2.2.4 Establishment probability

A key unknown in the underlying model is the probability of establishment. The probability of establishment is one of the most difficult ecological properties to understand. About all that can be said with confidence is that the probability of establishment is positively related with inoculation frequency and inoculum size – ie. the number of viable organisms that are discharged into the environment. Inoculum density will vary as a function of the initial exposure density at each of the departure nodes, the type of vector and the journey duration. Exposure and infection are likely to be highly variable both between and within departure nodes, hence the mean and variance of the distribution used to represent these variables is likely to have an important bearing on the results of the simulation. In the southeastern region of Australia we have some data from which to estimate establishment probability, because:

- *Asterias* from Japan established in Hobart but nowhere else, despite similar or high frequency inoculation elsewhere – this can provide a probability of establishment for *Asterias* from Japan (although the vector is not clear)
- *Asterias* from the Derwent established in Port Phillip Bay after approximately 10 years following frequent inoculation in ballast water
- *Asterias* from the Derwent have just started to establish in Mercury Passage despite many years of passive transport in the currents
- *Asterias* established in Henderson Lagoon – recent spat bag data indicates that this was unlikely to have occurred from larval advection, but is more likely to have occurred through transport on fishing gear
- There are many ports that have received Asterias larvae in ballast water and presumably juveniles as hull fouling or on anchor ropes, but no establishment has occurred.

None of these data sources are sufficient to directly inform the probability distribution for the establishment of *Asterias* for any vector, however, they provide a constraint on the model that can be used to select probability distributions – ie. the parameters of the probability distributions for the different vectors will be chosen that are consistent with the invasion history of *Asterias* in southeastern Australia to date. For example shipping statistics between Hobart and Melbourne can be used to determine the number of “trials” prior to the first successful establishment of *Asterias* in Port Phillip Bay. These data can be used to constrain the mean probability of success within a negative binomial model for the probability of establishment via the ballast water vector.

2.2.5 Post-establishment population growth

The best dataset we have for this is that of the Port Phillip Bay population. These data will, if anything, overestimate the rate of post-establishment growth as they may not include a lag-time that could have occurred between establishment and detection of the first seastar in 1995[9].

A lack of exact information on the lag time between first establishment and first detection also applies to the second dataset – that for the Derwent estuary. The Derwent estuary population data also raise a second complication – is the initial rapid increase in population followed by a decline to a lower population level that is sustainable over the longer term. The data for the Derwent are not definitive, however data now being collected on larval densities, when compared with earlier data are expected to indicate a population decline. Circumstantial data – a decline in shellfish fragments in the benthos over the last ten years (Graham Edgar, personal communication) – suggest a mechanism that could lead to this population decline after initial maximum.

Both of the well-established invasions of *Asterias* in Australia, occurred in semi-enclosed waters. A third – Henderson's lagoon that was eradicated before a second generation could be spawned – also occurred in semi-enclosed waters. There are indications that a population may be establishing on Tasmania's east coast in Mercury Passage, quite a different environment.

2.3 Management model

2.3.1 Management objectives

Three meetings have been held with the aim of gaining clearer definitions of management objectives that could be linked to measurable performance criteria.

Scoping Workshop, Adelaide May 2002

A scoping workshop was held on 6 –7th May 2002 at the Haven Marina Inn, Adelaide. Invitations to the workshop were extended to managers, scientists and industry representatives. The outcome of the workshop is summarised in Appendix 1. Participants agreed that management actions should be initiated on the most significant vectors of *Asterias* using the precautionary principle. Participants used six criteria (Table 6) to qualitatively score 18 identified vectors (Table 7) that could potentially spread *Asterias* larvae and non-larvae (adults and juveniles) beyond the Derwent River and Port Philip Bay. Vectors were ranked based on the six criteria on their threat in spreading *Asterias* larvae and non-larvae as well as a measure of the vector strength. The likelihood of a vector leading to the establishment of *Asterias* larvae and non-larvae at a recipient site was based on four criteria -- frequency, volume, entrainment and discharge. The likelihood of dispersing *Asterias* larvae and non-larvae by a particular vector was based on two criteria scores -- promiscuity and range.

---

[9] See footnote 4.

Table 6 – Criteria used to score the likelihood of vectors spreading Asterias and the dispersive characteristics of vectors by workshop participants.

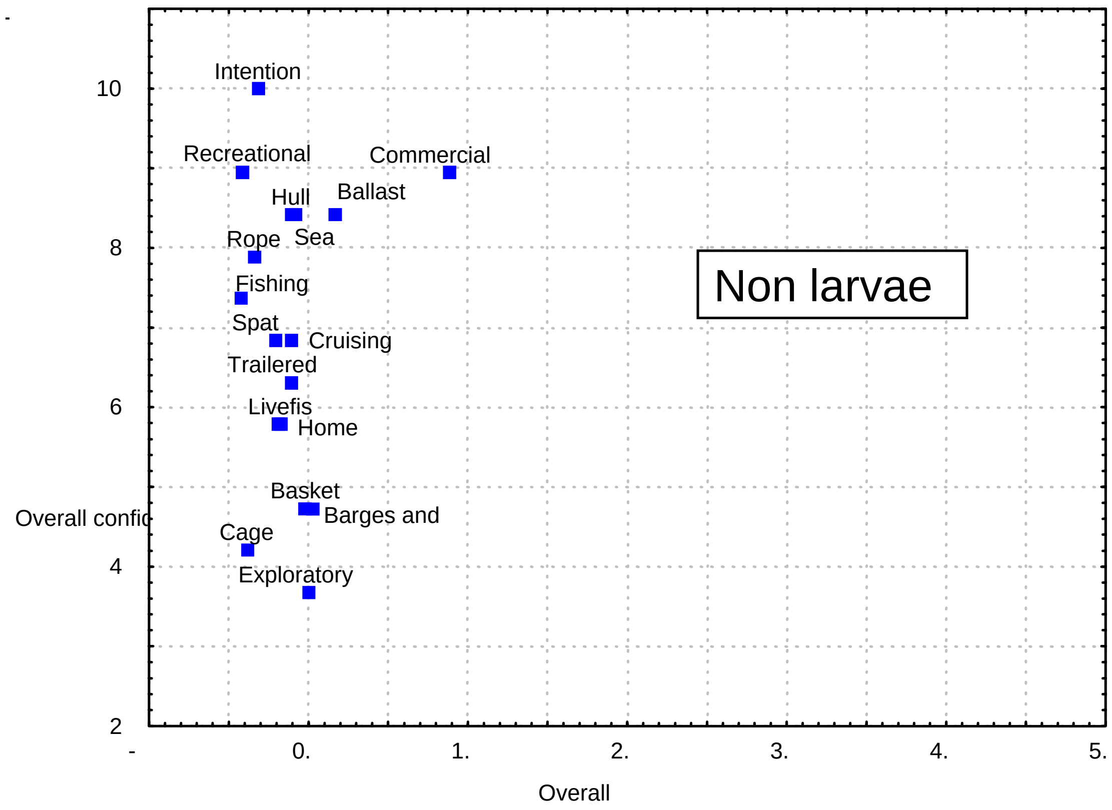
Parameter	Definition
Likelihood of spreading	
Frequency	Frequency of vector movement
Volume	Inoculation volume of vector per unit measure
Entrainment	Likelihood of being entrained as either a larvae or non-larvae at donor site
Discharge	Likelihood of being discharged as either a larvae or non-larvae at recipient site
Dispersive characteristics	
Promiscuity	Number of sites visited by vector
Range	Distance travelled by vector (state, interstate)

Table 7 – Vectors identified by workshop participants that could spread *Asterias*

Vectors	Comment
Barges/Dredges[1]	
Commercial fishing[2]	Includes all fisheries (trawling etc), wet wells not treated as ballast (continuos exchange)
Exploratory Oil rigs	Both semi submerged
Fishing bait	Both live and dead
Fishing gear	All fishing gear (nets, lines etc)
Intentional introductions	Includes bio-terrorism, aquarium trade
Live fish trade[3]	Does not include live bait
Mariculture - Baskets	Oyster and scallop
Mariculture - Cages	Live fish (salmon)
Mariculture -Spat bags	Mussel, oyster
Mariculture – ropes[4]	Mussel ropes.
Marine hardware	Navigation buoys, marine hardware, research buoys, etc.
Recreational equipment	Jet skis, windsurfers, scuba gear etc
Ships ballast water	Not oil rig ballast water
Ships-hull fouling	
Ships-sea chests & chains	Includes nooks and crannies on vessel
Trailered boats	Transfer across land
Yachts - cruising (home based)	
Yachts - cruising (visitors)	Includes racing yachts (hulls cleaned)

Notes for Table
1. Barges and dredges were recognised as a potential hazard but as a whole the group did not know a lot about these vectors. However, participants were happy with the level of scrutiny these vectors currently receive and recommended that current permit regulations be extended to consider marine pests.
2. Sale of commercial vessels is one activity that can spread Asterias long range, but as a whole vessel movements are generally medium ranges. Processes unrelated to fishing may also infect fishing vessels.
3. Live fish may be discharged to storm water or sewage
4. Asterias can be entrained on ropes as either larvae that have settled from the water column or adults in the event that the ropes or gear contact the seafloor. This prompted a discussion of the life-stage of Asterias on discharge. It was decided that where there may be a change in life-stage of Asterias in transit (entrainment to discharge) that discharge value would be scored as <1 (0.01 for multiplying for products of criteria scores- see Appendix 1).
5. Fishing bait is treated as different from recreation equipment because this vector has a history of spreading pests

Ballast water was ranked the most important vector for spreading *Asterias* larvae (overall score 4.4). Commercial fishing vessels were ranked as the most important vector for spreading *Asterias* non-larvae but its vector strength(1.4), was much lower than that obtained for spreading larvae with ballast water. Less important vectors for spreading *Asterias* non-larvae were ballast water (overall score = 0.7), barges and dredges, and mariculture baskets (overall score = 0.5). Vectors having the greatest likelihood of dispersing of *Asterias* (both adult and larvae) were cruising yachts and trailered boats. However, although these vectors were highly promiscuous and covered long ranges, the likelihood of entraining and discharging *Asterias* larvae and non-larvae by these vectors was considered low (trailered boats) to medium (cruising yachts), and therefore they were not considered important vectors. Gaps in vector knowledge were recognised for exploratory oilrigs and barges & dredges.



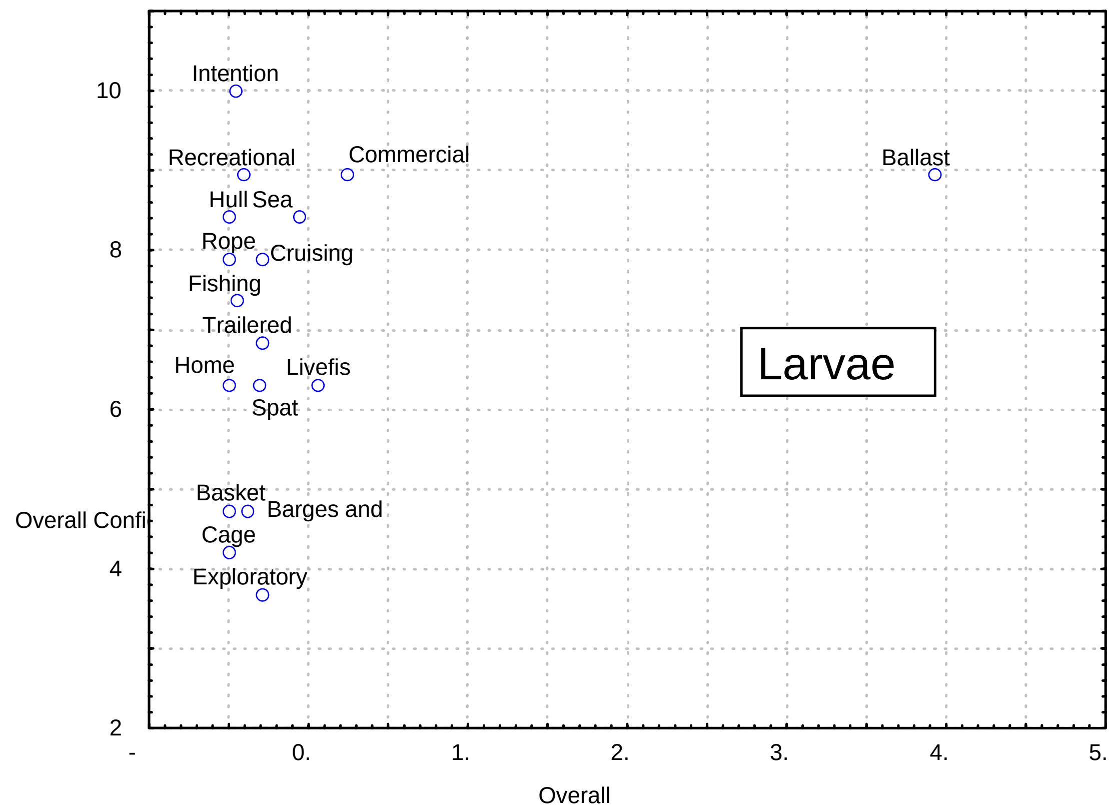


Figure 12 – Overall score and confidence associated with vectors for Asterias larvae and non-larvae

First Steering Group Meeting, Hobart June 2002

In the first steering group meeting, held June 19, 2002, it was determined that management objectives included:

- protecting marine industries;
- restricting spread;
- restricting *Asterias* to 2 currently infected locations;
- ensuring that *Asterias* does not spread to other areas in Victoria;
- ensuring that *Asterias* does not reach Eden.

It was recognised that it was necessary to separate natural from human-assisted dispersal to work out what can be managed and that there is a need to look at the problem from the overall Australian perspective (ie. biggest mistake to date, not reducing the risk of spread from Hobart to PPB). ISO-14001 could provide useful framework for the progressive refinement of management questions.

One use of the model could be to look at initial spread from Hobart and compare costs/impacts of doing nothing with what could have been achieved through management intervention.

Second Steering Group Meeting, Hobart September 2002

A second meeting was held on September 27, 2002 with Keith Sainsbury (CSIRO), Don Hough (DNRE Victoria) Gwen Fenton and Alice Morris (DPIWE Tasmania) and project personnel to further define management objectives, management options and performance criteria in a management strategy evaluation context. The MSE approach requires operational objectives that are measurable; it requires that the managed system is monitored, and that monitoring information is analysed in a specific way so that performance measures can be addressed; the ways in which this information will inform the management process is specified; the implementation, lack thereof, or delays in implementation of management recommendations, need to be captured in the modeling process.

Four elements were identified during the meeting as critical to the success of any management strategy evaluation:

1. the system simulation – the biological, economic and social models used to represent the system must be capable of representing model and parameter uncertainty and all divergent views held by stakeholders;

2. the management simulation – the simulation should allow for different observation rates, different parameter estimates, alternative decision rules and imperfect implementation of management decisions;

3. inputs – models, proposed outcomes, stakeholder views and performance measure should be predefined within a stakeholder forum; and

4. scenario visualization – the effects of alternative management strategies must be clearly and concisely communicated to stakeholders.

Management objectives were recognized as being scale-dependent – there are local and national issues that need to be addressed. In addition there could be a hierarchy of objectives and performance criteria and actions. For example, if the management objective is to restrict *Asterias* to two ports, and we fail in this objective, then there needs to be a secondary objective in place (eg. early eradication if possible in the newly established area). Management options to address the first objective would focus on prevention; management options to address the secondary objective would focus on early detection, rapid response and population control.

2.3.2 Management options

Management options were identified that would reduce the risk of larvae arriving at a new area, decrease the probability of establishment, decrease the probability of population increase, and increase the probability of early detection:

- antifouling and hull cleaning
- reballasting at sea
- no discharge of ballast water in recipient ports
- options needed for non hull-fouling or ballast water vectors – aquaculture, live fish trade, fishing gear etc.
- education
- reducing invasibility of receiving ports and other areas (eg. excess food around wharf pilings or excess food from aquaculture pens that could provide a high nutrient habitat)
- good housekeeping (aquaculture, wharves, vessels)
- increasing probability of detection – on-going monitoring
- daughterless construct to reduce probability of second generation

It was recognized that a mix of short and long-term objectives options would be required and that options examined should not be restricted to only those that would work for *Asterias* as management options are needed for other marine pests.

The management options explored in the current iteration of the MSE model were focused on the discharge of ballast water between ports and reballasting at sea. The lack of quantitative data precludes the inclusion of other potential options at this stage. Six management options were explored. All reballasting was simulated as flowthrough reballasting (Rigby and Hallegraeff 1994) assuming well mixed conditions in the ballast tanks.

Table 8 Management options explored in the MSE model

	Natural Dispersal	Ship Traffic	Management option	Number of Tanks
Natural	Yes	None	None	None
No Exchange	Yes	Yes	None	None
Exchange_5nm	Yes	Yes	Reballast 5nm from coast	Required 3
Exchange_33nm	Yes	Yes	Reballast 33 nm from coast	Required 3
Exchange_200m	Yes	Yes	Reballast at 200m depth	Required 3
Exchange_5nm_MS	Yes	Yes	Reballast 5nm from coast	3 tanks if possible

In all options except Exchange_5nm_MS, ships are required to complete reballasting for 3 full tank volumes and must slow down to complete this exchange if the distance between the ports is too short to proceed at maximum speed (13 knots). For option Exchange_5nm_MS, ships complete 3 volumes if possible but are not required to reduce speed. Ships in the model using the Exchange_5nm option and the Exchange_5nm_MS option follow the same routes. The algorithm for the selection of routes is detailed in section 2.1.5. Routes are selected to optimally balance requirements for reballasting sites enroute against the need to divert the ship the shortest distance possible to meet these requirements. The consequences of the Natural management option are similar to the result of simulations where ships are able to kill all larvae that are loaded into the ballast tanks or where all ships use freshwater ballast. Because the cells of the model are 22km * 22km, exchange at 5nm effectively means exchange in the 1st cell from the coastline and exchange 33nm means exchange in the 2nd cell from the coastline.

2.3.2 Performance criteria

Further discussion is required before we can start to develop performance criteria, however some observations were made:

- if reducing population numbers were a performance criterion, then what reduction is required to a) reduce impacts, and b) reduce risk of infection to connected areas
- the community is interested in fixing the problem, most directly by reducing the number of seastars. Is any reduction in numbers inherently good? How could the effectiveness of community participation be maximized?

2.3.3 Description of Simulations

Each simulation runs for 50 years, starting from an initial condition with *Asterias* populations in the Derwent estuary and Port Phillip Bay at the current abundances. The simulations are repeated 100 times and the results summarised over the 100 simulations. A total of 18 sets of simulations were run; combinations of 6 management options and 3 sets of larval mortality and settlement parameters.

3 Results of *Asterias* simulations

3.1 General Results

The failure of management options to restrict the spread of *Asterias amurensis* is assessed by examining the establishment of populations of adult starfish at new sites. Establishment success was defined as a population of greater than 100 starfish persistent over at least 2 years. After this period, two year old starfish will be reproductively viable and populations will be producing sperm and eggs, and hence larvae.

The median number of established populations after 50 years, summarised over the 100 simulation repeats, are shown in Table 9. For larval mortality and settlement Sets 1 & 3, reballasting at sea reduces the number of established sites compared with the no exchange management option. However, all options where ballast water is discharged at destination ports have a higher number of established populations than the option where there is no ship traffic or where 100% of larvae are killed in the ballast water, or freshwater water ballast was used.

Table 9 Number of oceanic cells and estuaries with established populations after 50 y

	Management option					
	Natural	No Exchange	Exchange 5nm	Exchange 33nm	Exchange 200m	Exchange 5nm MS
Set 1	111	153	135	140	140	141
Set 2	131	155	172	167	163	166
Set 3	112	156	142	144	142	145

3.2 Probability of Establishment

The probability of a population of adult *Asterias* establishing at a particular site was calculated as the number of times a population established in 100 simulations at a particular site/100 calculated from each combination of management option and larval mortality/settlement set. Sites that establish, go locally extinct and then re-establish are treated in the same way as sites that establish and never go extinct. The distribution of these probabilities was calculated for all combinations of management options and larval mortality/settlement sets. Cells and estuaries that never have an established population in any simulation are excluded from this analysis.

The results are presented for each larval mortality/settlement set to allow comparison of the management options. The quantiles of the distributions are shown below in Figure 13 for larval mortality/settlement Set 1, in Figure 15 for Set 2 and Figure 16 for set 3. These figures show the proportion of sites with a probability of establishment less than a given level. Thus, in Figure 12, 20% (or quantile 0.2) of sites had a probability of establishment less than or equal to 0.5 for the No_Exchange management option. These figures allow for the comparison of management options within a particular set of larval mortality/settlement rates.

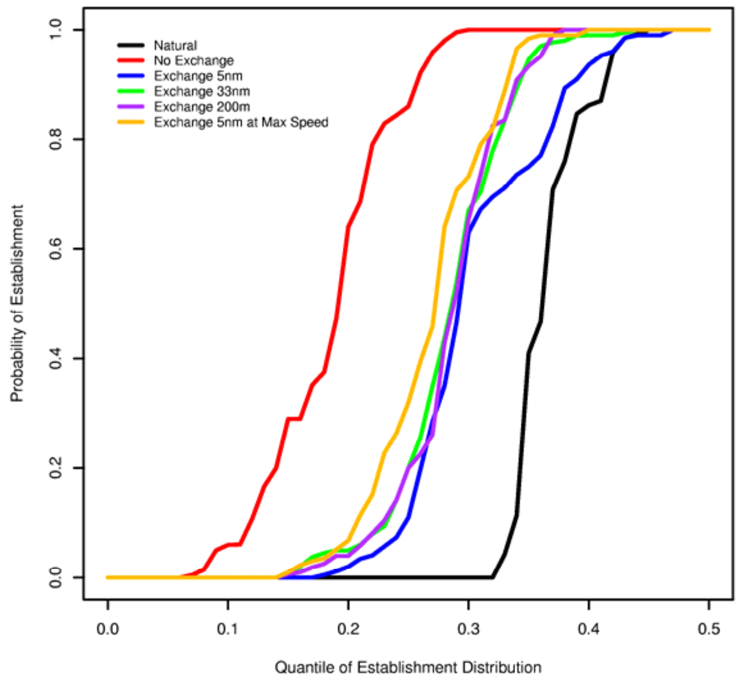


Figure 13 The quantiles of the distribution of probability of establishment for Set 1.

The actual distribution of probabilities of establishment for Set 1 is shown in Figure 14. Sites with no established populations and sites where populations always established dominate the distributions. However, the distributions show important differences. The simulations where no exchange occurred had proportionally more sites where establishment always occurred (i.e. probability of establishment =1). The simulations where the only dispersal of *Asterias* occurred by oceanic currents had the fewest sites where the probability of establishment was one, and the distributions of simulations where reballasting occurred were distributed between the Natural and No_exchange simulations.

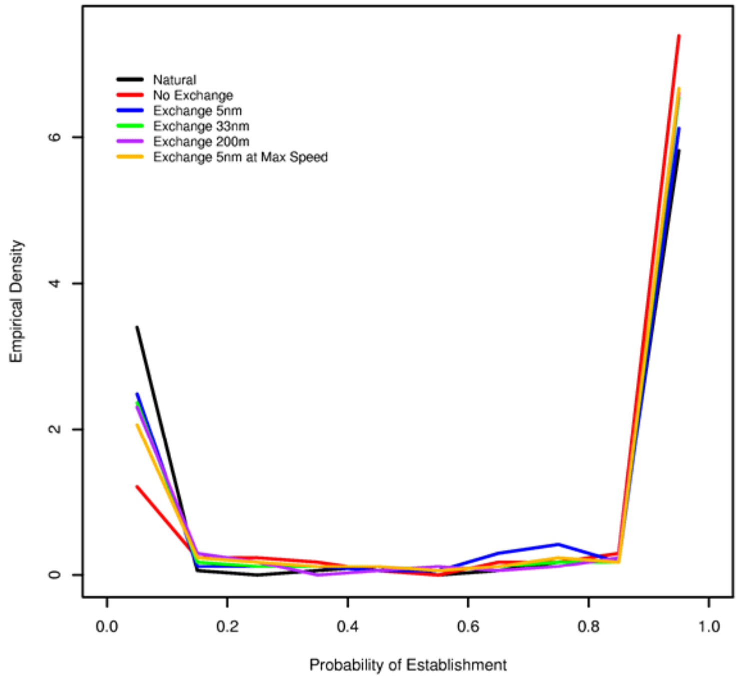


Figure 14 The empirical density distribution of the probability of establishment for Set 1

Simulations using larval mortality/settlement Set 2 produced quite different results. In these simulations, ships that reballasted at sea had similar distributions to the ships with no exchange at the lower end of the distribution. However, these simulations also had proportionally fewer sites where the probability of establishment was 1.

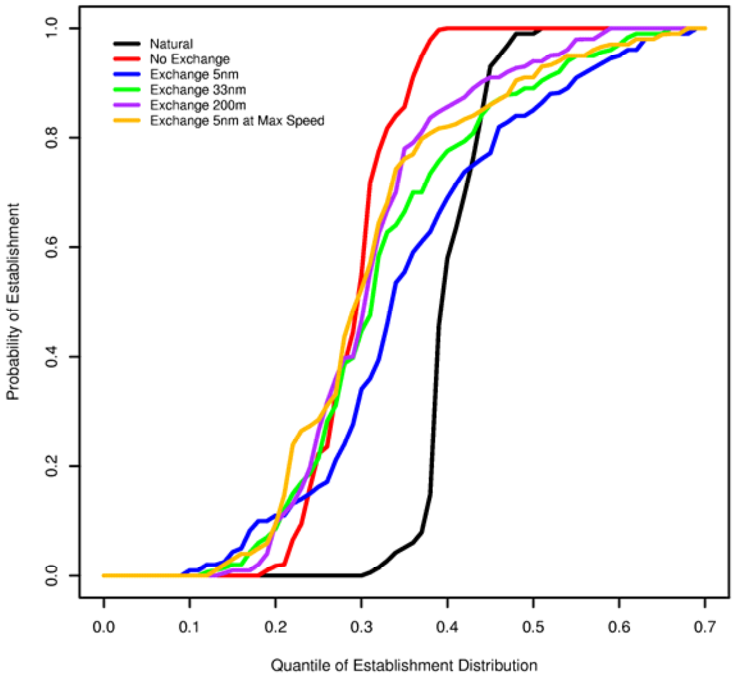


Figure 15 The quantiles of the distribution of probability of establishment for Set2.

The results of simulations with larval mortality/settlement Set 3 were similar to the simulations with Set 1. As in Set 1 & 2, there are not marked differences between the management options using reballasting. As with Set 1, reballasting reduces the impact of ballast discharge.

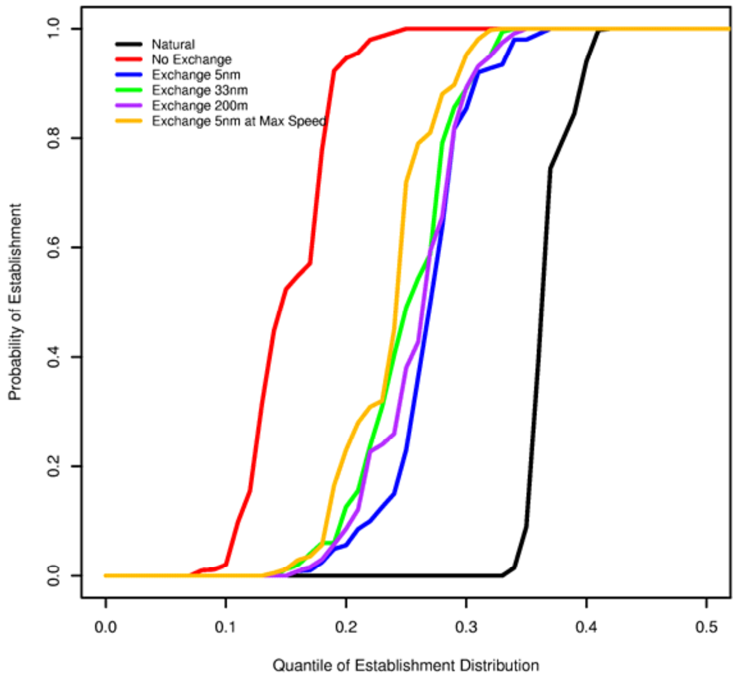


Figure 16 The quantiles of the distribution of the probability of establishment for Set 3

3.3 Time to establishment

The rate of establishment of new populations was also important in separating the management options. The time to establishment was calculated as the median (50th percentile) time for a population to establish at a particular site, including simulations where a population did not establish. Thus, sites with a probability of establishment < 1 are given equal weighting to sites that always had established populations. The 10th and 90th percentiles are also plotted as dashed lines.

For simulations using larval mortality/settlement Set 1, the total number of sites established is similar for all management option up to 10 years after model initialisation. After this the No exchange options leads to a larger number of sites established, and after 20 years, the number of established populations in the Natural management option asymptotes. The trajectories of management options that involved reballasting are difficult to separate. The final numbers of established sites for all reballasting options are also very similar.

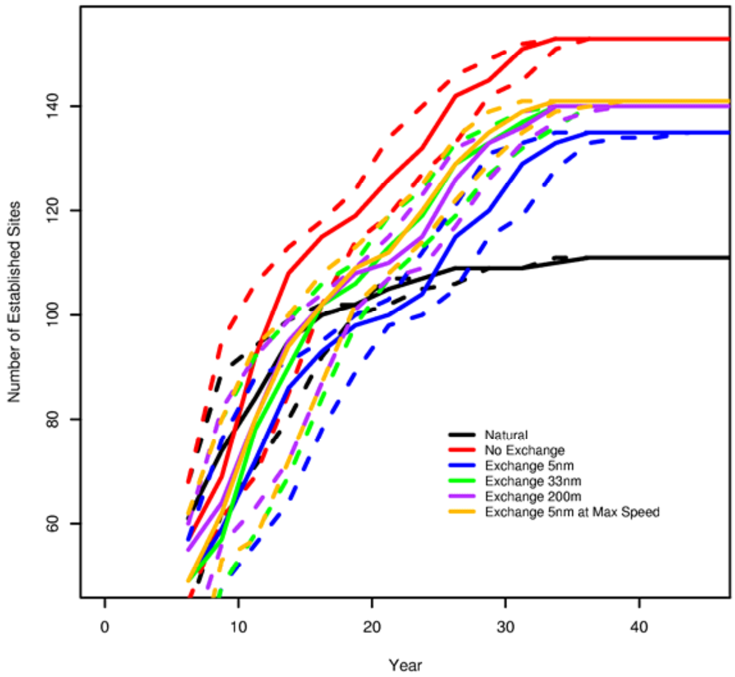


Figure 17 The median time taken for populations to establish at sites with Set 1 (dashed lines are 10th and 90th percentiles)

The simulations using larval mortality/settlement Set 2 (Figure 18) show different patterns to the simulations using Set 1. All simulations with ship movement and ballast discharge resulted in significantly higher numbers of established sites than simulations with no ship movement (i.e. Natural management option). It is worth noting that the final numbers for simulations with reballasting are higher than the numbers where no exchange occurs.

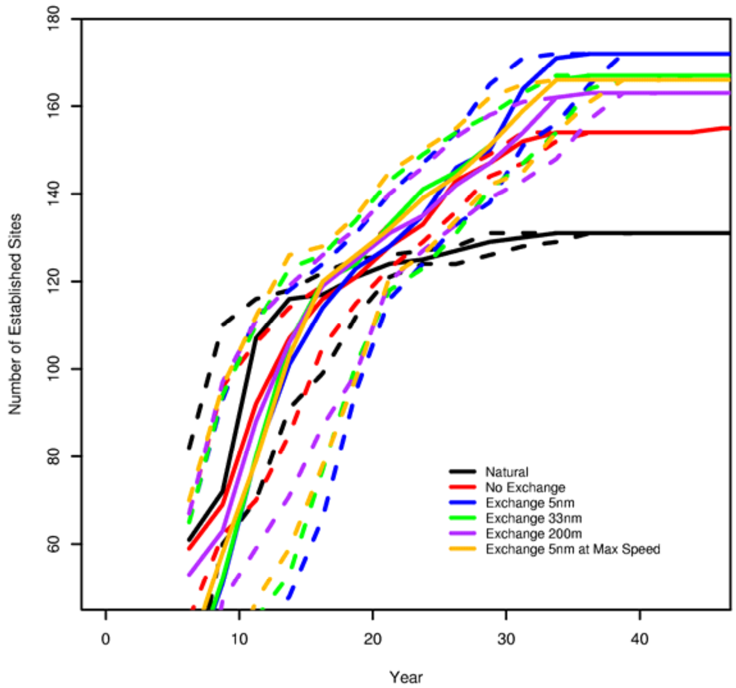


Figure 18 The median time taken for populations to establish at sites with Set 2 (dashed lines are 10th and 90th percentiles)

Establishment in simulation using Set3 are similar to those using Set 1 (Figure 19). The results of the simulations using reballasting management options are very similar and the total number of sites with established populations is less than the No_Exchange option and more than the Natural option. The numbers of established sites are similar in the first 15 years for all management options.,

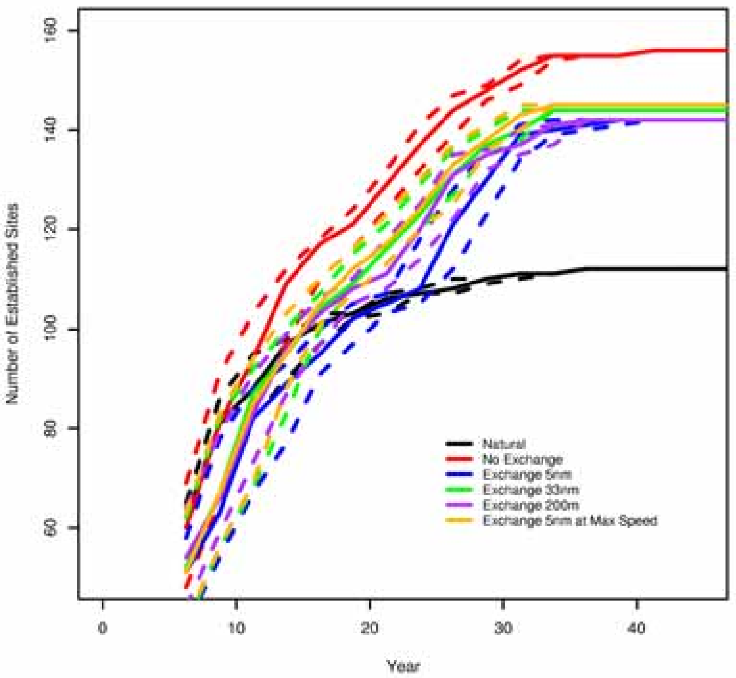


Figure 19 The median time taken for populations to establish at sites with Set 3 (dashed lines are 10th and 90th percentiles)

3.4 Establishment of populations in south eastern Australia

Simulations using larval mortality/settlement Set 1

The spatial distribution of established population was mapped onto the coast of south eastern Australia. The sites are coded according to the probability of establishment. In simulations with a Natural management option, established populations are restricted to the eastern section of the model (east of 143° E). Established populations do not extend westward from Cape Otway in Victoria. However, there are numerous populations east of 143° E, and population can be found around a large section of Tasmania. Most sites that do not have established population have small transient populations.

In all simulations with ship movements, irrespective of reballasting options, there are large populations on the southern coast of South Australia from 131° E to 136° E. in the Great Australian Bight. There are also persistent populations at Adelaide and numerous populations scattered throughout South Australia. It is also worth noting that the only management option with populations between Cape Jervis (138° E) and Cape Otway (143° E) is Exchange_5nm.

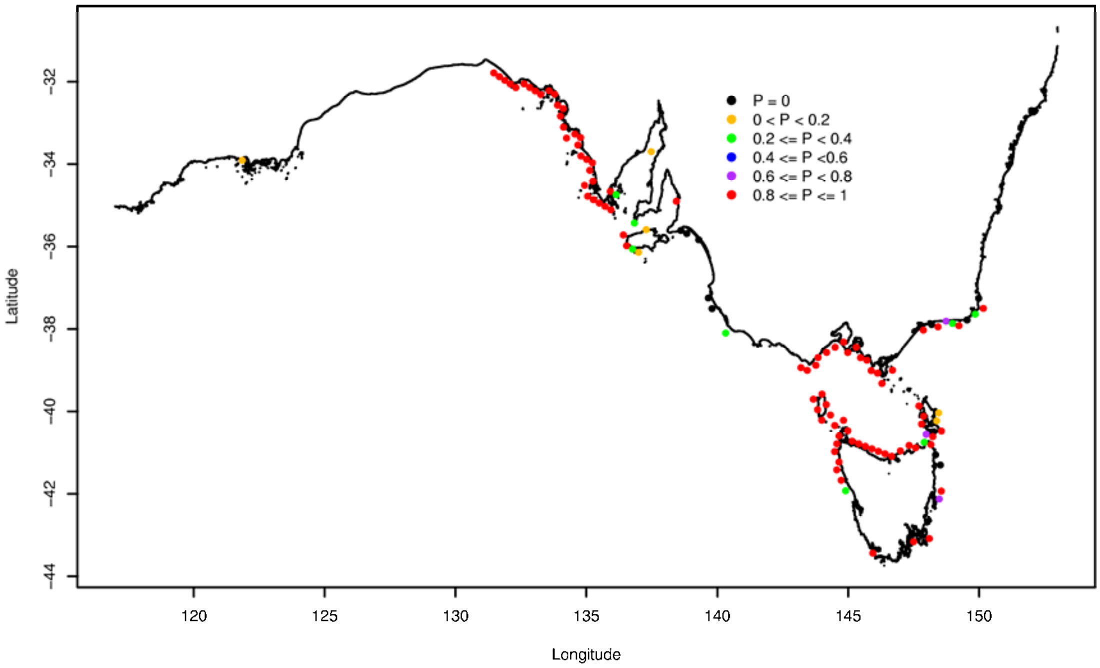


Figure 20 **Establishment of population in south eastern Australia for simulations with Set 1 and Natural management option. Sites are coded by probability of establishment**

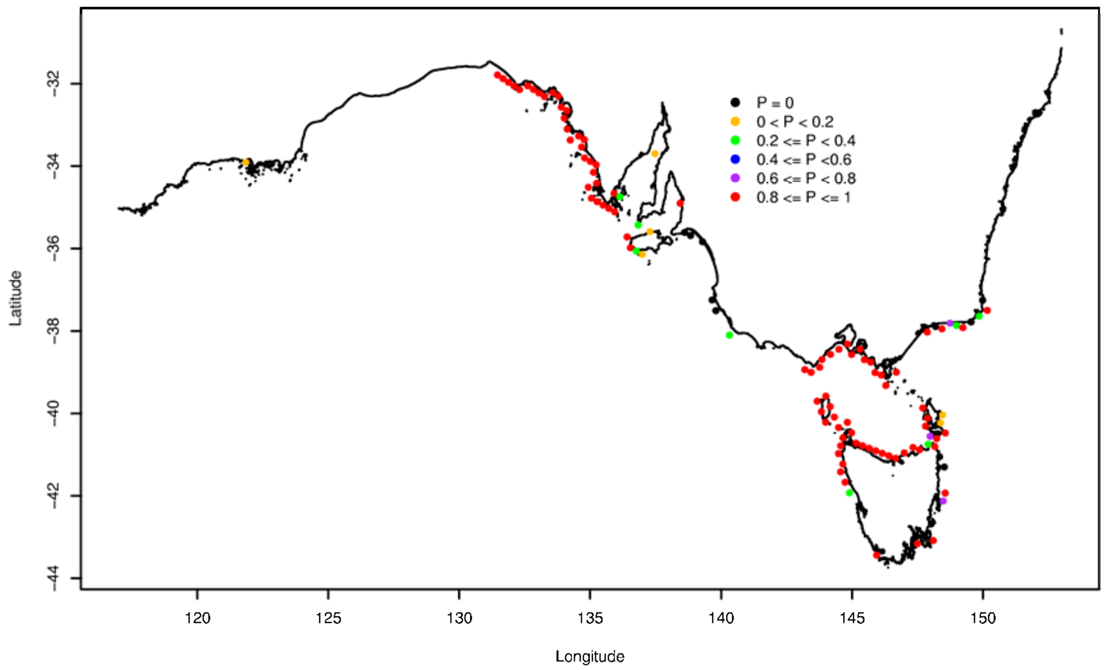


Figure 21 Establishment of population in south eastern Australia for simulations with Set 1 and No_Exchange management option. Sites are coded by probability of establishment

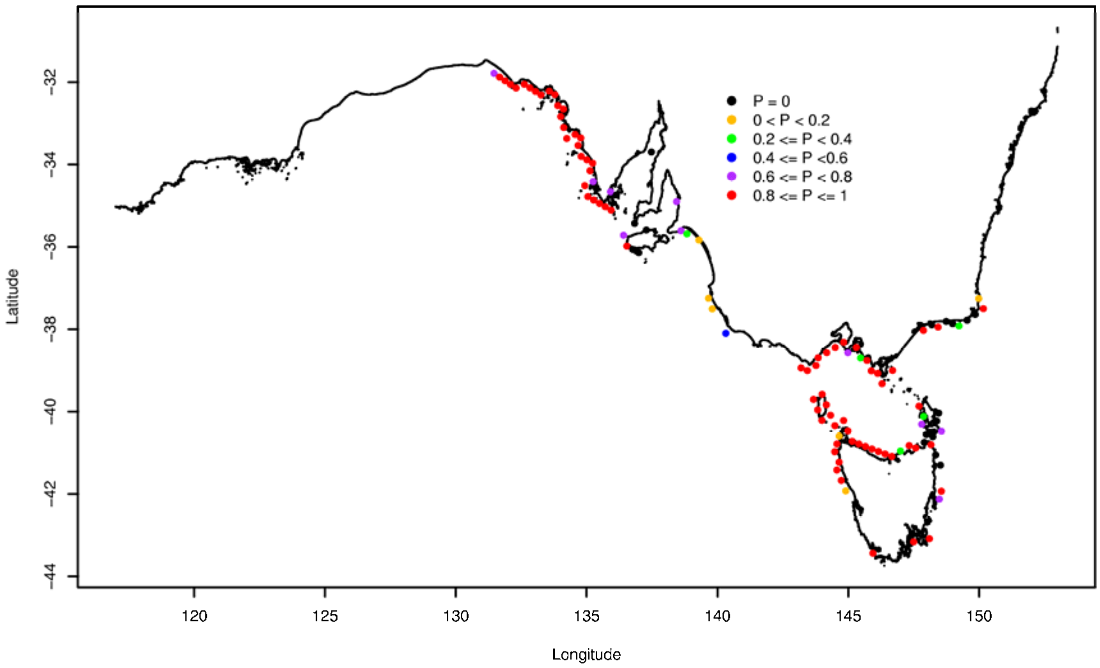


Figure 22 Establishment of population in south eastern Australia for simulations with Set 1 and Exchange_5nm management option. Sites are coded by probability of establishment

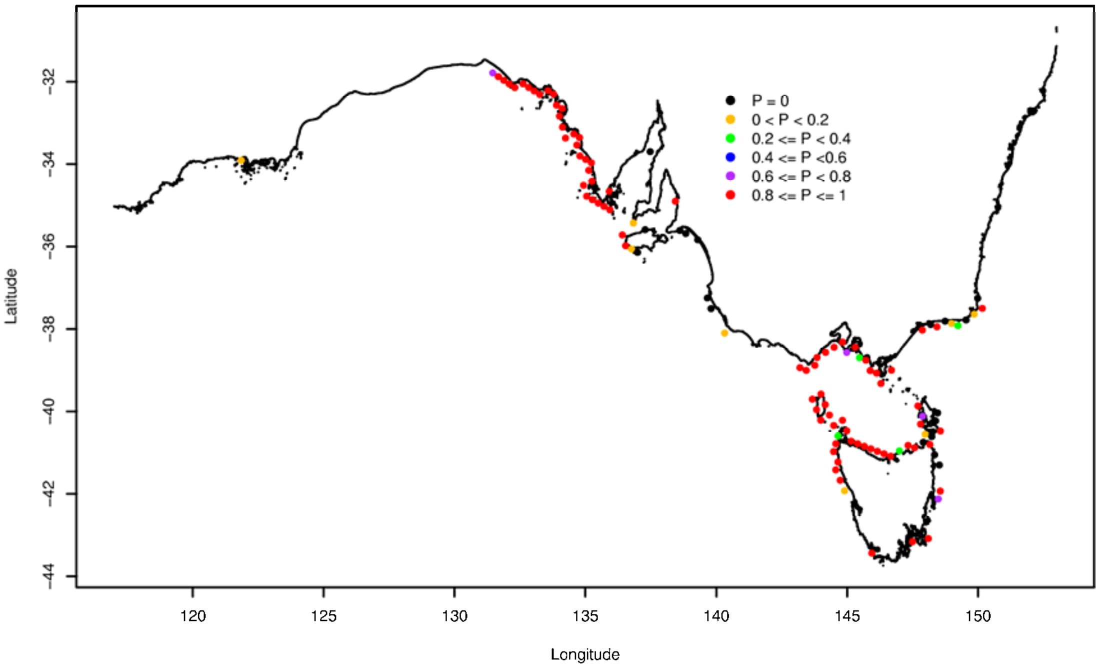
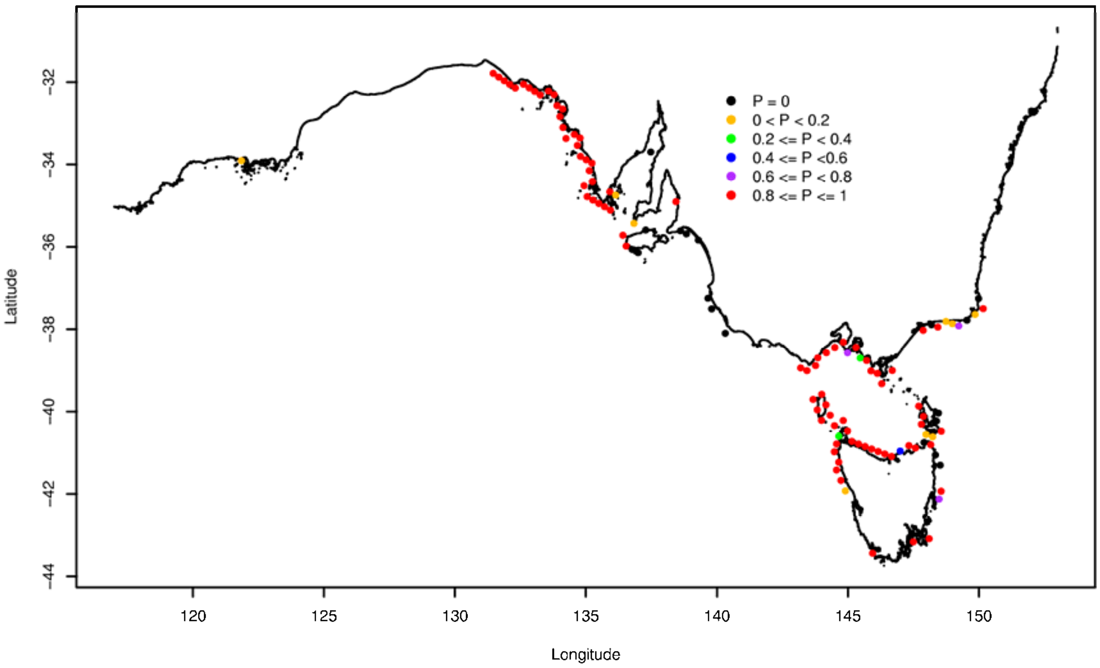


Figure 23 **Establishment of population in south eastern Australia for simulations with Set 1 and Exchange_33nm management option. Sites are coded by probability of establishment**

F



probability of establishment.

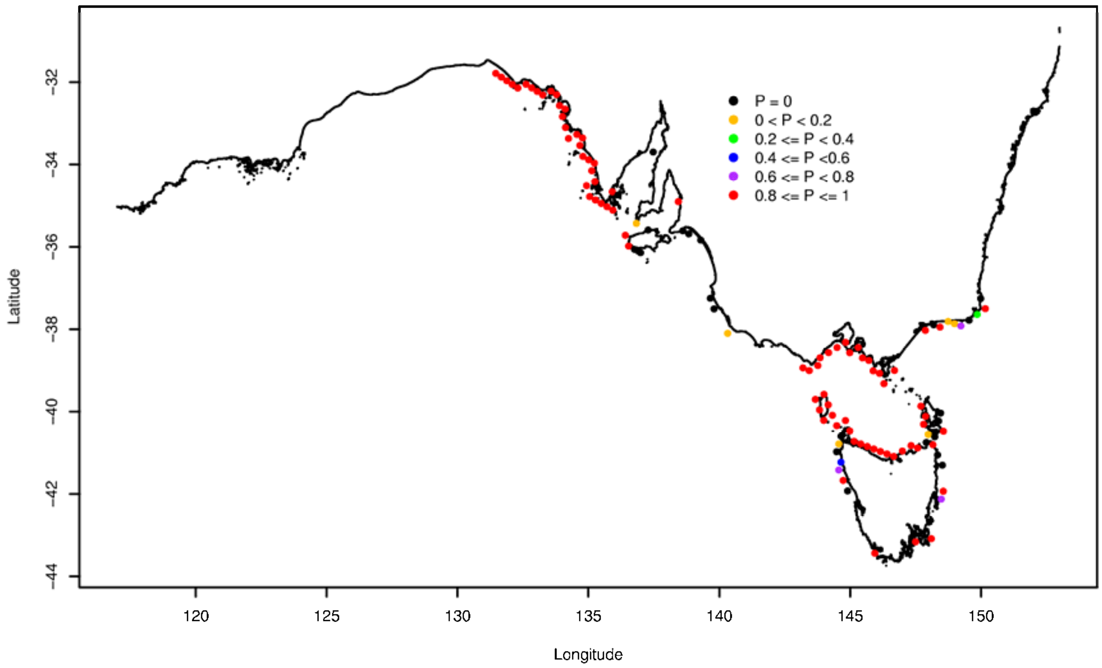


Figure 25 Establishment of population in south eastern Australia for simulations with Set 1 and Exchange_5nm_MS management option. Sites are coded by probability of establishment.

Simulations using larval mortality/settlement Set 2

A Natural management option resulted a similar spread of Asterias the simulations with Set 1. Populations established along the Victoria and Tasmania coastline but westward spread was restricted. Movement of ships introduced Asterias to South Australia, results similar to the simulations with Set 1. Simulations with reballasting have a higher number of populations with a probability of establishment less than one than simulations with no exchange, but are also the only simulations that have established populations between Cape Jervis and Cape Otway. These simulations have more established populations than either the simulations using Set 1 or 3, due to the reduced larval mortality rate.

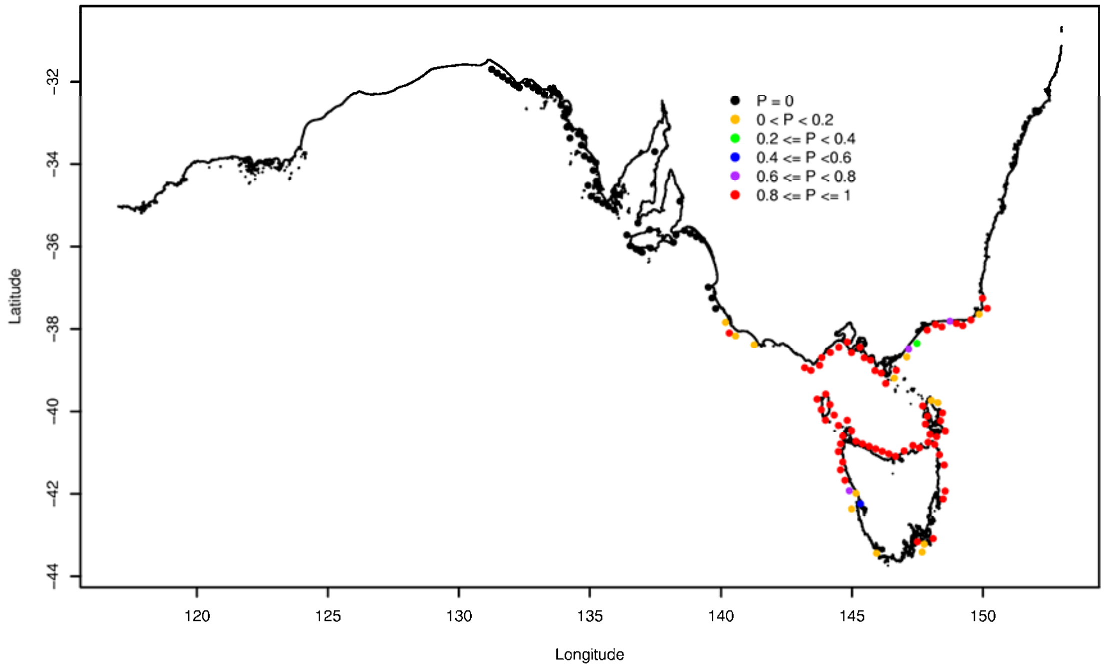


Figure 26 **Establishment of population in south eastern Australia for simulations with Set 2 and Natural management option. Sites are coded by probability of establishment.**

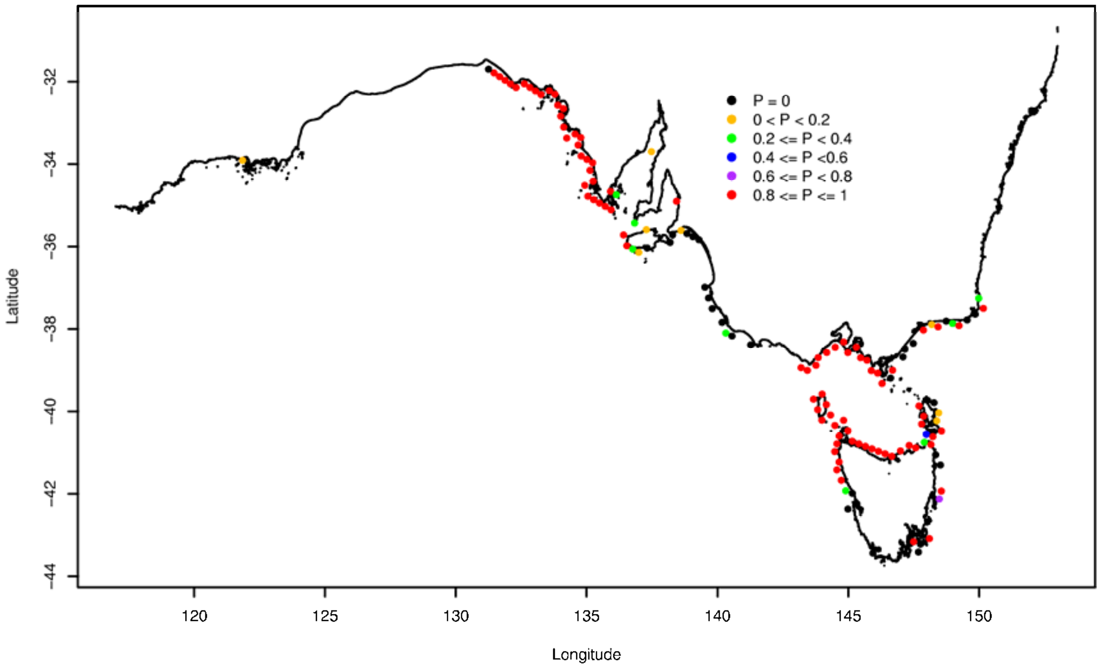


Figure 27 **Establishment of population in south eastern Australia for simulations with**

Set 2 and No_exchange management option. Sites are coded by probability of establishment.

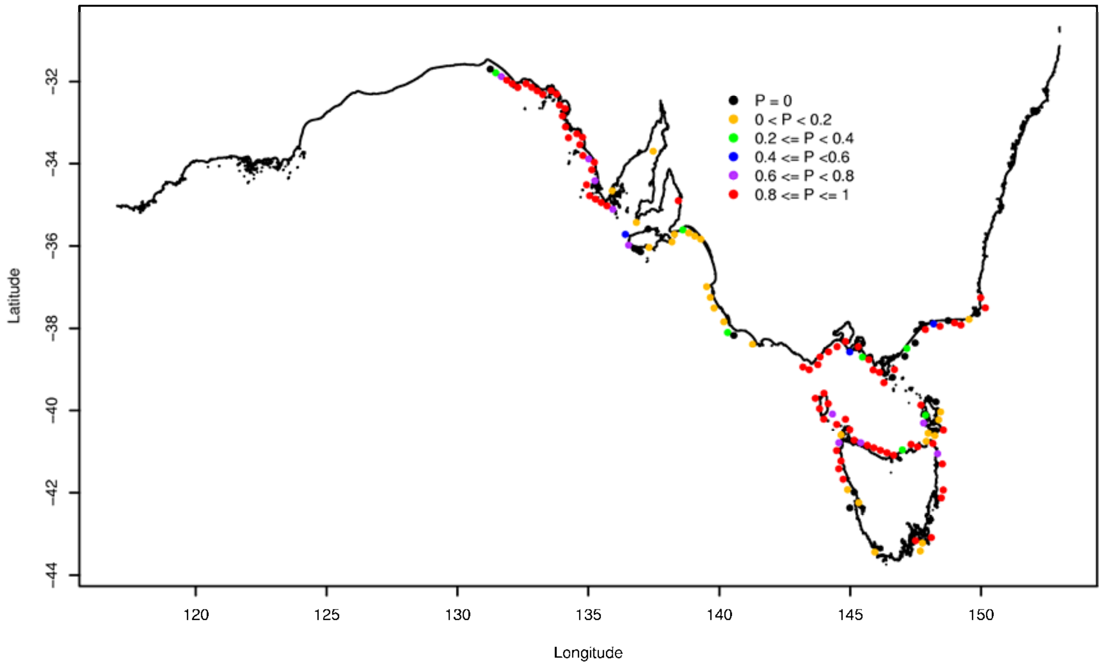
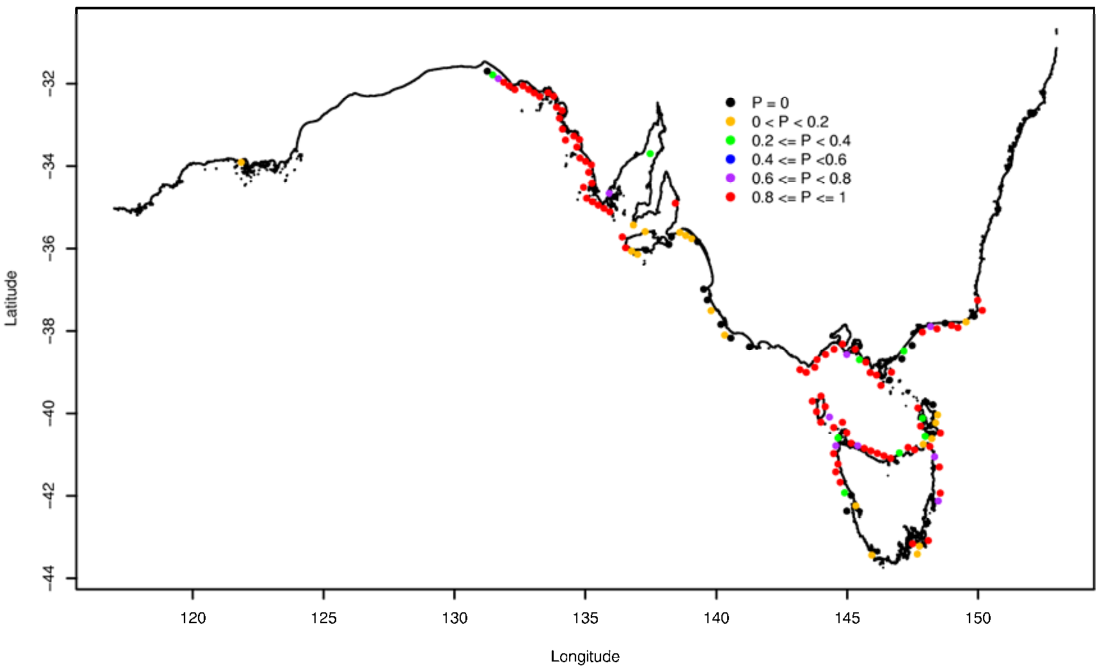


Figure 28 Establishment of population in south eastern Australia for simulations with Set 2 and Exchange_5nm management option. Sites are coded by probability of establishment.



Simulations using larval mortality/settlement Set 3

The simulations using larval mortality/settlement Set 3 were similar to those from set 1, distinguished only by an increase in the number of sites where the probability of establishment was equal to 1. The spatial distribution is very similar to the spatial distribution of simulations using Set 1, though slightly more restricted.

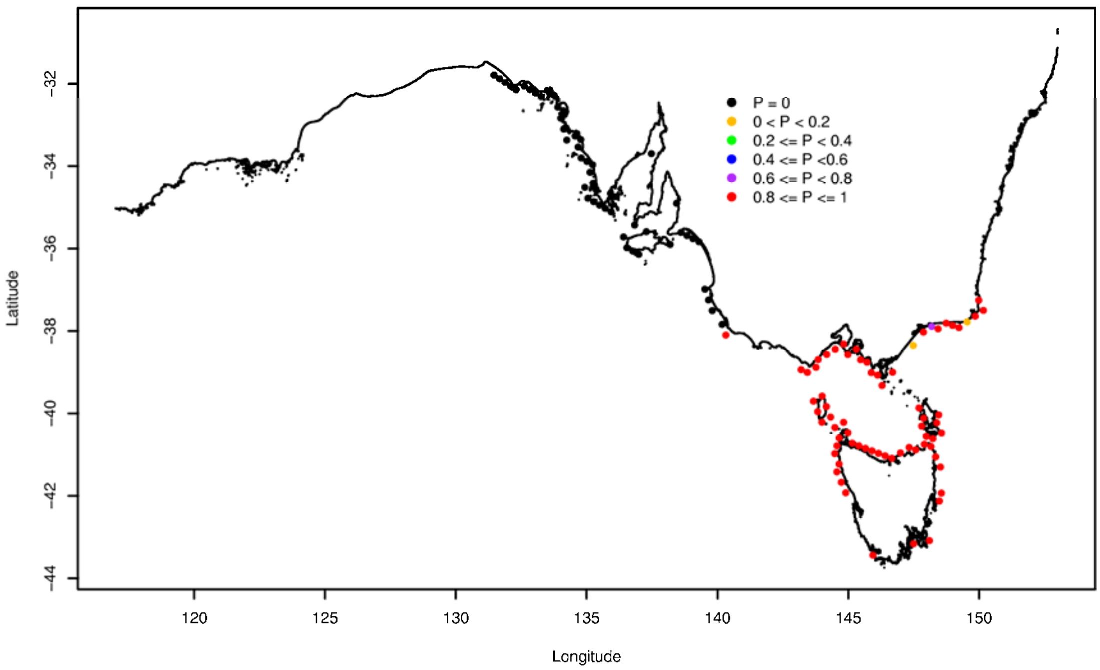


Figure 30 Establishment of population in south eastern Australia for simulations with Set 3 and Natural management option. Sites are coded by probability of establishment.

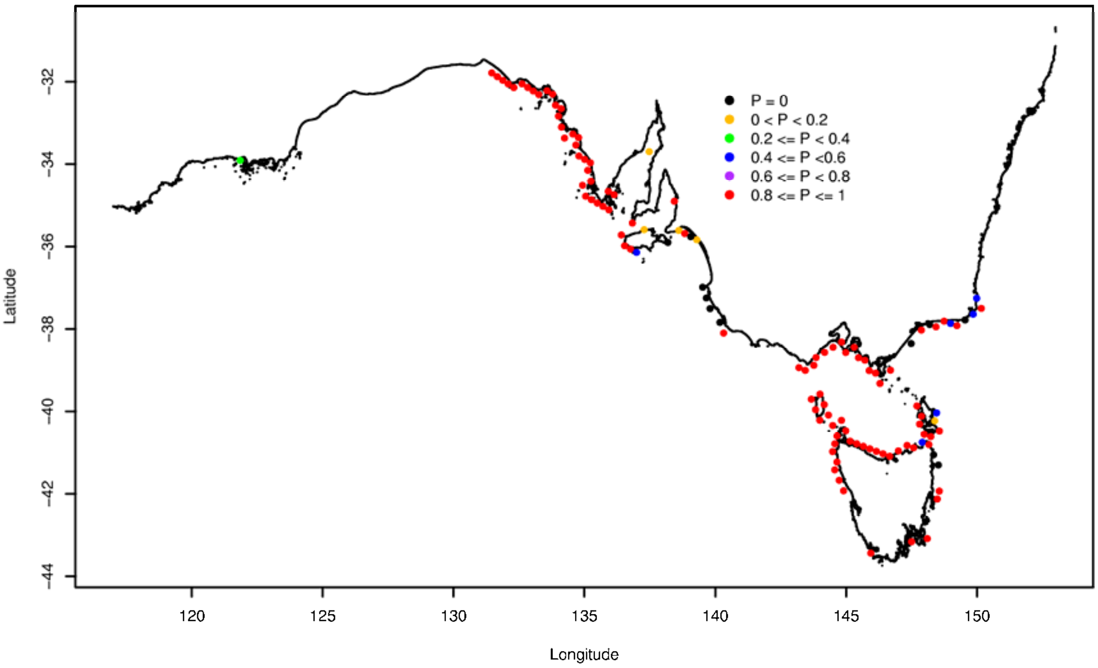


Figure 31 Establishment of population in south eastern Australia for simulations with Set 3 and No_Exchange management option. Sites are coded by probability of establishment

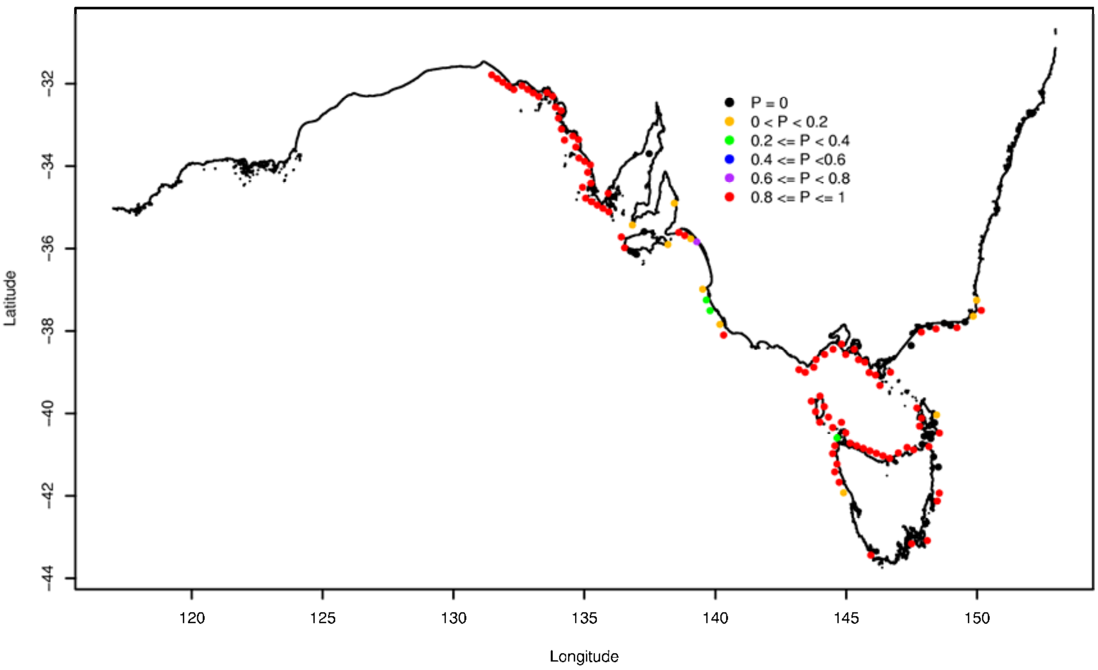


Figure 32 Establishment of population in south eastern Australia for simulations with Set 3 and Exchange_5nm management option. Sites are coded by

probability of establishment.

3.4 Effect of discharge management on local populations

The effectiveness of management options on the total population numbers at a particular port varied across the area of the model (Fig. 33). For some ports the population sizes were similar irrespective of the management option applied (i.e. Westernport and Lakes Entrance). These ports are invariably in or east of Bass Strait.

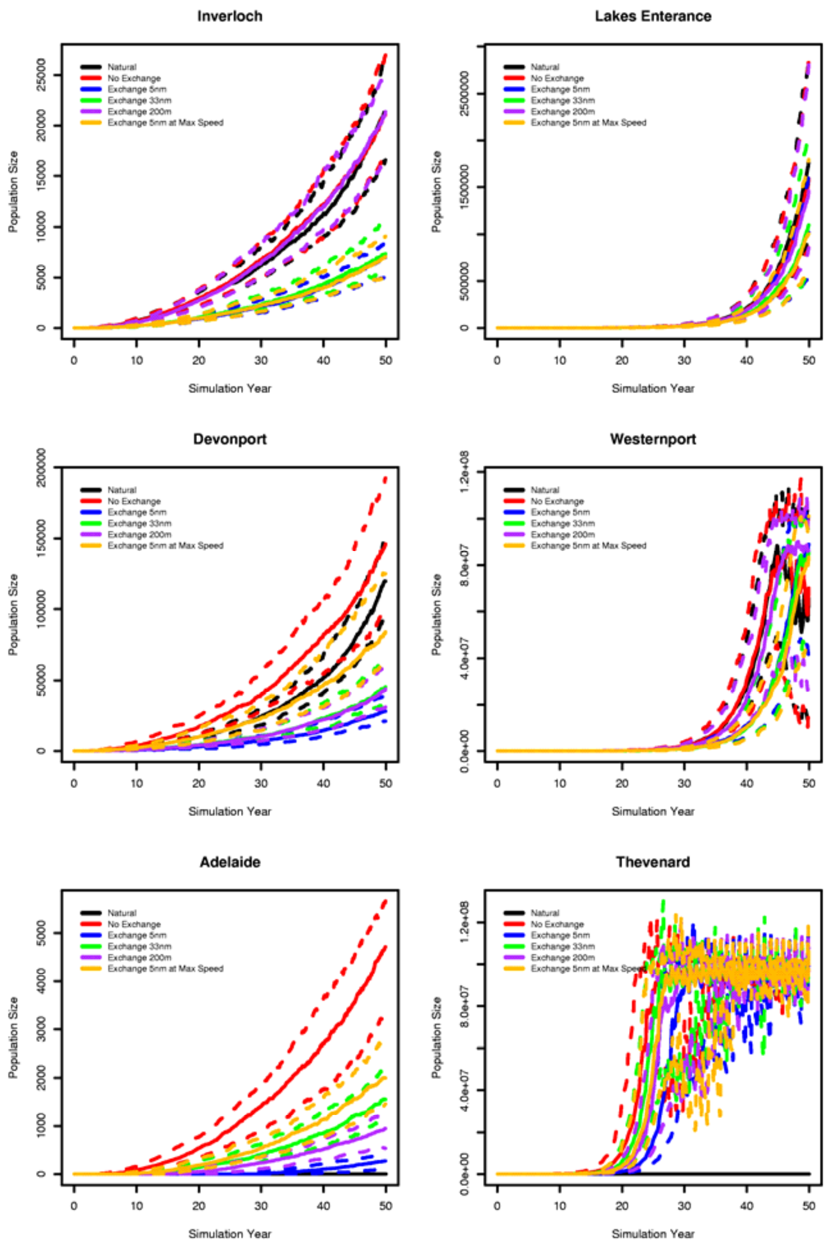


Figure 33 Population growth over the 50 year duration of simulations. Solid line indicated the median population, dashed lines the 90th and 10th percentiles.

This is the range of spread by *Asterias* by oceanic currents. For some ports, particularly in South Australia, the populations were identical for all simulations with ship movements, irrespective of whether the ship reballasted or not (i.e. Thevenard).

However, different management option resulted in different population dynamics for other ports. Adelaide had no established populations when ship movement was removed and the population numbers were highest in when no reballasting occurred as ships moved. All other management options reduced the total numbers but not to zero. The ports of Devonport and Inverloch (Anderson Inlet) both had high population numbers in the Natural and No_Exchange option, but reduced numbers for the other management options involving reballasting.

3.5 Journey Duration

The imposition of reballasting on ships did not significantly change the duration of journeys for most options when compared to the durations when ships did not have to reballast. The obvious exception is exchange at 200m minimum depth. When exchange is mandated outside 200m, vessels operating in Bass Strait or inshore in the Bight are compelled to divert across the continental shelf, adding significant delays. The journey times for other exchange options are slightly increased, but in most cases no diversion is necessary. Increases in time result from

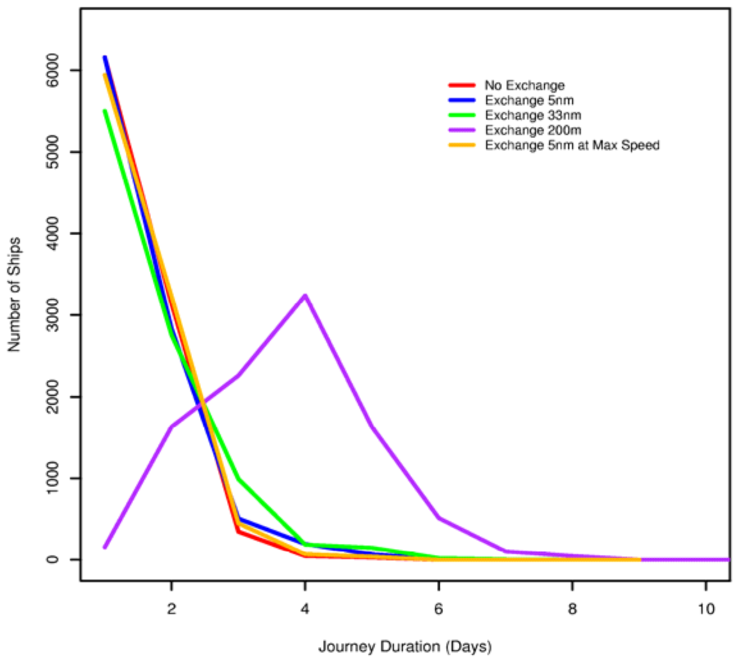


Figure 34 The journey duration for vessels with different exchange options

ships reducing their speed to exchange. As exchange rate is determined by DWT (Figure 6), many of the ships in the model could reballast within 1-2 days as a consequence of relatively low dead weights. However, several assumptions made in the model may also have contributed to the small difference between no exchange and exchange journey durations. First, the influence of weather conditions on the ability to reballast was not explored. Some of the smaller ships crossing waters such as Bass Strait are unable to exchange in anything above light seas (Theresa Hatch, pers. comm.). Second, ships began to reballast from the first instant possible and continued to the last without pause. Because the time step in the model is 1 day, rounding off errors may be obscuring smaller differences in journey duration. Further consideration of weather and increased resolution of vessel journey times is required before the economic consequences of exchange can be reliably explored.

4 Discussion

Reballasting ships at sea while underway has been suggested as a management option that will reduce the risk of establishment and spread of invasive species (Rigby and Hallegraeff 1994, Rigby *et al.* 1999, Wonham *et al.* 2001,). However, it is apparent that this ballast water management does not remove all risks. There are even some indications from this modelling that discharge of ballast at sea could under some circumstances increase the risk of spread and establishment in some non-intuitive ways.

Differences in larval mortality and settlement

The differences in dynamics in the model using the larval mortality and settlement rates Sets 1& 3 compared to Set 2 resulted from differences in the larval dynamics of *Asterias*. Sets 1 and 3 had higher rates of larval mortality (Z_L = 0.177 and 0.184) but also higher rates of settlement (S = 0.5 and 0.9). Sites along the coast receive smaller groups of *Asterias* larvae, but because the probability of successful settlement is higher, supply to a site is more consistent. These populations will be less effected by the stochastic elements of larval dynamics.

In contrast, larvae in Set 2 had lower rates of mortality (Z_L = 0.148) but also commensurately lower rates of settlement success (S = 0.1). Each site on the coast received a larger number of larvae than the models using Sets 1 & 3, but the likelihood of these larvae successfully settling was lower. Thus, these populations were more influenced by the stochastic elements of larval dynamics. Although successful settlement occurred less frequently, the consequences, in terms of the resulting population size, were considerably greater.

The three sets are an exploration of two alternative life history strategies for marine species. Sets 1 and 3 represent a strategy of continual supply of relatively few larvae, ensuring that populations receive a supply of new recruits. This strategy would suit survival in enclosed areas (i.e estuaries and bays) where larvae will have a relatively high chance of settlement in an appropriate site. If the species evolves a strategy closer to that explored in Set 2, the larvae are more suited to dispersal over large distances. The likelihood of successful settlement will not be as high, but once settled the newly established population will have a greater chance of establishing a long term population as a consequence of higher initial numbers than for Sets 1 or 3.

Implications of different management options

The performances of each of the reballasting options were remarkably similar. In most cases reballasting reduced the risk of establishment at new sites marginally and increased the time taken for these sites to establish compared with the option of no exchange. Movement offshore does not seem to reduce the risks of establishment for the principle locus of invasion in the Great Australian Bight.

Because exchange is proportional to the density of larvae in the ballast tanks, the density of larvae released will be maximised when reballasting commences and will reduce as reballasting continues. Thus, ships that are reballasting while travelling west from Bass Strait are distributing the greatest density of larvae from their ballast tanks along the stretch of coast between Cape Jervis and Cape Otway. The larvae from ships that reballast away from the coast (i.e. 2 cells/ 33nm or 200m depth) do not appear to reach suitable habitat in sufficient numbers to establish permanent populations. In contrast, ships that are reballasting close to the coast (i.e. 1 cell/5nm) distribute larvae sufficiently close that populations establish at some sites. The probabilities of establishment along that section of coast are generally less than 0.6, although the probability that at least one site along the stretch of coast will develop an established population will equal one.

Although the reballasting management options produced similar results for a particular larval mortality/settlement sets, there were considerable differences in the performance between sets, particularly between Sets 1/3 and Set 2. Because the numbers of larvae were higher in simulations with Set 2, the effectiveness of reballasting on reducing the likelihood of establishment was reduced and ships that reballasted enroute were more likely to establish populations along the coastline between the departure and destination ports. The conclusion must be that the effectiveness of reballasting depends on reducing the propagule pressure at potential sites, and the reballasting does not always achieve this.

How robust are these model results

Although a high degree of synergy between model and reality is not a requirement of the MSE process, serious attempts were made to derive a realistic model from available data. It is not possible to determine from current information which particular sets of larval mortality and settlement are correct, or even if they represent the reality of larval dynamics. Certainly, it does not seem likely that larval mortality rates are constant throughout the duration of the larval phase of a species. Overall, the limitations of the model reflect the uncertainties in the understanding of the physical and biological processes that underpin the potential movement of Asterias in southern Australia. These uncertainties highlight the pressing need to expand the understanding of marine invasive species and suggest several areas of basic biological research.

The model does provide of structured framework to compare differing management options, providing an estimation of the relative risks posed by each option, and a framework to select options that meet some/all of the management criteria. The relative risks should be insensitive to the limitations of the underlying model and can be used to inform decision making, in spite of model uncertainties.

Despite these limits, the spread of *Asterias* in the model seems similar to the spread of *Asterias* through Bass Strait. Given that the initial conditions of the model are similar to the distribution of Asterias in 1999-2002 (i.e. a large population in Port Phillip Bay and in the Derwent Estuary), it is not surprising that that current distributions and the equivalent model distribution is similar. The model continues to show a realistic number of established populations after 10 years, and shows a reasonable swift invasion of sites near Port Phillip Bay without generating absurd population numbers. Anderson's Inlet is an appropriate example (Figure 33).

Lastly, it is important to remember that in MSE the model does not have to represent reality accurately. All that is required it that it be a sufficient description to reality to enable the comparison of different management interventions, in this case ballast water management. While the time scales of invasion in this model need to be the subject of further investigation, the comparisons of risk for the different ballast water management strategies are likely to be more robust.

Future Directions

The development of the MSE model will continue in several directions. First, the number of simulations for each management option will be increase to at least 1000. This will allow the further refinement of probabilities and risks (down from 0.01 to 0.001). Arrangements have been made to use several computer clusters located at CMR Hobart. Second, the National System table-based risk assessment will be incorporated into the model to act as a management decision tool and further refine the management options. An element of this will be to incorporate a detection probability model to describe the likelihood of detection at a particular site for a given population size. This will represent the probability that a newly established population of *Asterias* can be detected while there is remains an opportunity for eradication. Third, additional vector information will the incorporated into the model. Currently, the only available additional information is data on the movements of fishing vessels operating in Commonwealth fisheries (source: AFMA). However, attempts are being made to source data from State fisheries, aquaculture and recreational boat movement. For these vectors appropriate risks of transport will have to be derived. This will complete the MSE components of the model (Figure 4).

As a further enhancement, method will be added to simulate either eradication or control methods (with appropriate probability distributions) and to extend the model to more than one species (further testing the sensitivity to larval duration). Some of the eradication/control potions to be explored are genetic techniques and physical removal of food sources (with commensurate changes in the density distributions). Adapting the model requires a relatively simple re-parameterisation of the variables defining population demography. There will also be further adaptations to further identify the source and sink populations as the range of *Asterias* increases.

Conclusions

A biological simulation of the population dynamics of *Asterias* was developed that successfully represented the observed dynamics of this species in Australia. This model was used to seed *Asterias* larvae into an oceanographic model of southern Australia, simulating the natural spread of this species. Establishment of new populations matched observations of new populations around Australia, eg. establishment of a population in Hendersons Lagoon within 10 years from the establishment of a population in Port Phillip Bay. The model also suggests a wider distribution of low abundances of *Asterias* than has been reported to date. Given the criterion for establishment – 100 individuals present for 2 years – and the size of oceanic cells it is perhaps not surprising that these populations would not be detected, however this needs to be checked further. There might be a need for special consideration of the likely success of small population densities.

With the addition of transport of *Asterias* larvae in ships' ballast water to the model, there was a marked increase in the number of ports containing established populations of *Asterias.* This was primarily due to the transport of larvae to ports in South Australia that would not receive larvae in the natural current flows. A range of ballast water management options was tested to test their effectiveness in reducing this increased spread of *Asterias.* All ballast water management options had a similar effect in reducing the risks of spread, although increasing the number of model runs in the future should improve the discrimination between options. All management options were better than no action; no ballast water management option was reduced the risk of spread as much as elimination of *Asterias* larvae from the ballast tanks (either by new treatment processes or through the uptake of freshwater, for example). The efficacy of ballast water management may be overstated, if smaller vessels are unable to effectively exchange ballast water given moderate or severe seas.

With one exception, the alternative management options did not appear to effect the transit time of vessels, although this is partly due to the time step of the model being greater than the change in transit times and the preponderance of smaller vessels in the area. Requiring vessels to travel to waters deeper than 200m to reballast did lead to a significant increase in transit time. The management option that enabled vessels to reballast whenever possible without delaying their transits was as effective as other management options. However, this result may be constrained by available transit times being measured in days.

Future development options for the MSE approach were identified. Further discussion with stakeholders will be required to ensure that the approach continues to match their objectives and management options.

5. Acknowledgements

Many people have contributed to the success of this project. Chris O'Brein (NZ Ministry of Fisheries), Colin Chalmers (WA Fisheries), Craig Johnson (University of Tasmania), Don Hough (Victoria DSE), Dough Montfort (Cawthorn Institute, New Zealand), Geoff Hicks (DOC, New Zealand), Graeme Inglis (NIWA New Zealand), Greg Parry (MAFRI), Gwen Fenton (DPI Tasmania), John Gilliland (SA Primary Industries and Resources), Keith Hayes (CSIRO), Martine Kinloch (BRS), Michael Drynan (DAFF), Michaela Dommisse (Victoria DSE), Mike Nunn (DAFF), Peter Cassels (DAFF), Ron Thresher (CSIRO) , Roy Johnson (SA Maritime Policy, Planning and Infrastructure), Tim O Hara (Melbourne Museum), Warren Geeves (DEH), Scott Porter (Transport South Australia), Val Boxall (SARDI) and Christian McDonald (DAFF) attended the first workshop. Gwen Fenton, Don Hough and Keith Sainsbury attended the first steering group workshop. Don Hough, Alice Morris (DPI Tasmania), John Gilliland, Warren Geeves, Sarah Johnstone (DEH), Jacinta Innes (DAFF), Simon Barry (BRS) and Naomi Parker (DAFF) attended the second steering group meeting.

Michaela Dommisse prepared the summary of the first workshop. Scott Condie (CSIRO) and Beth Fulton (CSIRO) provided the oceanographic data. Biological data were provided by Alice Morris, Scott Ling (UTAS), Greg Parry and Caroline Sutton (CSIRO). Keith Hayes (CSIRO) and Jemery Day (CSIRO) provided comments on the initial model design.

This project was funded by the Australian Government's Natural Heritage Trust.

6. References

Bruce, B.D., Sutton, C.A., Lyne, V. (1995). Laboratory and field studies of the larval distribution and duration of the introduced seastar Asterias amurensis with updated and improved prediction of the species spread based on a larval dispersal model. Final report to Fisheries Research and Development Corporation #93/235. CSIRO Hobart.

Byrne, M., Morrice, M.G., Wolf, B. 1997. Introduction of the northern Pacific asteroid Asterias amurensis to Tasmania: reproduction and current distribution. Mar. Biol. 127: 673-685

Carlton, J.T. (1999), The scale and ecological consequences of biological invsions in the world's oceans, IN: *Invasive Species and Biodiversity Management*, (Sandlund, O.T., Schei, P.J., Viken, A. eds) Kluwer Academic Publishers, The Netherlands pp.195-212.

Cohen, A.N. & J.T. Carlton (1995). Nonindigenous aquatic species in a United States Estuary: A case study of the biological invasions of the San Francisco Bay and delta. U.S. Fisheries and Wildlife and National Sea Grant College Program. Report NTIS Number PB96166525.

Devroye, L. 1986. Non-Uniform Random Variate Generation. Springer-Verlag, New York, USA.

Hewitt, C., Campbell, M., Thresher, R. & Martin, R. (1999). Marine Biological Invasions of Port Phillip Bay, Victoria. CRIMP Technical Report 20, CSIRO Marine Research, Hobart, Tasmania.

Hatanaka, M. and Kosaka, M. 1958. Biological studies on the population of the starfish, *Asterias amurensis*, in Sendai Bay. Tohoku Journal of Agricultural Research 9(3): 159-178.

Hayes K. R. and McEnnulty F. (2001) DSS SLA interim report, Centre for Research on Introduced Marine Pests, Hobart, Australia

Hayes K. R., McEnnulty F. and Sliwa C. (2002) DSS SLA final report, Centre for Research on Introduced Marine Pests, Hobart, Australia

Kinloch, M., R. Summerson, and D. Curran (in press). Identifying marine pest translocation threats associated with non-commercial port nodes and non-trading vectors. BRS Report.

Kolar, C.S and D.M. Lodge (2001). Progress in invasion biology: predicting invaders. Trends in Ecology and Evolution **16**(4): 199-204.

Ling S.D., Johnson C.R., Mundy C.N. and Morris, A. (in prep.) Reproductive output of the northern Pacific seastar *Asterias amurensis*(Lutken) in the Derwent estuary: the role of anthropogenic structure.

Martin R, and Sutton C. (2000). Survival of Target Taxa in Ballast Tanks. Final Report for the Strategic Ballast Water Research and Development Program. Project No. 8/98.

Morris A. (2002). Early Life History of *Asterias amurensis*. PhD Thesis, University of Tasmania.

Rigby, G and Hallegraeff, G. 1994. The transfer and control of harmful marine organisms in shipping ballast water: Behaviour of marine plankton and ballast water exchange trials on the MV "Iron Whyalla". Journal of Marine Environment Engineering 1: 91-110.

Rigby, G, Hallegraeff, G and Sutton C., 1999. Novel ballast water heating technique offers cost-effective treatment to reduce the risk of global transport of harmful marine organisms. Marine Ecology Progress Series, 191:289-293.

Silverman, B.W. (1986) Density Estimation for Statistics and Data Analysis. Monographs on Statistics and Applied Probability 26. Chapman & Hall, London, UK.

Sutton,C.A., Bruce B.D. (1996). Salinity and temperature tolerances of larvae of the northern Pacific seastar Asterias amurensis. CSIRO Centre for Research on Introduced Marine Pests, Technical Report 6, 26 pp.

Sutton, C.A. and Green, M.A. (1999). A Laboratory Staging Guide for the Larvae of the Northern Pacific Seastar, Asterias amurensis. CRIMP Technical Report Number 19, pp 35.

Wasson, K., C.J. Zabin, L. Bedinger, M.C. Diaz, and J.S. Pearse (2001). Biological invasions of estuaries without international shipping: the importance of intraregional transport. Biological Conservation **102**: 143-153.

Wonham, M.J., Walton, W.C., Ruiz, G.M., Frese, A.M. and Galil, B.S. 2001. Going to the source: role of the invasion pathway in determining potential invaders. Marine Ecology Progress Series, 215:1-12.