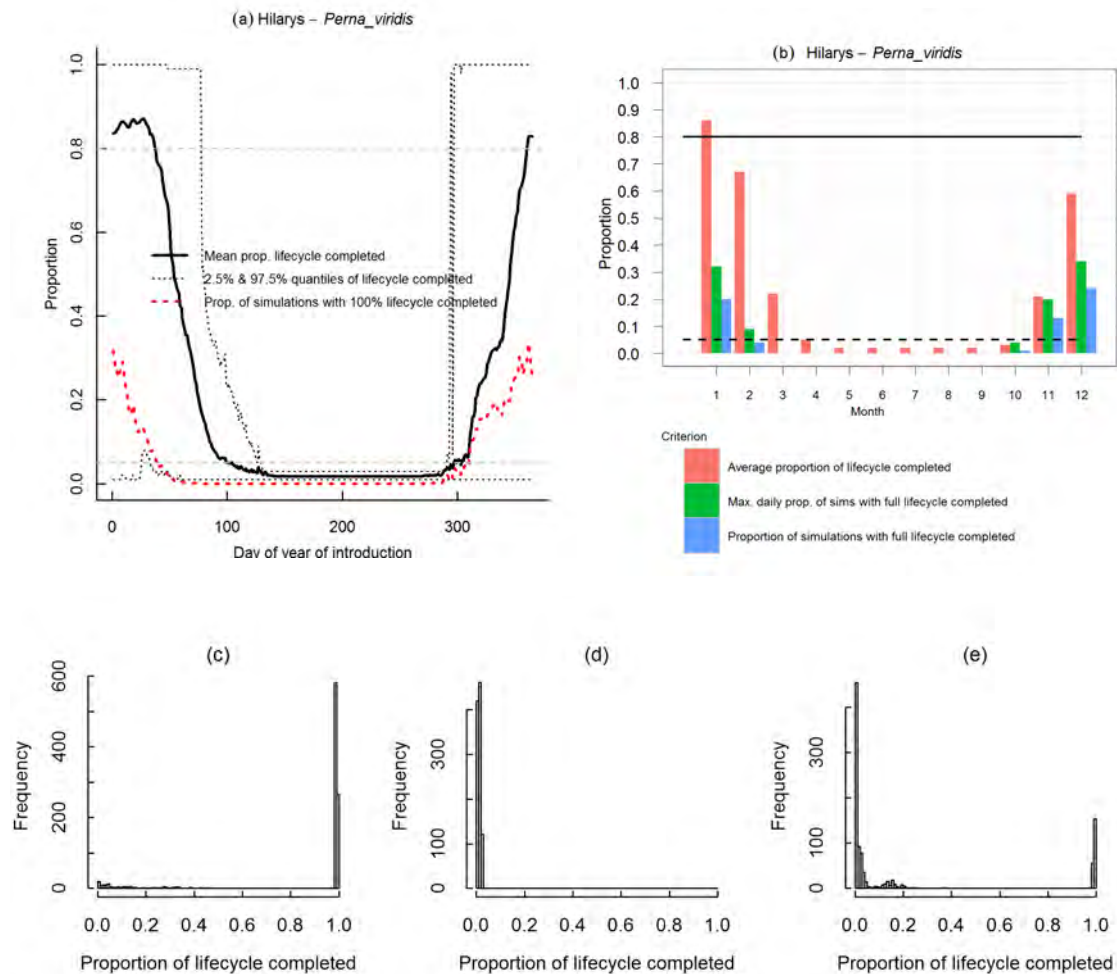**Figure B.112:** Simulation results for lifecycle completion of *P. viridis* in Rosslyn Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 250.

Port Kembla

Under the old rule, *P. viridis* would never be considered a risk of establishing in Port Kembla, with the average proportion of lifecycle completed always less than 0.8. However, we see that from day 363 to day 22 the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period under the new rule. For the new monthly rule this corresponds to November – January.
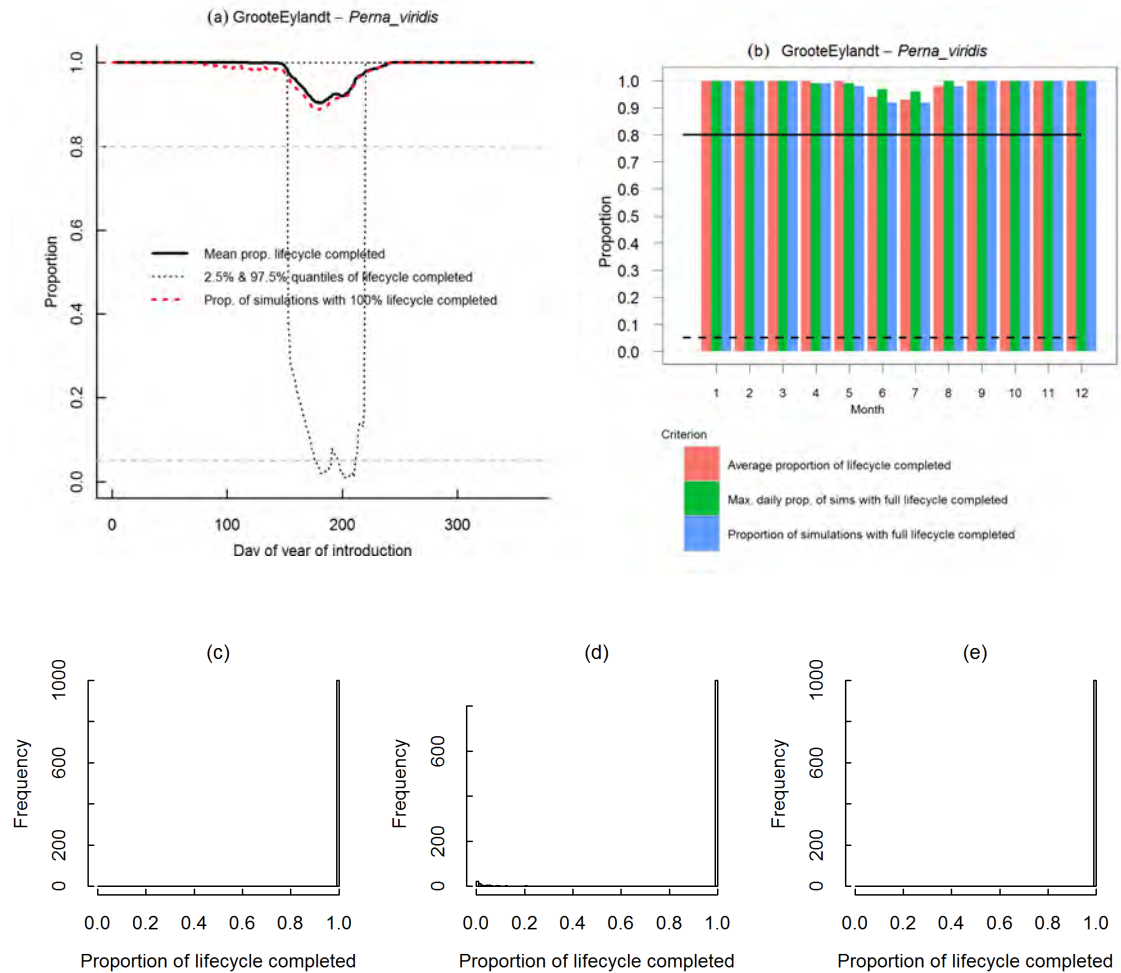

Figure B.113: Simulation results for lifecycle completion of *P. viridis* in Port Kembla. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 30; (d) day 100; (e) day 300.

Portland

In Portland establishment would be considered unlikely throughout the year under the old rule and the new rule.
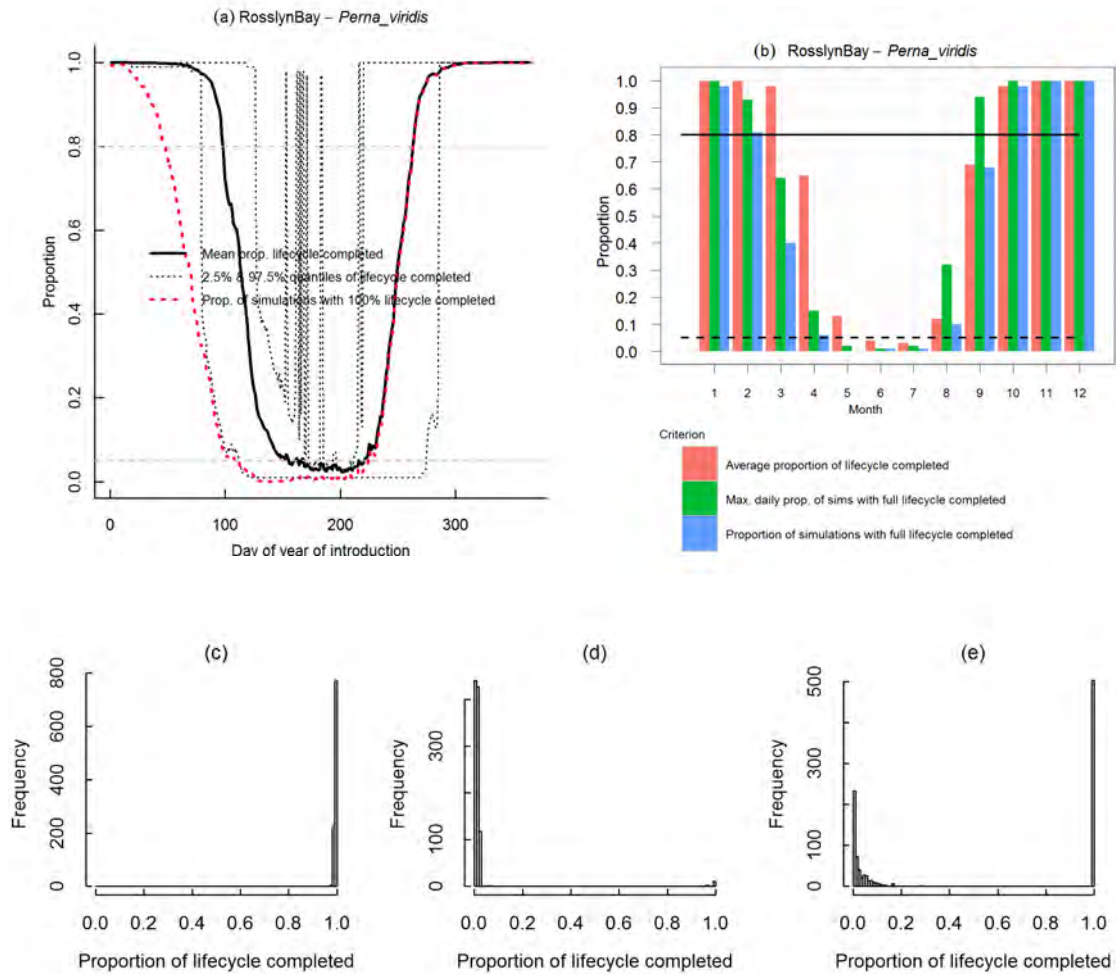

Figure B.114: Simulation results for lifecycle completion of *P. viridis* in Portland. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 40; (e) day 300.

Port Stanvac

Under the old rule, establishment of *P. viridis* at Port Stanvac would be considered unlikely. Under the new rule, we see that the species completes 100% of its lifecycle in at least 5% of simulations on some occasions in December and establishment would be considered possible over that period. For the new monthly rule this corresponds to December.

Figure B.115: Simulation results for lifecycle completion of *P. viridis* in Port Stanvac. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 50; (d) day 200; (e) day 330.

Spring Bay

In Spring Bay establishment would be considered unlikely throughout the year under the old rule and the new rule.
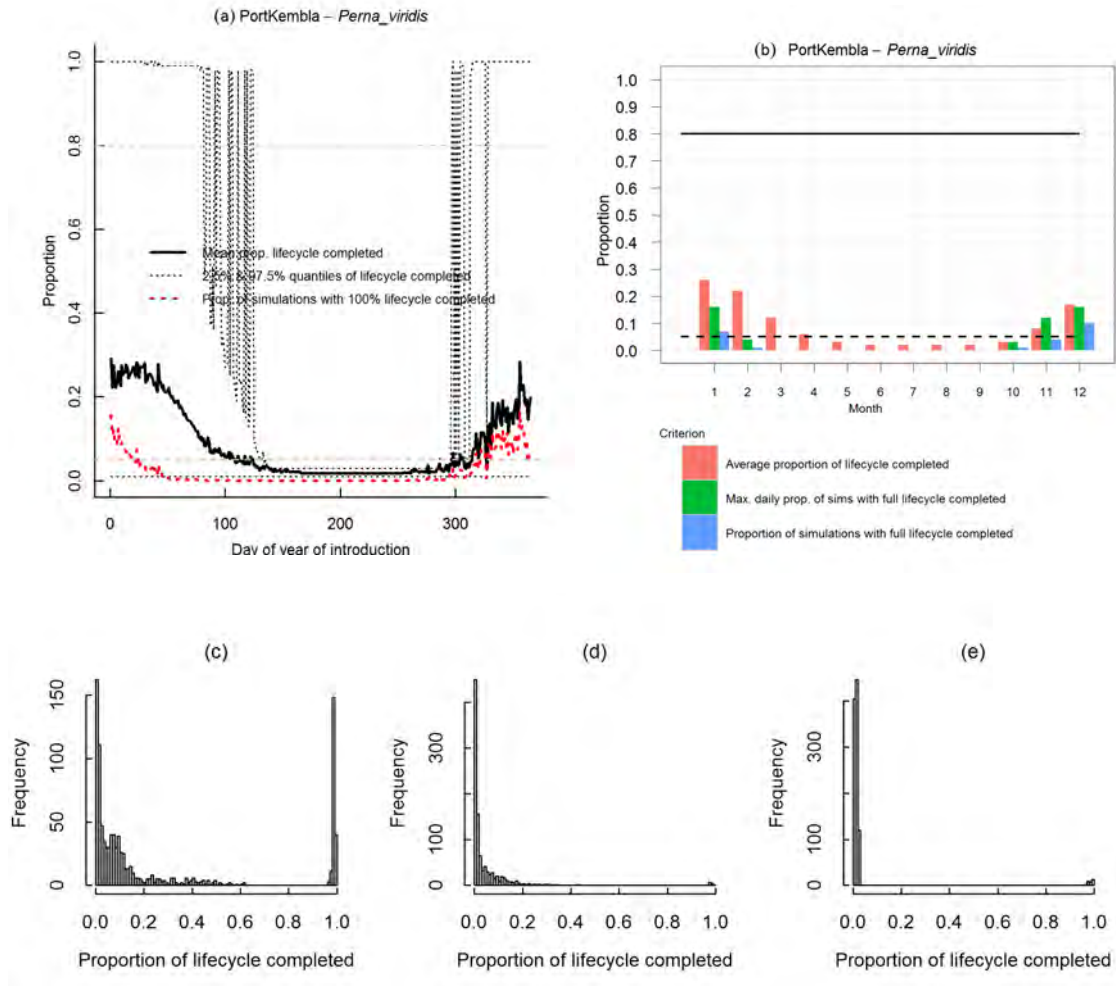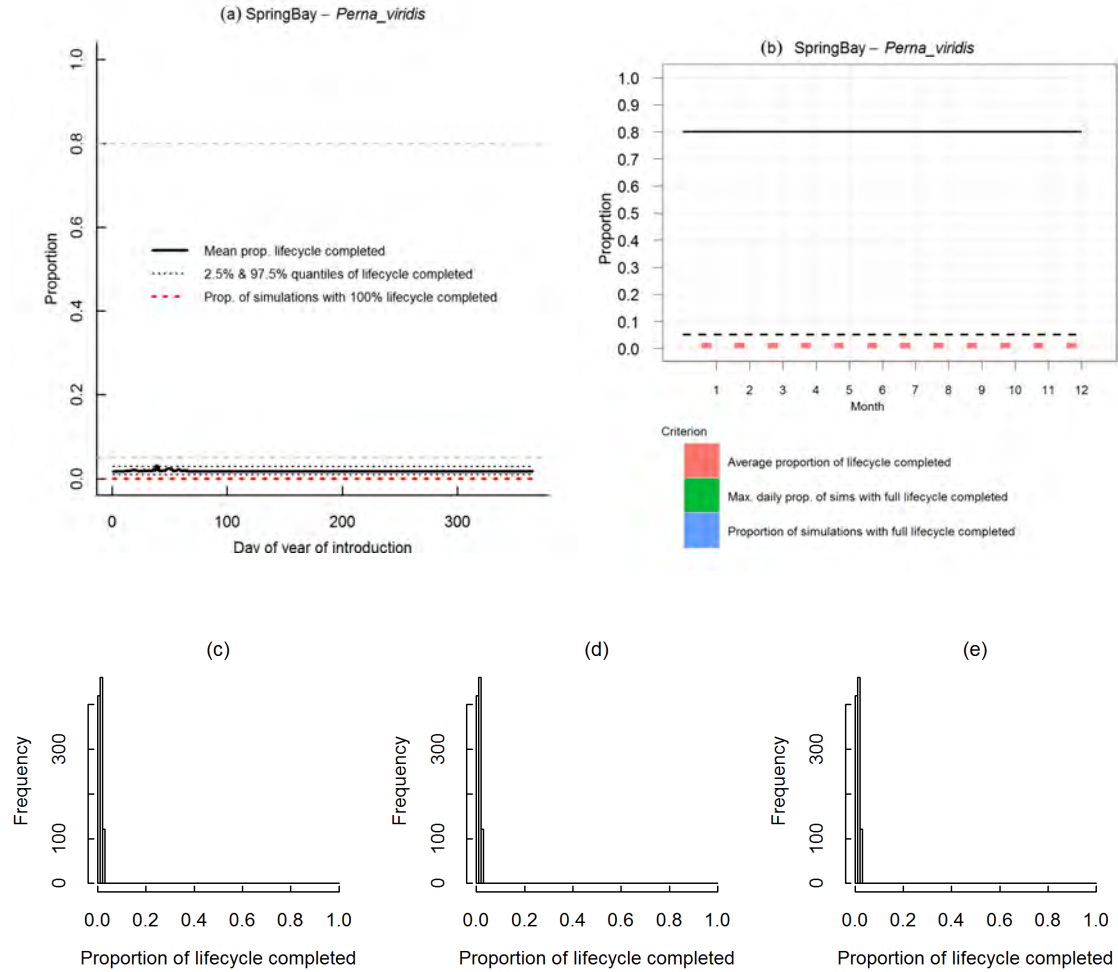

Figure B.116: Simulation results for lifecycle completion of *P. viridis* in Spring Bay. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 200; (e) day 300.

Thevenard

Under the old rule, establishment of *P. viridis* at Thevenard would be considered unlikely. Under the new rule, we see that there are periods where the species completes 100% of its lifecycle in at least 5% of simulations and establishment would be considered possible over that period. For the new monthly rule this corresponds to November – January.
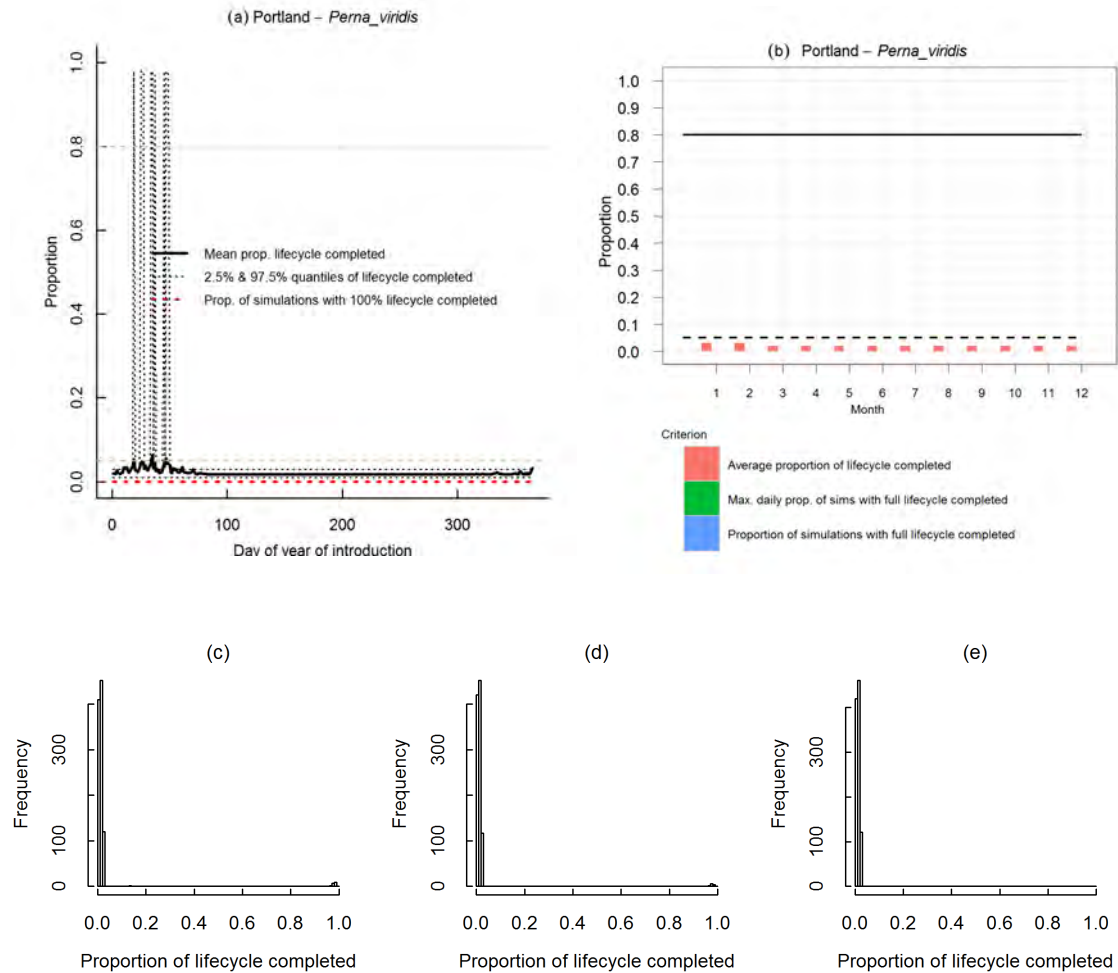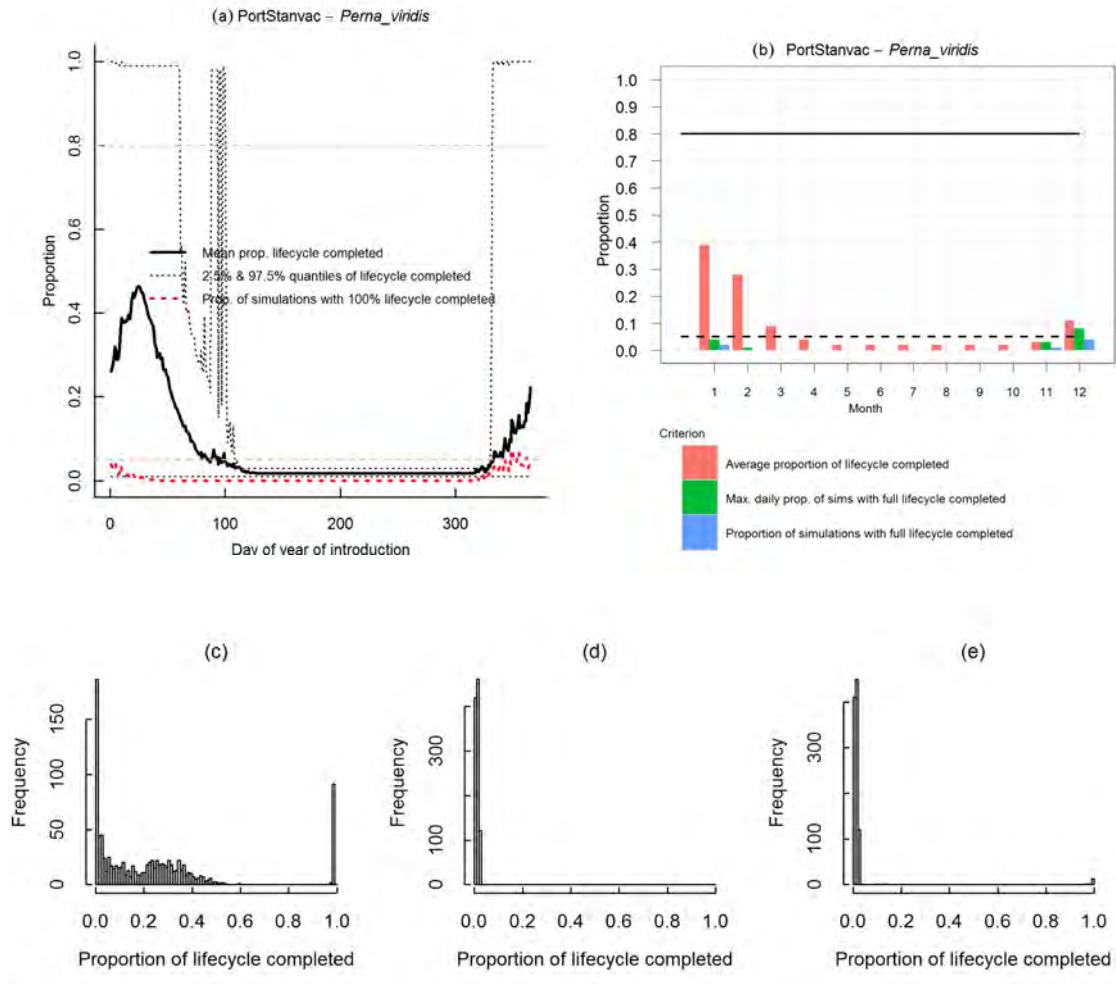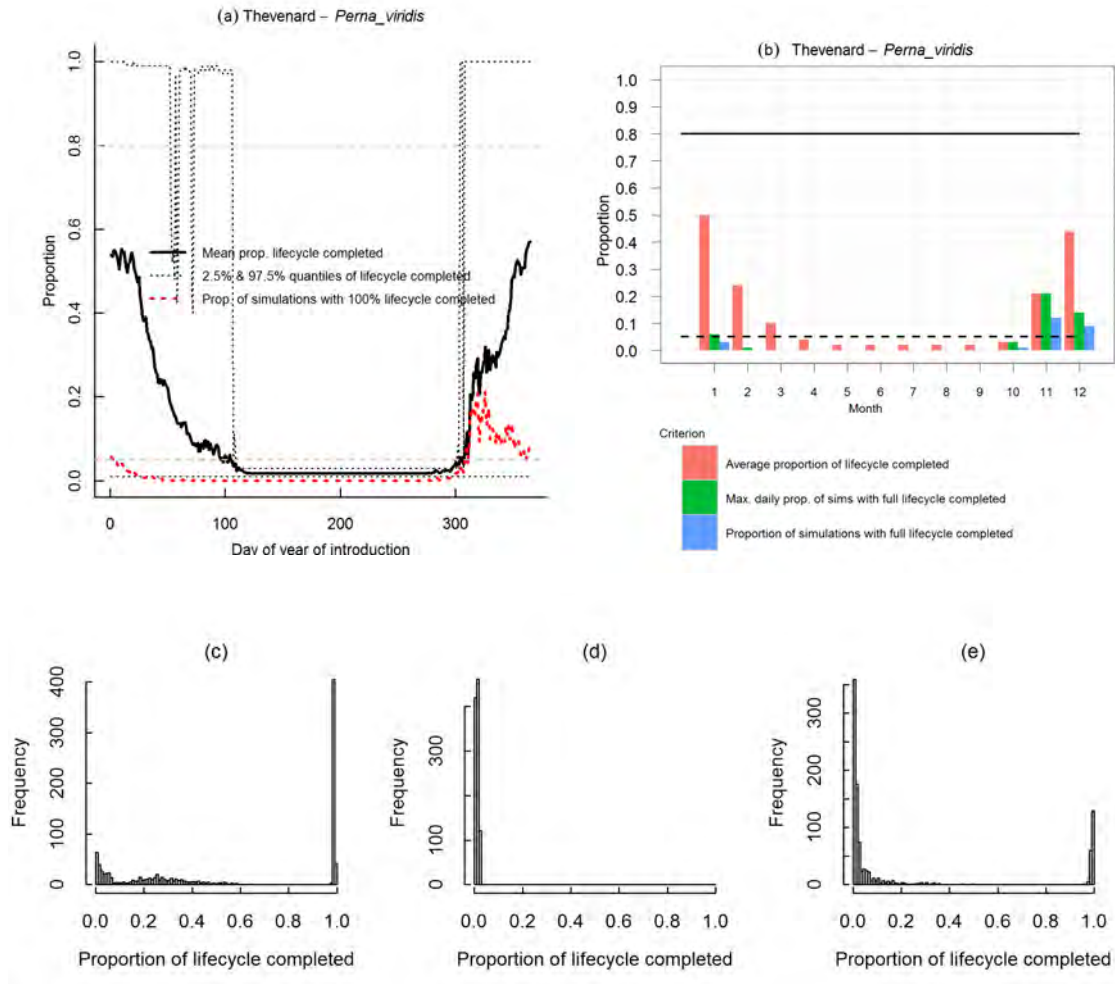

Figure B.117: Simulation results for lifecycle completion of *P. viridis* in Thevenard. Horizontal lines show a 0.05 and a 0.8 cutoff. (a) daily; (b) monthly. Histograms of proportion of lifecycle completed: (c) day 10; (d) day 200; (e) day 320.

Appendix C

Statistical model fits

Here we show figures for statistical model fits (GLM or GAM) to lifecycle simulation data. The models fit the maximum daily proportion of full lifecycle completion against latitude. Resultant models are used to predict the maximum daily proportion of full lifecycle completed for each each species/month combination for all ports without SeaFRAME data.

Figure C.1: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Asterias amurensis*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).

***Carcinus meanas* - GLM fit**

Figure C.2: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Carcinus meanas*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).

Crassostrea gigas - **GAM fit**

Figure C.3: GAM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Crassostrea gigas*. Circles are datapoints derived from simulation model, and solid lines are fitted GAM models with 95% confidence intervals (dashed line).

Musculista senhousia - **GAM fit**

Figure C.4: GAM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Musculista senhousia*. Circles are datapoints derived from simulation model, and solid lines are fitted GAM models with 95% confidence intervals (dashed line).

Mytilopsis sallei - GLM fit

For *Mytilopsis sallei* generalised linear models do not fit well for May - August, but for these months all values of maximum daily proportion of lifecycle completed were well above 0.05. Hence, these models would still provide appropriate estimates of likelihood for the ports, i.e. all ports in Australia at risk for those months.
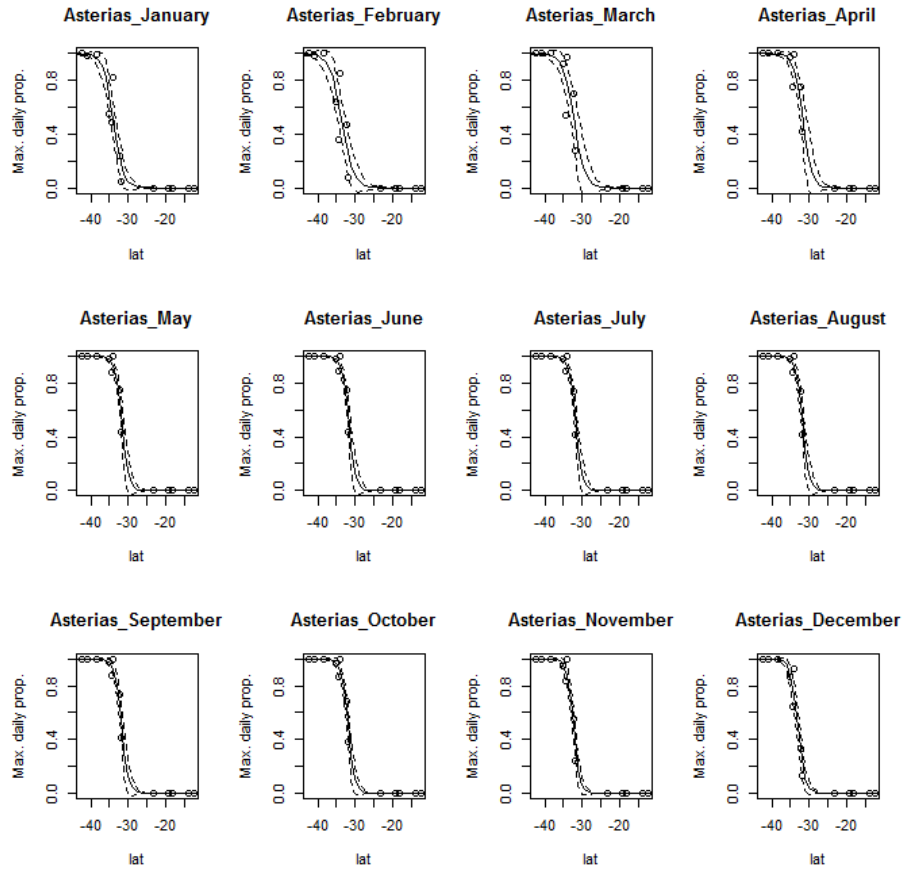

Figure C.5: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Mytilopsis sallei*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).
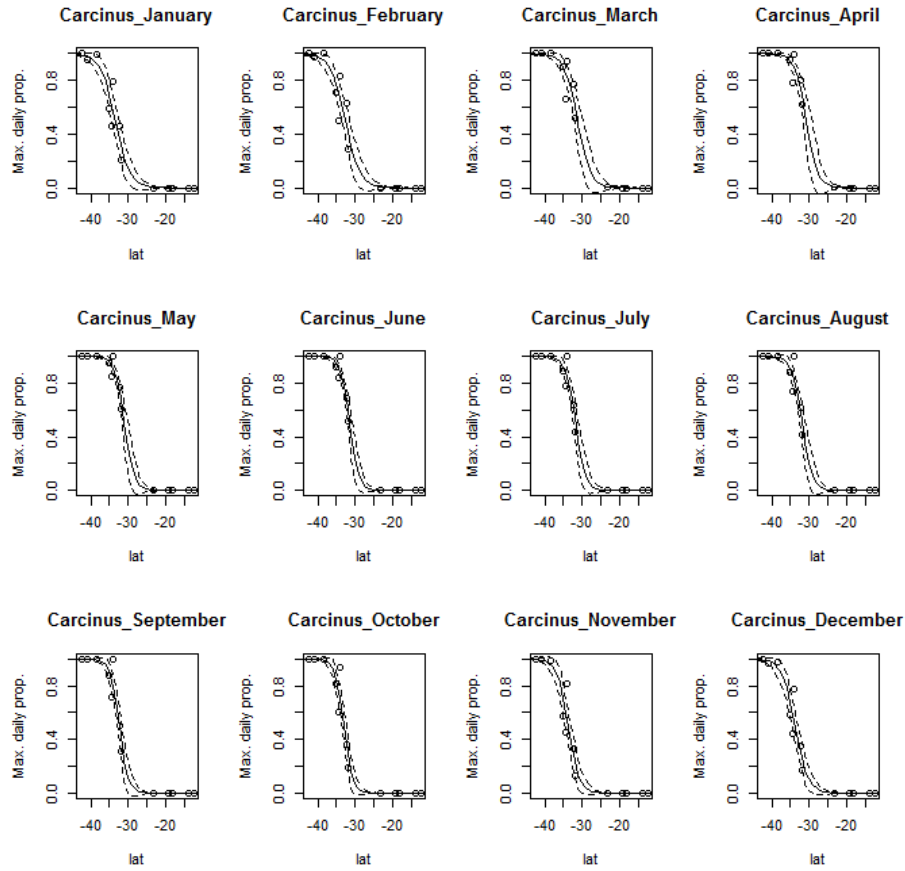
Perna viridis - GLM fit

Figure C.6: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species _Perna viridis_. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).
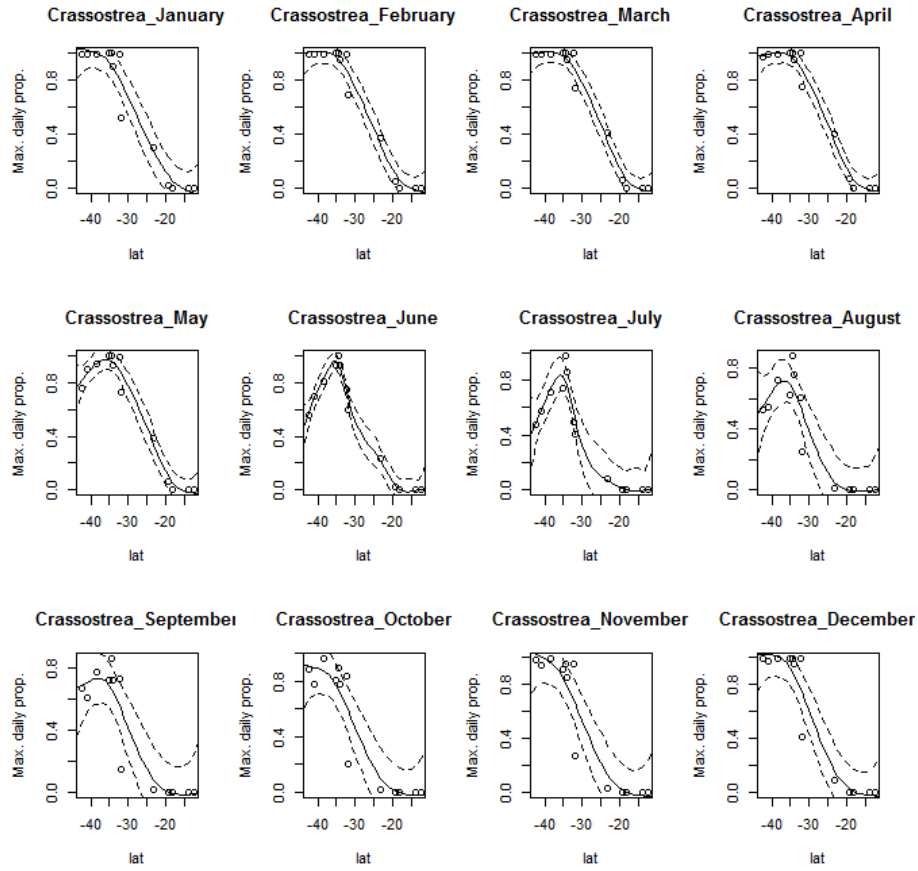
Sabella spallanzani - GLM fit

Figure C.7: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Sabella spallanzani*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).
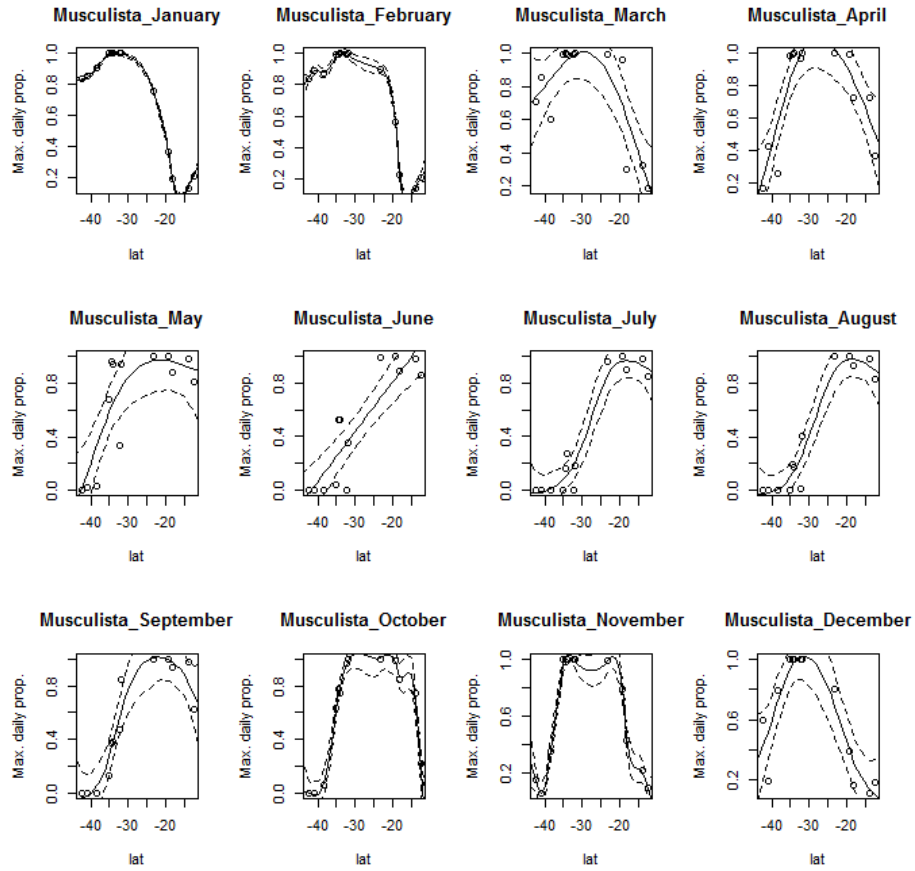
Undaria pinnatifida - GLM fit

Figure C.8: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Undaria pinnatifida*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).

Varicorbula gibba - GLM fit

For *Varicorbula gibba* there is a problem with the fit for November and December, because of the jump from 0 to 1 in the proportion of simulations with lifecycle completed between latitudes 23.16 and 31.83. To account for this and to provide a conservative estimate of risk, the cutoff was set to 23.16; that is ports with a latitude south of 23.16 were considered at risk of establishment.
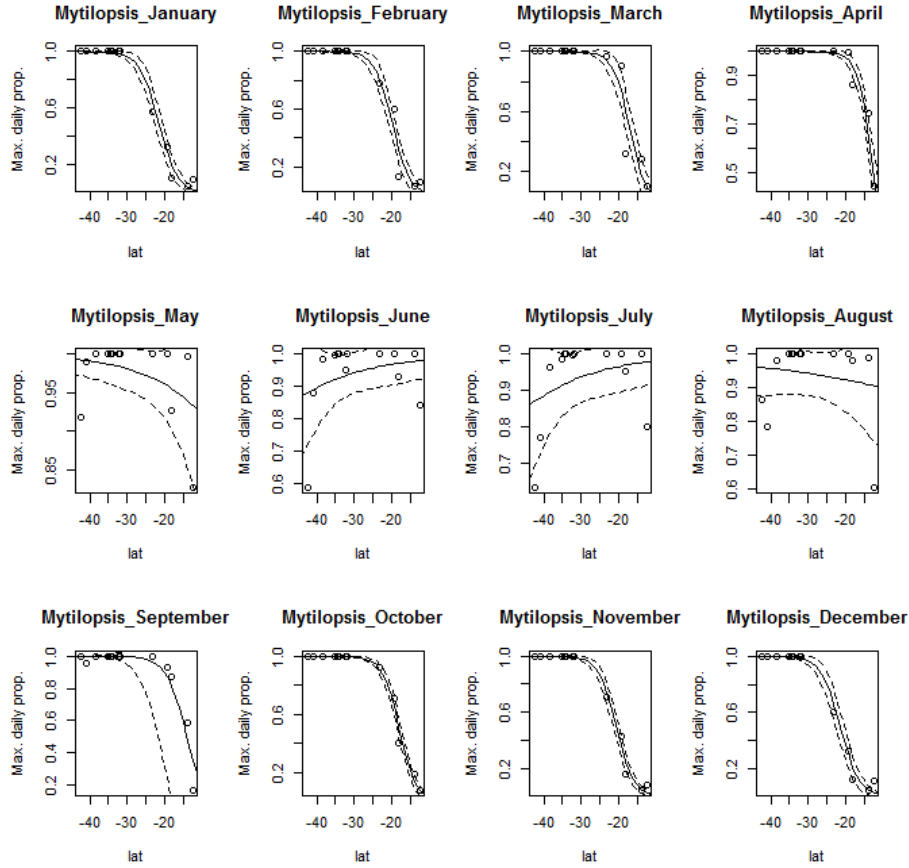

Figure C.9: GLM fitted maximum daily proportion of full lifecycle completed upon introduction against latitude for the species *Varicorbula gibba*. Circles are datapoints derived from the simulation model, and solid lines are fitted GLM models with 95% confidence intervals (dashed line).

Appendix D

Code errors
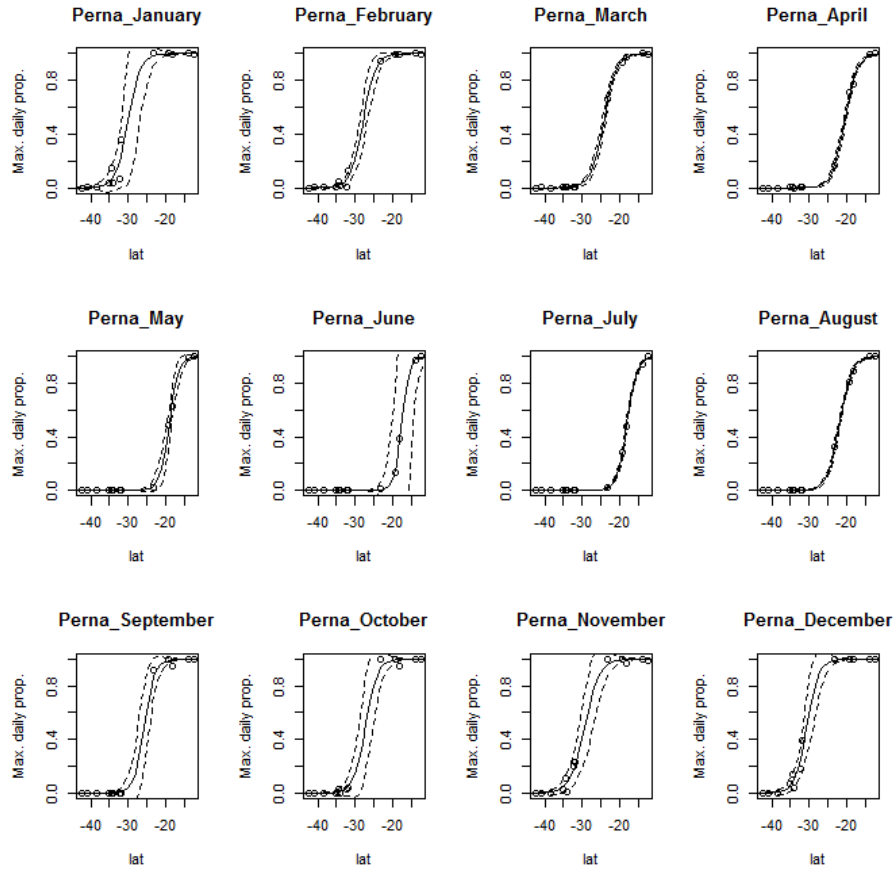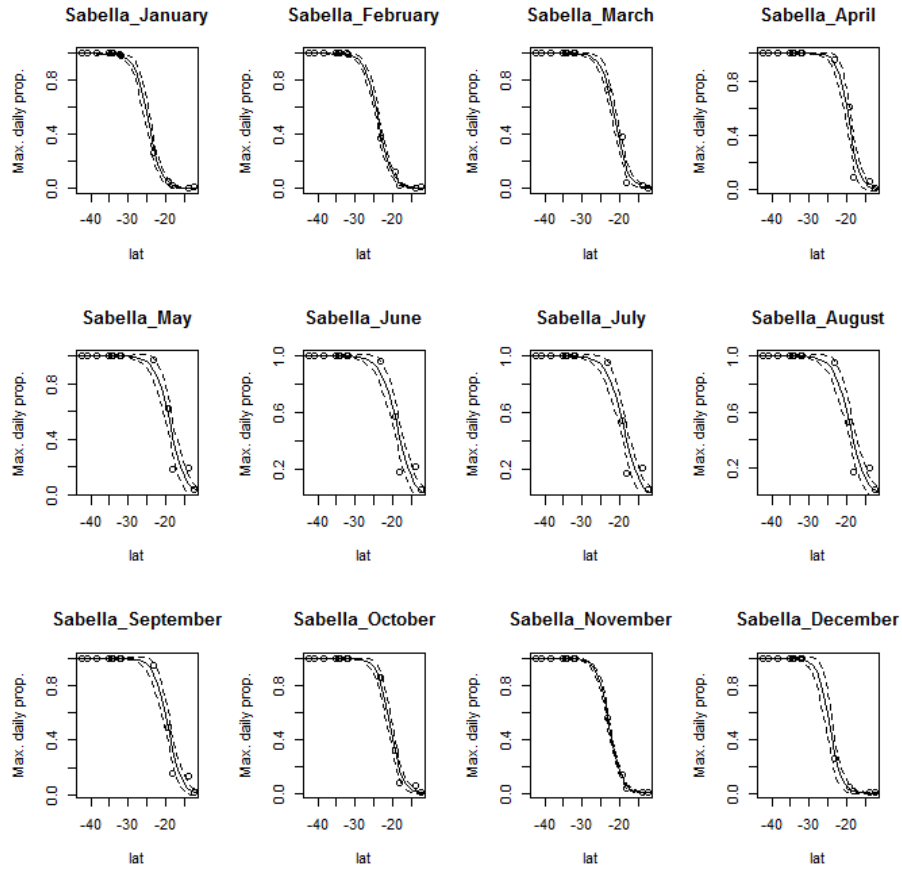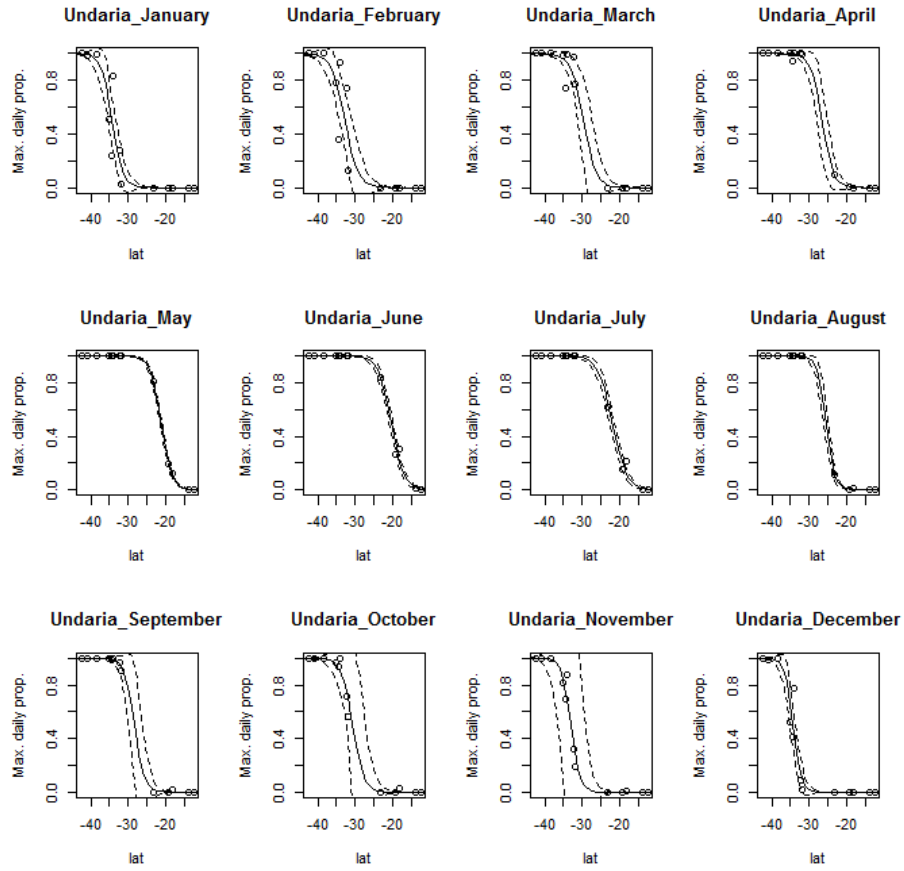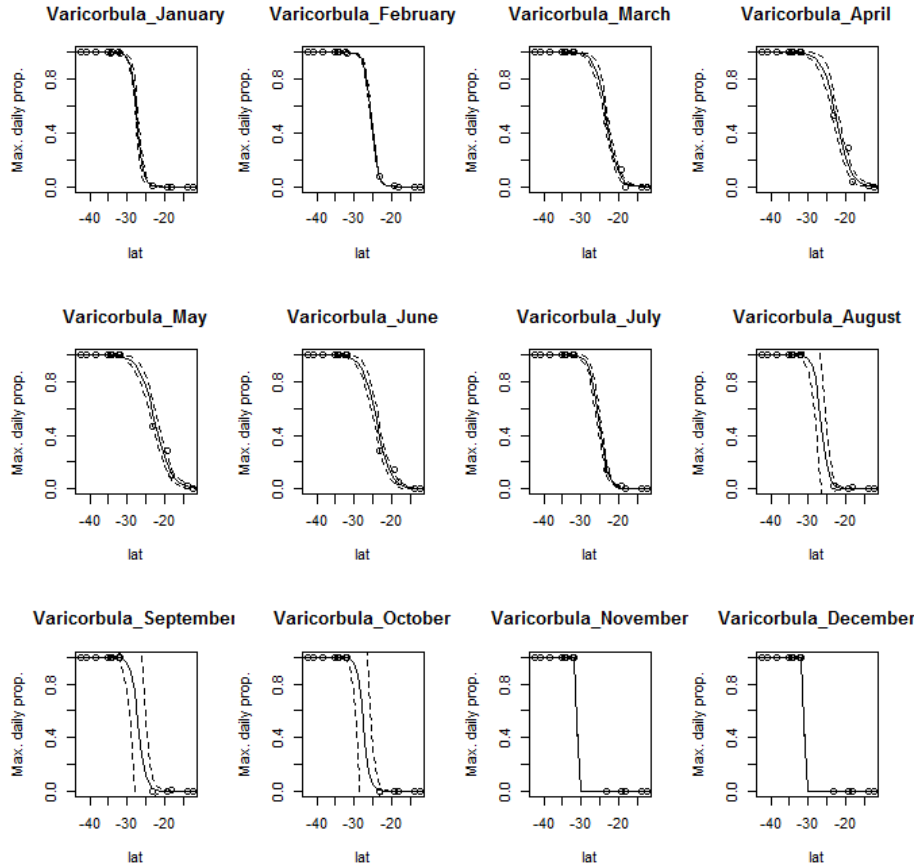
D.1 Introduction

A number of errors with the original code have been discovered during this project. These errors would not have affected the results using the original method for deciding risk. However, they have a major impact on the estimate of risk under the proposed new method. Most of the errors meant that a species did not complete its lifecycle when it should have, but most errors occurred very late in the lifecycle so that the species still got close to 100% of its lifecycle completed. That meant that the average percentage of lifecycle completed could still be very high. However, if we consider the proportion of simulations where the lifecycle was **completed**, this clearly causes a problem. The errors and how they have been fixed are documented here.

D.2 Spawning of sub-tidal invertebrates

The signs for test3 and test4 were the wrong way around and the comparison should be between MinSpawn and max.temp and MaxSpawn and min.temp. Changing these makes them consistent with the rules for zoospore release in the sub-tidal plant model.

Old code:

```
> adult.spawn.function <- function(life.stage.data, max.temp, min.temp, i,
+ count.day, adult.spawn) {
+ test1 <- which(life.stage.data$MinTempTol[i] > max.temp[count.day:(count.day + 365)])
+ test2 <- which(life.stage.data$MaxTempTol[i] < min.temp[count.day:(count.day + 365)])
+ test3 <- which(life.stage.data$MinSpaTol[i] >= min.temp[count.day:(count.day + 365)])
+ test4 <- which(life.stage.data$MaxSpaTol[i] <= max.temp[count.day:(count.day + 365)])
+   spawning.days <- test4[match(test3,test4)]
+   spawning.days <- spawning.days[!is.na(spawning.days)]
+   if(min(test1, test2) > min(spawning.days)) {
+     adult.spawn <- T
+     count.day <- count.day + min(spawning.days) } else {
+     adult.spawn <-F
+   }
+   return(list(adult.spawn = adult.spawn, count.day = count.day))
```

```
+ }
> #here's a dummy example:
> #set spawn tolerance
> life.stage.data <- list(MaxSpaTol = 9, MinSpaTol = 4)
> #Make up some temperature data:
> min.temp <- c(5,5,2,10,2,2,rep(2,400))
> max.temp <- c(10,8,7,11,3,11, rep(3,400))
> i <- 1
> count.day <- 0
> adult.spawn <- FALSE
> adult.spawn.function(life.stage.data, max.temp, min.temp, i, count.day, adult.spawn)

$adult.spawn
[1] TRUE


$count.day
[1] 6
```

We see with the old code that the species spawns on the day when both the maximum and
minimum temperature fall outside the spawning tolerance values (day 6); this is clearly
wrong. If we change the code:

```
> adult.spawn.function <- function(life.stage.data, max.temp, min.temp, i, count.day,
+ adult.spawn) {
+ test1 <- which(life.stage.data$MinTempTol[i] > max.temp[count.day:(count.day + 365)])
+ test2 <- which(life.stage.data$MaxTempTol[i] < min.temp[count.day:(count.day + 365)])
+ test3 <- which(life.stage.data$MinSpaTol[i] <= max.temp[count.day:(count.day + 365)])
+ test4 <- which(life.stage.data$MaxSpaTol[i] >= min.temp[count.day:(count.day + 365)])
+   spawning.days <- test4[match(test3,test4)]
+   spawning.days <- spawning.days[!is.na(spawning.days)]
+   if(min(test1, test2) > min(spawning.days)) {
+     adult.spawn <- T
+     count.day <- count.day + min(spawning.days) } else {
+     adult.spawn <-F
+   }
+   return(list(adult.spawn = adult.spawn, count.day = count.day))
+ }
> adult.spawn <- FALSE
> adult.spawn.function(life.stage.data, max.temp, min.temp, i, count.day, adult.spawn)

$adult.spawn
[1] TRUE


$count.day
[1] 1

> #code within function
> test3 <- which(life.stage.data$MinSpaTol[i] <= max.temp[count.day:(count.day + 365)])
> test4 <- which(life.stage.data$MaxSpaTol[i] >= min.temp[count.day:(count.day + 365)])
>   test3

[1] 1 2 3 4 6
```

```
>   test4[1:10]

 [1]  1  2  3  5  6  7  8  9 10 11

>   spawning.days <- test4[match(test3,test4)]
>   spawning.days

[1]  1  2  3 NA  6
```

With the new function the species could spawn on day 1, where although the maximum temperature is outside the range the temperature must have been in the range for some period; day 2, where both temperatures are in the range; day 3, where although the minimum temperature is outside the range the temperature must have been in the range for some period; and day 6, where although both the minimum and maximum temperatures are outside the range the temperature must have been in the range for some period. It wouldn't spawn on day 4, temperature always too high; or day 5, temperature always too low.

For inter-tidal invertebrates *C. gigas* the error in the original code had been picked up perviously, and the problem fixed by just reversing the signs in test3 and test4. With that fix the species would only spawn when **both** the maximum and minimum temperatures on the day were within the tolerance limits. The inter-tidal invertebrate function has been changed to be consistent with the sub-tidal plant and invertebrate functions.

D.3   Gamete survival function

The way the original gamete survival function was coded caused two problems. The first was that a species could die at gamete stage, but still appear to have a completed lifecycle. The second was that in some cases a species that survived the gamete stage could have **over** 100% of its lifecycle completed. We can demonstrate this with *M. sallei*, which has a gamete lifestage duration of 1 day.

The original code was:

```
> gam.surv.function <- function(life.stage.data, max.temp, min.temp, i,
+       count.day, gam.grow.days, gam.death) {
+   #browser()
+   test1 <- which(life.stage.data$MinTempTol[i] >
+   max.temp[count.day:(count.day + life.stage.data$Duration[i])])
+   test2 <- which(life.stage.data$MaxTempTol[i] <
+   min.temp[count.day:(count.day + life.stage.data$Duration[i])])
+   if(length(test1)==0 & length(test2)==0) {
+     gam.death <- F
+     gam.grow.days <- life.stage.data$Duration[i]
+     count.day <- count.day + gam.grow.days} else {
+     gam.death <- T
+     gam.grow.days <- min(test1, test2)
+   }
+   return(list(gam.death = gam.death, count.day = count.day,
+       gam.grow.days = gam.grow.days))
+ }
```

We can see that test1 and test2 in the original code produce a vector of length = 2 (temp[count.day:(count.day + life.stage.data$Duration[i])]). Because of this the species could die on day 2, but it shouldn't actually get to that day. To fix this the code has been changed to: temp[count.day:(count.day + life.stage.data$Duration[i]-1)]. Now the species can die on day 1 only; if it doesn't it survives and gam.death is set to FALSE. The code also needs to be modified to ensure that if the species does die on that day it does not appear to complete all of its lifecycle. If the above was the only fix we made, then with the remaining original code, if it did die on day 1, gam.grow.days would be set to min(test1,test2), which is '1'. This is the same as the length of that lifestage, so the species would appear to complete its lifecycle even though it didn't. The following completed function addresses both problems:

```
> gam.surv.function <- function(life.stage.data, max.temp, min.temp, i,
+       count.day, gam.grow.days, gam.death) {
+
+ test1 <- which(life.stage.data$MinTempTol[i] >
+ max.temp[count.day:(count.day + life.stage.data$Duration[i]-1)])
+ test2 <- which(life.stage.data$MaxTempTol[i] <
+ min.temp[count.day:(count.day + life.stage.data$Duration[i]-1)])
+   if(length(test1)==0 & length(test2)==0) {
+     gam.death <- F
+     gam.grow.days <- life.stage.data$Duration[i]
+         count.day <- count.day + gam.grow.days} else {
+
+     gam.death <- T
+       if(life.stage.data$Duration[i] == min(test1, test2))
+         {gam.grow.days <- life.stage.data$Duration[i] -1} else
+         {gam.grow.days <- min(test1, test2)}
+   }
+   return(list(gam.death = gam.death, count.day = count.day,
+       gam.grow.days = gam.grow.days))
+ }
```

The first part of the fix is relevant to survival tests at all lifestages, i.e. they should be based on count.day:(count.day + duration - **1**). Without this fix all stages could die on a day they should not even reach. All functions have been changed to reflect this. The second part of the fix is only relevant to the gamete stage, which is the last stage considered in the lifecycle modelling. If species die in other stages they don't progress to the next stage and the maximum number of days that lifestage contributes to the lifecycle is equivalent to the duration of that lifestage; so if they die in earlier stages the percentage of the lifecycle completed can never reach 100%.

D.4   Larval duration

The length of the larval period for *C. gigas*, *A. amurensis* and *P. viridis* is temperature dependent and needs to be calculated depending on the time of year of a particular simulation. In the original code, the calculation was based on the first temperature time series (i == 1 of n.sim = 1000 different simulations) for each day (d) of the year (p indexes the port). Here we show the function for *A. amurensis* as an example.

```
> # Asterias larval duration function (original)
> ast.larv.function <- function(max.temp, min.temp, aalarv.save, s, p, d) {
+   #browser()
+   if(max.temp[d] < 26 & min.temp[d] > 8)
+     aalarv.dur <- rep(as.integer(exp(5.68 + mean(max.temp[d],
+         min.temp[d])*-0.11)), n.sim) else aalarv.dur <- rep(1, n.sim)
+     aalarv.save <<- rbind(aalarv.save,
+         c(p, d, mean(aalarv.dur), var(aalarv.dur)))
+   return(aalarv.dur)
+ }
>
```

The call to the function is:

```
if(i ==1 & s == Asterias amurensis")
spp.list[[s]]$Larvae$Duration <- ast.larv.function(
max.array[ ,i, p], min.array[ ,i, p],
aalarv.save, s, p, d)
```

It is not clear why the larval duration function was implemented in this way, because larval duration can vary from one temperature simulation to the next. The code has been modified so that a new larval duration is calculated for each of the 1000 simulations for each day of the year. The new code, which is called for each simulation is shown below. The code within the simulation loop also been modified to capture the larval durations (i.e. results are stored to aalarv.save at a different point in the code rather than from within the duration function.

```
> # Asterias larval duration function (new)
> ast.larv.function <- function(max.temp, min.temp, aalarv.save, s, p, d) {
+   #browser()
+   if(max.temp[d] < 26 & min.temp[d] > 8)
+     aalarv.dur <- as.integer(exp(5.68 + mean(c(max.temp[d],
+         min.temp[d]))*-0.11)) else aalarv.dur <- 1
+   return(aalarv.dur)
+ }
```

We see this code generates a range of possible durations for a given day (Fig. D.1) whereas the old code would only use the first value (which was 45 in this case) for all 1000 simulations on that day.

D.5   Smaller miscellaneous code errors

D.5.1   Dealing with the 29 February

The code needs to remove the 29 February from temperature time series data to allow the best fitting of the stl models. The data format for the temperature data is not consistent between yearly data sets, so the 29 February was not always being removed. The code has been modified to ensure the 29 February is always removed.
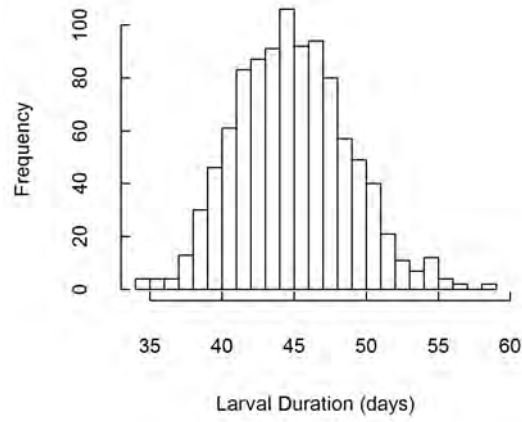
Figure D.1: Simulated larval durations for *A. amurensis*.

D.5.2 Calculation of mean

In the larval duration functions the intention was to calculate the mean of the maximum and minimum temperature on the day of interest. The syntax was not correct for calculating the mean and the function was only using the maximum temperature on the day (see original version of function, above). The syntax has been changed to use the mean (see new version of function, above). The difference between the maximum sea surface temperature and the minimum sea surface temperature on any given day is usually small, so this error would not have had a major effect on the model outputs.

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