Risk Factors for Fouling Biomass: Evidence from Small Vessels in Australia

Tracey Hollings[1], Stephen E. Lane[1], Keith R. Hayes[2], Felicity R. McEnnulty[3], Mark Green[3], and Andrew P. Robinson[1]

[1]Centre of Excellence for Biosecurity Risk Analysis, The University of Melbourne
[2]Data61, Commonwealth Scientific and Industrial Research Organisation
[2]Oceans and Atmosphere, Commonwealth Scientific and Industrial Research Organisation

January 15, 2018

Abstract

Invasive marine non indigenous species are a major threat to marine biodiversity. Recreational vessels have been recognised by the scientific community as an important vector of non indigenous species, but have been slow to be picked up by recreational boaters/vessel owners and marina management. In particular, the translocation of invasive species from one region to another (domestically) may be at least partially due to recreational vessels.

This paper reports on a statistical analysis of biomass samples gathered from the hull and other external surfaces of recreational yachts and fishing vessels in order to quantify the relationship between the wet biomass of biofouling and vessel-level characteristics. Unsurprisingly, we find that the number of days since the vessel was last cleaned was strongly related to the wet weight of biomass. The number of days since the vessel was last used was also related to the wet weight of biomass, yet was different depending on the type of vessel. Similarly, the median number of trips undertaken by the vessel was related to the wet weight of biomass, and varied according to the type of antifouling paint used by the vessel. The relationship between vessel size, as measured by hull surface area, and wet weight biomass per sample unit area was not significant.

In order to reduce the domestic spread of invasive species, owners of small vessels (that sit around in marinas/moorings for extended periods between uses in particular) should be encouraged to maintain a regular cleaning and maintenance schedule, and use an appropriate type of antifouling paint.

1 Introduction

Commercial and recreational vessels are the most important vector for the introduction and spread of marine non indigenous species globally (Molnar et al., 2008), effectively removing natural barriers to dispersal, including ocean currents and distance (Paini and Yemshanov, 2012; Ruiz et al., 1997). Invasive marine non indigenous species are a major threat to marine biodiversity leading to dramatic shifts in population, community and ecosystem dynamics, and many have serious environmental and economic implications (Carlton and Geller, 1993; Ruiz et al., 1997; Vitousek et al., 1996). For example, the annual cost (losses and control costs) to the United States resulting from the introduction of the Zebra mussel (*Dreissena polymorpha*), Asian clam (*Corbicula fluminea*) and Shipworm (*Teredo navalis*) is estimated at over USD$3bn (Pimentel, 2011).

Knowledge of invasion processes and pathways for non indigenous species in marine environments has developed considerably since Carlton and Geller (1993) but research studies and government policies have tended to focus exclusively on initial points of invasion which are predominantly biofouling and ballast water from international commercial shipping (Acosta et al., 2010; Campbell and Hewitt, 2011; Clarke et al., 2017). There is, however, growing recognition of the role of recreational vessels as vectors of non indigenous species (Ashton et al., 2014; Clarke Murray et al., 2011; Minchin et al., 2006), and recent studies have revealed the significant risk of secondary introductions in stepping stone invasions (e.g. Burgin and Hardiman, 2011; Clarke Murray et al., 2011; Hewitt et al., 2007; Lacoursière-Roussel et al., 2012a; Minchin et al., 2006), whereby the movement of vessels within domestic borders has the potential to translocate invasive species from one port or region to another (Campbell and Hewitt, 2011). The secondary spread of non indigenous species will ultimately determine the magnitude of economic and environmental damage caused by invasive species (Zabin et al., 2014). In Australia impacts from secondary invasions are increasingly likely as recreational boat ownership continues to increase. In the decade from 1999-2009 boat ownership increased by more than 36% to more than 800,000 individual registered vessels nationwide (Burgin and Hardiman, 2011).

Limited knowledge and complexities within the recreational boating pathway means that risk based assessment and non indigenous species management of the pathway is absent in most countries (Acosta et al., 2010); concerns about recreational boating in the translocation of invasive species are often not acknowledged, even by local and international authorities (Burgin and Hardiman, 2011).

Furthermore, unlike large international and commercial shipping vessels, recreational yachts, boats and domestic fishing vessels are often unregulated by biosecurity agencies, and such vessels represent a significant gap in managing non indigenous species

in marine environments (Zabin et al., 2014). In Australia, most commercial and recreational vessels are not required to inspect their hulls for non indigenous species upon first entry in Australian waters or for travel domestically within Australia. Rather the government relies on education programs and voluntary actions by the vessel operators/owners to mitigate the risks of introduction and translocation (Piola and McDonald, 2012).

Recreational vessels have been implicated in several high profile and significantly damaging incursions of non indigenous species including the introduction of the black striped mussel (*Mytilopsis sallei*) into a recreational marina in Darwin, Australia in 1999. Strong evidence suggests it was introduced by hull fouling on an international yacht, and detections of the mussel outside of the marina were traced to movement of smaller vessels. This species has similar ecological and morphological characteristics to the Zebra mussel and when it was discovered densities were as high as 24,000 per square metre (Thresher, 1999). This incursion was successfully eradicated due to the fact that the mussel was contained within marinas with lock gates due to the 8 metres tidal fall (Willan et al., 2000), unlike the majority of other eradication attempts that have ultimately failed often despite concerted efforts. The inherent difficulties of marine invasion control has led to a focus on reducing the human-mediated spread of non indigenous species from major ports via high risk transport vectors (Drake and Lodge, 2004; Floerl et al., 2005; Forrest and Hopkins, 2013) and recreational craft may constitute a significant portion of these vectors.

Biofouling is the most common pathway for introduction of marine non indigenous species for both commercial and recreational vessels (Acosta et al., 2010; Hewitt et al., 2004; Minchin et al., 2006; Thresher, 1999). Studies of international and domestic recreational boats have demonstrated a range of fouling rates, with most surveys showing that over 50% of vessels, and sometimes as high as 80%, having some level of fouling (Ashton et al., 2014; Floerl et al., 2005; Lacoursière-Roussel et al., 2012b; Minchin et al., 2006; Zabin et al., 2014). The extent of fouling on any individual vessel, however, is often highly variable, irrespective of sample sizes and methodology (Ashton et al., 2014; Brine et al., 2013; Clarke Murray et al., 2011; Floerl et al., 2005). Some areas on a vessel are inherently more susceptible to fouling due to their complex structure or isolation; these "niche" areas contribute to fouling variability as they can have considerably higher levels of fouling than the hull (Lacoursière-Roussel et al., 2012b) and include internal water systems and intake pipes, rudder, propeller, anchors/chain cabinets, sea chests, fishing rods and ropes (Acosta et al., 2010; Burgin and Hardiman, 2011; Hewitt et al., 2007; Minchin et al., 2006).

Characteristics of recreational boats that increase both the rate and extent of fouling are substantially different to those of commercial vessels (Lacoursière-Roussel et al.,

2012b). Small vessels can have irregular maintenance and cleaning schedules, may spend significant amounts of time in port where opportunities for colonisation are high, travel at low speeds, and have varied presence and abundance of niche areas (Brine et al., 2013; Clarke Murray et al., 2011; Floerl et al., 2005; Minchin et al., 2006). Considerable variation in boat users maintenance and vessel usage means there is equally likely to be variation in transport frequency and risk of non indigenous species (Floerl et al., 2005). In addition, recreational boats visit pristine and often protected marine areas which may be highly susceptible to invasive marine species and disconnected from commercial shipping ports and aquaculture (Clarke Murray et al., 2011).

No movements of vessels are without risk but minimising translocation of species requires a relevant and transparent risk based assessment (Campbell and Hewitt, 2011); such assessments have been proposed in Australia as part of regulatory interventions to manage biofouling risk (Piola and McDonald, 2012; Clarke et al., 2017; Lott and Rose, 2016). If specific attributes of small vessels can be identified which increase fouling biomass and therefore facilitate the movement of non indigenous species, then management actions and regulations can be implemented by authorities which could reduce their spread and impacts.

This paper investigates the recreational boating vector and aims to identify characteristics of recreational vessels which potentially increase the extent of fouling biomass. We develop predictive tools to estimate the effect of these vessel-level characteristics, including transport and maintenance history, on the biofouling wet weight biomass. Our data comprises samples collected from the hull and niche areas of small vessels from five locations in south-east Australia. While several studies have estimated fouling extent on a measure or index of in situ fouling cover (e.g. Ashton et al., 2006; Brine et al., 2013; Floerl et al., 2005), this may be the first to link vessel-level characteristics with the complete wet weight fouling biomass of individual vessels and may offer an alternative perspective to determine vessel characteristics which influence fouling extent.

The rest of the paper proceeds as follows: in Section 2 we provide details on the data and the statistical models used for analysis; in Section 3 we present the results in detail for the full modelling procedure; and in Section 4 we provide a discussion of the results.

2 Methods

2.1 Data

The data used in this paper came from an exploratory survey in Australia conducted by the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Centre for Research on Introduced Marine Pests (CRIMP). Biomass samples were collected from 54 vessels[1] at 5 geographical locations during the project. All vessels were selected based on convenience, when pulled out of the water for maintenance; access and permission was gathered from owners via the Bosun and slipway managers at each of the sites.

Samples were collected from both external and internal surfaces using plastic and metal putty knives, immediately following the vessels removal from the water. All samples were washed with 0.2μm filtered seawater, sieved and subsequently weighed using Sartorius BL3100 scales. Due to the unreliability of low wet weight measurements, samples that weighed less than 1.5 gm were assigned a biomass of 0.5 gm; that is, the lower limit of detection was 1.5 gm.

Most vessels were sampled in Hobart, Tasmania, Australia at the Royal Hobart Yacht Club (17) and the Domain Slipyard (16). The remaining vessels were sampled in Melbourne, Victoria, Australia at the Sandringham Yacht Club (14), the Hobsons Bay Yacht Club (4), and the Royal Yacht Club of Victoria (2). Most of the sample vessels were yachts (31), followed by fishing vessels (12), motor cruisers and others (10).

Samples were collected from as many as 64 different locations in and around the hull, propeller, rudder and anchor, internal spaces, fishing gear and deck of the vessels. Samples taken from the hull, fixed keel and rudder surface were consistently collected using 0.5m^2 quadrats, so these form the focus of our analysis. There were 252 samples collected from the hull, 94 from the rudder surface, and 74 from the fixed keel; in all, 420 samples were taken. The number of samples collected per vessel ranged from 6 to as many as 10; most vessels (41) were sampled 8 times.

Vessel-level data collected from owners included: dimensions of the vessel; the type of antifouling paint applied (ablative, hard, and self-polishing); voyage history (number of days since the vessel was last used, median number of trips per year); the number of days since the vessel was last cleaned; the surface area of the hull (m^2); and the type of vessel (yacht, fishing, motor cruiser and others). Table 1 shows summary statistics for these observed characteristics.

[1] One vessel was removed from analysis due to its abnormally high biomass measurements.

For more details on the data collected during the survey, see Australian Government Natural Heritage Trust Project 46630 (Hayes et al., 2007).

Table 1: Summary statistics for vessel-level characteristics. Categorical variables are shown as n (%), and numeric variables are shown as median (interquartile range, IQR).

	Variable	n (%) / median (IQR)
Boat type		
	Fishing	10 (19%)
	Motor cruiser/Other	12 (23%)
	Yacht	31 (58%)
Paint type		
	Ablative	21 (40%)
	Hard	12 (23%)
	Self-polishing	15 (28%)
	Missing	5 (9%)
Numeric variables		
	Hull surface area	42.0 (28.0, 57.0)
	Days since last used	12.0 (4.0, 78.0)
	Days since last cleaned	249.0 (79.0, 352.0)
	Trips per year	17.2 (10.4, 45.6)

2.2 Statistical Analysis

Figure 1 shows histograms of the observed wet weight of biomass from the samples. Samples that were below the limit of detection (1.5 gm, of which there were 101) are not shown in this figure. The left column shows the measured wet weight, whilst the right column shows the log-transformed wet weight; the rows correspond to the sampled locations on each vessel (hull, keel and rudder).

Figure 1 suggests that the log-transform of the wet weight of biomass has an approximately Normal distribution, and that there is likely to be a location effect (most notably between Hull versus Keel and Rudder). We thus focus on a log-transform of the wet weight of biomass for the remainder of the analysis. Further, there appears to be the possibility of outliers, especially within the hull and rudder samples. Hence we will also consider a Student-t distribution for modelling.

It could be tempting to analyse the total (or average) wet weight biomass per vessel, as this would simplify the modelling procedure. However, as noted above, Figure 1 suggests that the wet weight of biomass varies with the location from which a sample was taken; hence averaging will mask this variation. Further, the variable number of samples taken per vessel (Section 2.1) means that the total biomass may be dependent

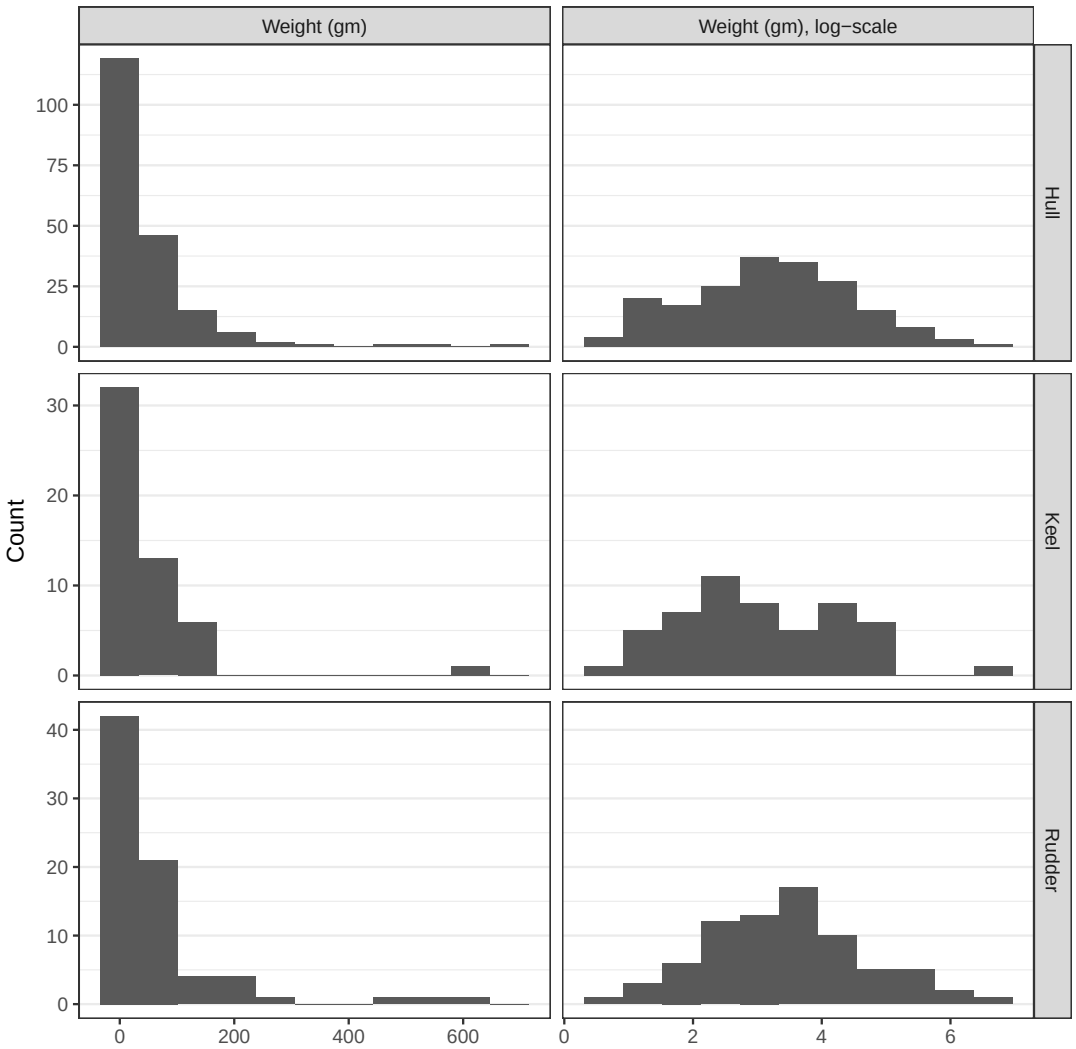


Figure 1: Measured wet weight of sampled biomass from the 53 vessels. The left column shows the measured wet weight, whilst the right column shows the log-transformed wet weight. Samples that measured less than the limit of detection (1.5 gm) have been removed.

upon the number of samples taken. For these reasons, we chose to use a multilevel regression model, in which a modelled intercept allows for the repeated measurements within vessels, whilst also allowing investigation of vessel-level relationships.

To allow for the possible effects of outliers we examined the effect of changing the outcome (or observation) model from Normal to Student-t. Let Y_i be the log wet weight of biomass for the ith observation, $i = 1, \ldots, 420$. Then:

$$Y_i \sim \text{Normal}(\mu_i, \sigma) \tag{O1}$$

$$Y_i \sim t_\nu(\mu_i, \sigma) \tag{O2}$$

$$\nu \sim \text{Gamma}(2, 10)$$

are two alternative models for the outcomes, where O1 is the model assuming a Normal distribution for log weight biomass, and O2 is the model assuming a t distribution with ν degrees of freedom. The hyperparameters for the degrees of freedom were chosen to be weakly informative, favouring a robust t model with lower degrees of freedom; indeed, the mode of the prior distribution for the degrees of freedom is 10.

We initially inferred the latent process — that is, the process that determines the log wet weight of fouling biomass on each vessel — as a linear function of the location of the measurement location allowing for a vessel-level intercept:

$$\begin{aligned} \mu_i &= \mu + \alpha_{j[i]} + \beta_{l[i]} \\ \mu &\sim N(0, 5) \\ \alpha_j &\sim t_3(0, \sigma_\alpha) \\ \beta_l &\sim t_3(0, \sigma_l) \\ \sigma, \sigma_\alpha, \sigma_l &\sim \text{half-cauchy}(0, 2.5) \end{aligned} \tag{M0}$$

where μ_i is the expected log wet weight in grams; μ is the intercept for the model; β_l are coefficients that measure the effect of location on the log wet weight of fouling biomass: $l = 1$ denotes the measurement was taken at the hull, $l = 2$ denotes the measurement was taken at the rudder, and $l = 3$ for measurements taken at the keel[2]. α_j is the vessel-level intercept that allows the hull intercept to vary from vessel to vessel, $j = 1, \ldots, 53$, which is modelled as a t distribution with 3 degrees of freedom, and scale σ_l. The intercept is given a weakly informative $N(0, 5)$ prior. Similarly the regression coefficients are given weakly informative $t_3(0, 1)$ priors; as are the observation model and latent process scale parameters using half-Cauchy$(0, 2.5)$ priors.

[2]The notation $l[i]$ denotes the location level (l) of the ith observation. The vessel-level intercept ($\alpha_{j[i]}$)is similarly referenced.

We subsequently investigated two alternative specifications for the vessel-level intercept by including various vessel-level characteristics and interaction terms:

$$\mu_i = \mu + \gamma_{j[i]} + \beta_{l[i]}$$
$$\gamma_j^* = \alpha_j + \beta_{d1} \cdot \text{days1}_j + \beta_{d2} \cdot \text{days2}_j + \beta_m \cdot \text{midTrips}_j + \beta_h \cdot \text{hullSA}_j + \beta_{p[j]} + \beta_{t[j]} \tag{M1}$$

$$\gamma_j^* = (\text{M1}) + \beta_{dt[j]} \cdot \text{days1}_j + \beta_{mt[j]} \cdot \text{midTrips}_j + \beta_{mp[j]} \cdot \text{midTrips}_j \tag{M2}$$

M1 includes all vessel-level characteristics, where days1_j is the number of days since vessel j was last used; days2_j is the number of days since the vessel was last cleaned; midTrips_j is the median number of trips undertaken by the vessel per year; and hullSA_j is the hull surface area. $\beta_{p[j]}$ is the effect of paint type p on vessel j, $p = 1$ denotes ablative paint, $p = 2$ denotes hard paint, and $p = 3$ denotes self-polishing antifouling paint. $\beta_{t[j]}$ is an effect for vessel type; $t = 1$ denotes motor cruiser/other, $t = 2$ denotes fishing vessels, and $t = 3$ denotes yachts. M2 adds interaction terms to M1 between: the number of days since the vessel was last used and the vessel type ($\beta_{dt[j]}$); the median number of trips and the vessel type ($\beta_{mt[j]}$); and the median number of trips and the paint type ($\beta_{mp[j]}$).

The choice of these regression models was guided by both subject matter/process considerations and graphical exploration of the posterior distribution of the random-effect terms in the latent process models. In particular, we expect there to be interactions between paint type and vessel usage predictors: both ablative and self-polishing paints require the vessel to be used in order to be effective, whilst hard paints do not. For more details on the graphical exploration, see Section 3.

2.3 Missing Data

There is missing data at the vessel level; Table 2 displays the observed data pattern, shown as (Days since last used, Paint type, Days since last trip), where a 1 denotes the variable is observed, and a 0 denotes the variable is missing. For example, Table 2 shows there are 41 observations with complete vessel-level data, and 1 observation that is missing all measurements of days since last used, paint type, and days since last trip.

A complete-case data analysis would only utilise 77.4% of the vessel-level data, and subsequently, this would result in 324 (77.1%) measurements of wet weight biomass being available for the complete-case analysis at the measurement (first) level.

Because of the amount of missing data, we used multiple imputation to impute the

missing vessel-level data. Specifically, we used iterative conditional imputation, with all vessel-level variables used in the imputation specification; to account for any non-linearities, random forest imputation was used.

As all missing data was at the vessel-level, we used the median wet weight of biomass as a predictor in the imputation models (Gelman and Hill, 2007). To account for the censoring in the wet weight of biomass (observations below the 1.5 gm limit of detection), we replaced the censored data by a random draw from a Uniform(0, 1.5) distribution. We justify this procedure in the following way: i) some level of variability is required as we don't know the true value of the censored observations; ii) Figure 1 shows that weights below 1.5 gm (0.4 on the log-scale) form a very small part of the range of observed values. This small variability will have limited impact in the imputation of the missing data due to the fact that we are summarising within-vessel wet weight of biomass measurements by the median for input into the imputation models.

To perform inference, we follow the advice of Zhou and Reiter (2010) and mix the draws from the posterior distributions from the analysis of each completed dataset[3]. Zhou and Reiter (2010) recommend a large number of imputations be used; we generated 50 imputed datasets. For each dataset, 2000 samples were drawn from the posterior after a burn-in of 2000. Convergence was monitored by inspecting the mixed chains across the 50 multiple imputations, and by assessing the Gelman-Rubin statistic (Gelman and Rubin, 1992).

All analyses were performed using R version 3.4.0 (R Core Team, 2017); the multilevel models were fit using the RStan interface to Stan (Stan Development Team, 2016), and multiple imputation was performed using the R package mice (Buuren and Groothuis-Oudshoorn, 2011). R code and data to reproduce the analysis may be found at https://github.com/SteveLane/blistering-barnacles.

Table 2: Observed data pattern for vessel-level characteristics. The patterns are shown as (Days since last used, Paint type, Days since last trip), where a 1 denotes the variable is observed, and a 0 denotes the variable is missing. A count of each type of pattern is shown.

Observed data pattern	Count
(1, 1, 1)	41
(0, 1, 1)	1
(1, 1, 0)	5
(1, 0, 1)	4
(0, 1, 0)	1
(0, 0, 0)	1

[3]The alternative would be to combine posterior estimates of summary parameters using Rubin's rules (Rubin, 1996), which necessarily gives point estimates as opposed to full posterior distributions.

3 Results

3.1 Multiple Imputation

Visual comparison between the observed and imputed data suggests that the imputation procedure has satisfactorily converged, i.e. there was no large discrepancies between the imputed data and the observed. The comparison between observed and imputed data is presented in the Supplemental Material.

3.2 Outcome Model

The t-distribution observation model (O2) outperformed the Normal distribution observation model (O1). The difference in the leave-one-out information criterion (LOOIC, analogous to AIC, see Vehtari et al., 2016) was 47 (standard error 13) in favour of the t-distribution observation model (O2).

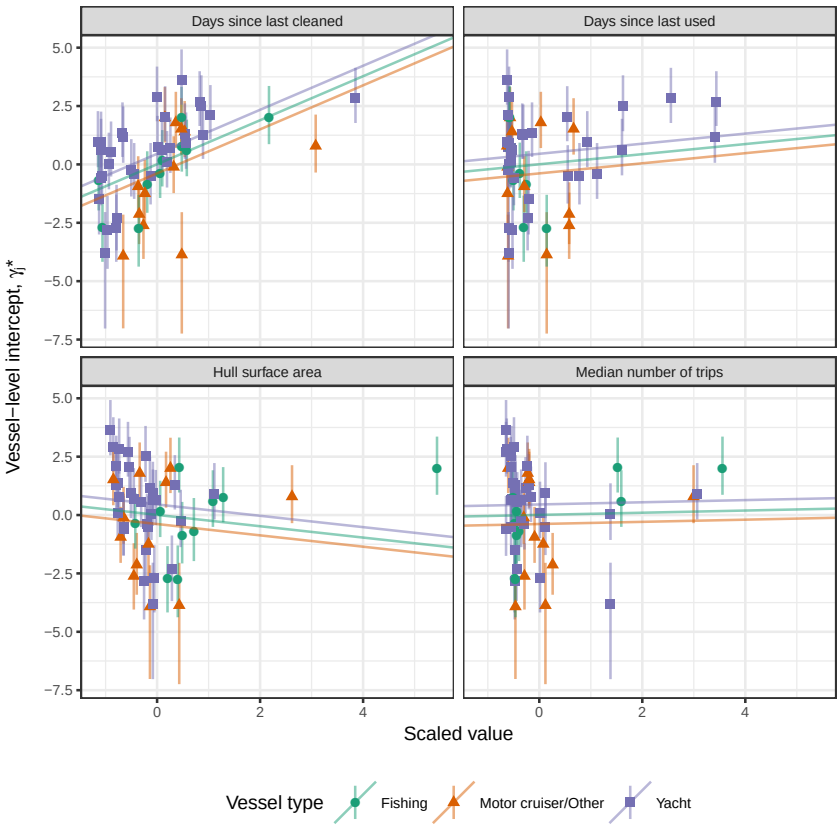
Posterior predictive checks likewise confirmed the superiority of the t-distribution observation model. Graphical checks were made using the proportion of posterior predictions that lie below the limit of detection; the median posterior predictions and the interquartile range (IQR) of the posterior predictions. The graphical checks and LOOIC comparisons can be found in full in the Supplemental Material.

3.3 Regression Results

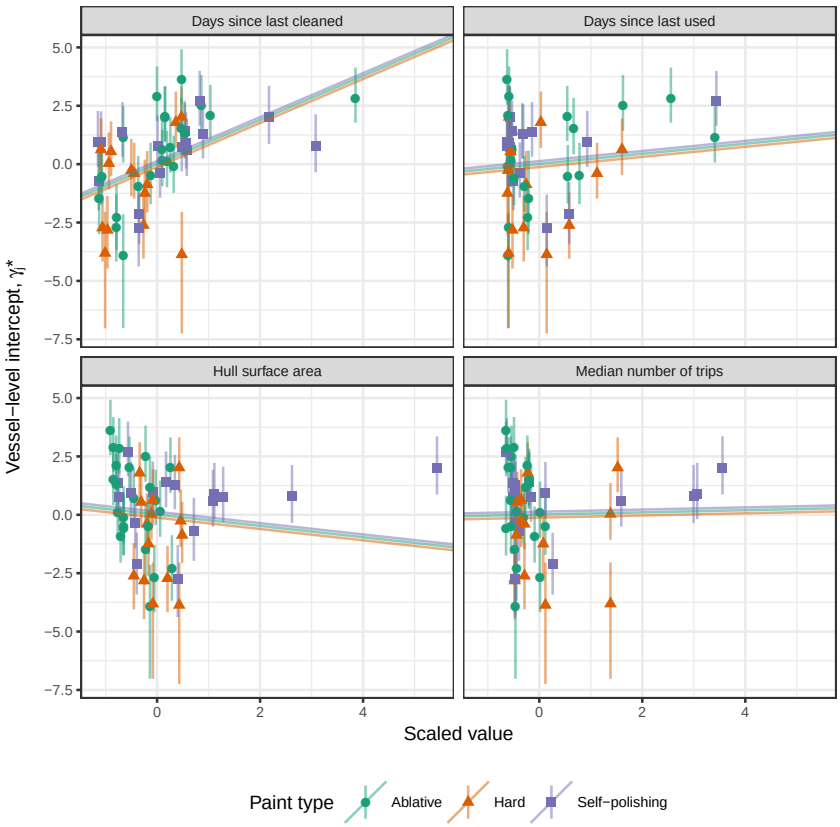
3.3.1 Exploration of Candidate Interaction Terms

Figure 2 displays the posterior median and 80% credible intervals of the regression coefficients in the vessel-level intercept models (for each of the four ordinal predictors — the number of days since the vessel was last used; the number of days since the vessel was last cleaned; the median number of trips undertaken by the vessel; and the vessel's hull surface area). Figure 2a shows the coefficients coloured by vessel type, whilst Figure 2b shows the coefficients coloured by antifouling paint type. Each panel also shows the posterior (median) estimate of the expected log wet weight from model M1, and is based on a randomly selected imputed dataset for display purposes.

Figures 2a and 2b are suggestive of interactions between the number of days since the vessel was last used and the vessel type, the median number of trips undertaken by the vessel and the vessel type, and the median number of trips taken by the vessel and



(a) Vessel-level intercepts coloured by vessel type.



(b) Vessel-level intercepts coloured by antifouling paint type.

Figure 2: Estimated vessel-level intercepts from M1, plotted against the four ordinal predictors. Each plot shows the median and 80% credible interval, coloured by vessel type (2a) and paint type (2b). The (median) regression lines for each predictor are overlaid.

the antifouling paint type. We form this opinion by visual comparison of the scatterplots. For example, the pattern in Figure 2a suggests that the effect of days since the vessel was last used is negative for fishing vessels and positive for yachts and motor cruiser/other vessels. Similarly, the effect of the median number of trips undertaken by the vessel appears to be positive for fishing vessels, and negative for yachts and motor cruiser/other vessels.

3.3.2 Final Model Form

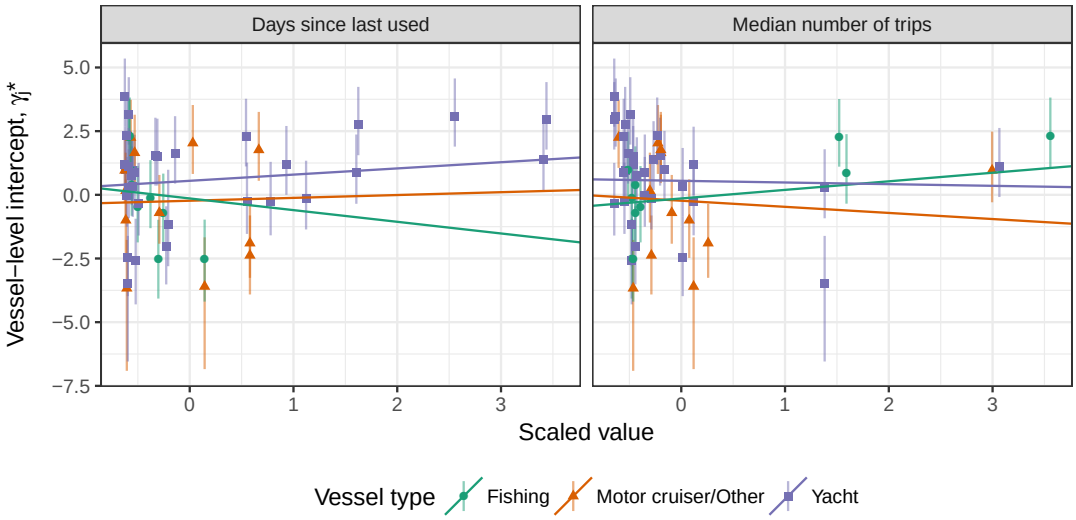
Figure 3 displays the median and 80% intervals of the estimated vessel-level intercepts, with respect to the two ordinal predictors used in interaction terms in (M2): the number of days since the vessel was last used and the median number of trips (per year) undertaken by the vessel. Figure 3a shows the vessel-level intercepts coloured by vessel type and Figure 3b shows the vessel-level intercepts coloured by antifouling paint type. Shown in each panel are the estimated (median) regression lines from M2.

Figure 3a suggests that the of the number of days since the vessel was last used varies by vessel type, as does the median number of trips taken by the vessel per year. Figure 3b further suggests that the effect of the median number of trips taken by the vessel per year varies according to the paint type of the vessel. The uncertainty in these effects is however, large relative to the estimates.

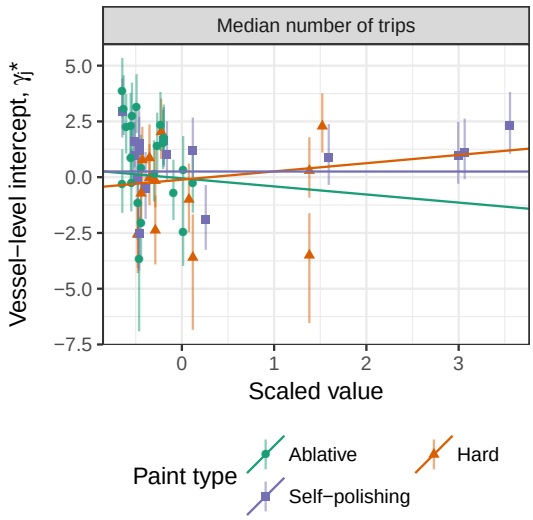
Figure 4 compares estimates of the measurement-level and vessel-level regression coefficients for each of the models considered. As can be seen in Figure 4, the effect of the number of days since the vessel was last cleaned (β_{d2}) is clearly larger than 0; the other predictors do not appear to have such a strong effect. Whilst the effect of these predictors is not estimated precisely, the direction and size of the coefficients is similar between models, and as such we choose Model (M2) as the final model form in order to estimate the interactions.

3.3.3 Predictive Model Comparison

Table 3 compares the models by their leave-one-out information criterion (LOOIC, analogous to AIC, see Vehtari et al., 2016). M2 is the best performing model based on LOOIC, but the variability is sufficiently large that all models are closely performing. The difference in LOOIC between M0 and M2 (3.5) is almost one and a half times the standard error of the difference.



(a) Vessel-level intercepts coloured by vessel type.



(b) Vessel-level intercepts coloured by antifouling paint type.

Figure 3: Estimated vessel-level intercepts from M2, plotted against the two ordinal predictors with interactions being assessed. Regression lines for each estimated interaction are overlaid.

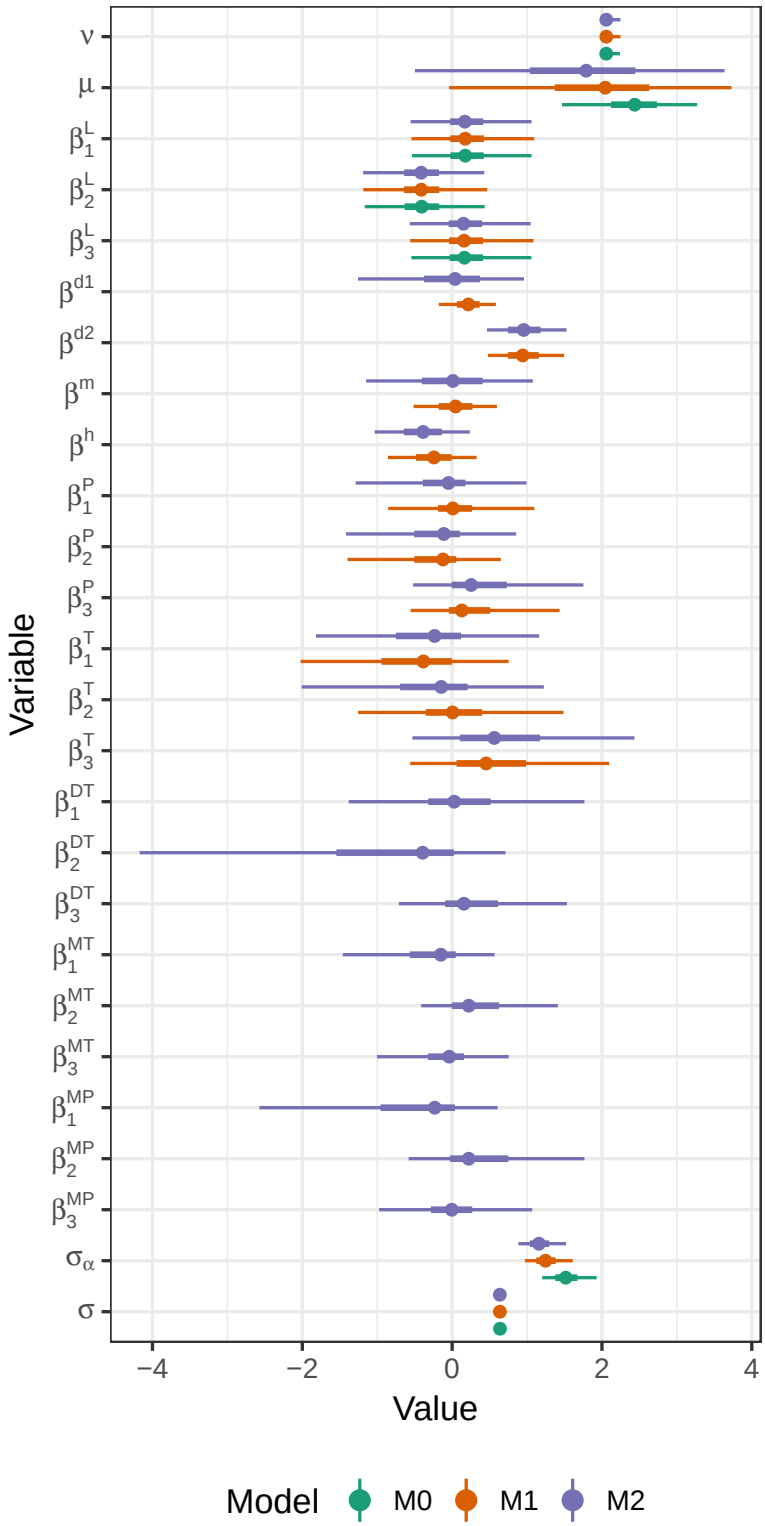


Figure 4: Estimated coefficients from M0–M2. Coefficients from each model (where applicable) are shown grouped within coefficient on the y-axis. The median is shown as a point estimate, with 50% and 90% credible intervals.

Table 3: LOOIC-based comparison of models M0–M2. The model with the smallest LOOIC (M2) is shown first, with subsequent rows ordered by increasing LOOIC (smaller LOOIC values are preferred). ΔLOOIC shows the difference in LOOIC between all models and M2; se(ΔLOOIC) shows the estimated standard error of the difference. Eff. P gives the estimated effective number of parameters; se(Eff. P) shows its standard error.

Model	LOOIC	se(ELPD)	Eff. P	se(Eff. P)	ΔLOOIC	se(ΔLOOIC)
M2	1102	21.7	70.2	4.29		
M1	1103	21.6	70.5	4.29	0.36	0.827
M0	1106	21.7	73.3	4.90	3.55	2.522

4 Discussion

Several previous studies have proposed vessel characteristics that should be indicative of biofouling translocation risks, including voyage time, time in the water, time since application of antifouling paint, frequency of vessel use and stationary period (Ashton et al., 2006; Hewitt et al., 2011).

Subsequent analysis, however, has often either failed to find a strong relationship between vessel characteristics and fouling extent or abundance, or provided contradictory evidence. Clarke Murray et al. (2011) for example, found percent fouling cover on recreational yachts was not related to travel frequency or the age of antifouling paint. Floerl et al. (2005) concluded that the abundance of non indigenous species on yacht hulls could not be associated with maintenance schedules, travel history or owners maintenance behaviour. Similarly, Ashton et al. (2014) did not find significant correlations between last cleaning and extent of fouling using in-water surveys, and also concluded that the type of recreational vessel does not explain differences in biofouling patterns.

Other studies however, suggest that time since the antifouling paint was applied to the vessel is a consistently reliable predictor of biofouling (Ashton et al., 2006; Floerl et al., 2005; Lacoursière-Roussel et al., 2012b; Ashton et al., 2014), and that time in the water, stationary periods, and voyage types are relevant factors (Ashton et al., 2006; Lacoursière-Roussel et al., 2012b). Lacoursière-Roussel et al., 2012b also suggest that vessel type does play a role because powerboats and catamarans, for example, have a greater risk of fouling due to the higher number of niche areas on such vessels.

The results presented here demonstrate relationships that are largely consistent with prior expectations about important risk factors; that is, the amount of hull fouling biomass is related to the time since a vessel was last cleaned and last used, how frequently a vessel is used and the type of antifouling paint applied. Consider for example a yacht that hasn't been cleaned in 249 days. The model predicts that for such a

vessel, there is a 74% probability that delaying cleaning by six months would result in an increase of wet weight biomass within a 0.5m^2 area on the hull of the vessel.

The size of the vessel, measured by the hull surface area, was found to have a small negative relationship if used to predict biofouling levels; however, the uncertainty in this estimate was relatively large. Given the same frequency of use, the modelling suggests that different types of vessels have different effects on biofouling levels. For example, assume that vessels have the same duration since last being cleaned, and the same duration since last being used; the model predicts that there is an 72% predicted probability that a yacht will have a larger wet weight biomass within a 0.5m^2 area than the motor cruiser/other vessel; compared to a fishing vessel, this probability is 75%.

A weak varying effect of the median number of trips taken by the vessel per year and paint type was found in the model. The limited number of data points at the vessel level (53) hampered the precision of estimating these effects, but the direction of effects conforms with prior expectations, namely that: both ablative and self-polishing paints require the vessel to be used in order to be effective, whilst hard paints do not.

There is also evidence that the location of the sample is an important predictor for the wet weight of biomass. Figure 4 shows a consistent result that the wet weight of biomass when sampled along the hull (β_1^L), is no different to samples made from the rudder (β_3^L). Measurements made on samples from the keel however, are generally smaller than those made along either the hull or on the rudder; in fact, there is a 69% predicted probability of this being the case. This is not a characteristic of vessels, and thus cannot be used for management purposes; the location of the measurement does however need to be considered in any future work, and in particular may restrict vessel-level summaries of wet weight of biomass being analysed (for example, total wet weight of biomass).

Previous studies have found fouling cover on boats can be up to ten times higher in niche areas than on hulls where antifouling paint and boat cleaning are generally overlooked (Clarke Murray et al., 2011), and therefore may be important pathways for non indigenous species (Lacoursière-Roussel et al., 2012b; Zabin et al., 2014). Ashton et al., 2014 also agree that the location of the sample is important, as they report the propeller shafts are frequently reported as having biofouling, yet the highest numbers of organisms were found on the keel.

This study is not without its limitations. We found that the (log-transformed) wet weight of biomass found on small vessels was best described by a t-distribution. Posterior predictive checks showed that the analysis regression models generated data consistent with the observed data for the interquartile range, but less so for the median and proportion of observations below the limit of detection. A possible approach to

allow for the larger number of censored observations than expected would be to fit a mixture model. It is not directly clear how this would work however, when vessels may contain some samples measured below and some above the limit of detection. Further, given the limited data available, it was considered that an attempt to fit such a mixture model was unfeasible.

The small number of vessels sampled also limits the precision at which we can estimate the effect of vessel-level characteristics, and in particular, any interactions between them. We demonstrated a number of possible interaction effects, yet the error in those estimates was found to be relatively large. The nature of these varying effects however, did conform to prior expectations of the direction of the effect; it is the size of such effects that is not known with a high degree of certainty.

Sample size reservations notwithstanding, we have demonstrated that vessel-level characteristics can be used to predict the amount of wet weight of fouling biomass that may be present on small vessels in Australia. The development of such predictive tools could aid authorities in assessing the risk posed by individual vessels and classifying those that are a risk of having high levels of fouling will potentially reduce the introduction and spread of invasive species (Minchin et al., 2006; Clarke et al., 2017).

The results suggest that in particular, owners of small vessels should be encouraged to maintain a regular cleaning and maintenance schedule, particularly wet areas of the vessel. Management interventions, such as diver inspections, directive to clean at a dry dock etc, can be implemented to varying degrees based on increasing levels of risk, but also with a prohibitive increase in resources, cost and time (Campbell and Hewitt, 2011). Therefore strategies and incentives could be investigated to encourage boat owners to improve their cleaning and maintenance, as well as education and outreach programs for boat owners to increase awareness of invasive species and their impacts (Brine et al., 2013; Minchin et al., 2006).

Authorities could also introduce regulated antifouling paint regimes, e.g. every 12 months, regular inspections and providing cleaning facilities for recreational boat users (Zabin et al., 2014). Many dry docks for recreational small vessels do not have the procedures and/or facilities to deal with the material removed from hull cleaning which is often released back into the ocean (Hewitt et al., 2007). Even if only a small percentage of recreational boats have biofouling, the sheer number of boats around Australia mean that the number transporting non indigenous species could in the tens of thousands. This danger can occur from just a few voyages of heavily fouled vessels, or large numbers of boats with minimal fouling but high transport frequency, and therefore propagule pressure is large (Clarke Murray et al., 2011; Kauano et al., 2016).

Preventing the introduction of invasive organisms is the key to reducing their spread,

requiring stringent implementation of measures to reduce invasions through all vector routes (Bax et al., 2001). No movements of vessels are without risk but minimising translocation of species will require a relevant and transparent risk based assessment (Campbell and Hewitt, 2011; Clarke et al., 2017) and characterising the risk of biological invasions requires understanding species assemblages at ports and the characteristics of transport vectors (Floerl and Inglis, 2005). Recreational boating in particular has complex and interacting risks and invasion scenarios, which need to be modelled and assessed in order to implement effective biosecurity management programs (Acosta et al., 2010).

Acknowledgements

The authors would like to acknowledge Dr Enamul Kabir for his contribution to earlier analyses that were not a part of this manuscript, and to Sandringham College, Melbourne, Victoria, for use of the school's laboratory space to process the samples taken within Melbourne. AR, SL and TH's contributions were funded in part by the Centre of Excellence for Biosecurity Risk Analysis.

References

Acosta, Hernando, Dongrui Wu, and Barrie M Forrest (2010). "Fuzzy experts on recreational vessels, a risk modelling approach for marine invasions". In: *Ecological modelling* 221.5, pp. 850–863. ISSN: 0304-3800.

Ashton, G V, Karin Boos, R Shucksmith, and E J Cook (2006). "Risk assessment of hull fouling as a vector for marine non-natives in Scotland". In: *Aquatic invasions / European Research Network on Aquatic Invasive Species* 1.4, pp. 214–218. ISSN: 1818-5487.

Ashton, Gail, Ian Davidson, and Gregory Ruiz (2014). "Transient small boats as a long-distance coastal vector for dispersal of biofouling organisms". In: *Estuaries and Coasts* 37.6, pp. 1572–1581. ISSN: 1559-2723.

Bax, N, J T Carlton, A Mathews-Amos, R L Haedrich, F G Howarth, J E Purcell, A Rieser, and A Gray (2001). "The control of biological invasions in the world's oceans". In: *Conservation biology: the journal of the Society for Conservation Biology* 15.5, pp. 1234–1246. ISSN: 0888-8892, 1523-1739.

Brine, Oriana, Lou Hunt, and Mark John Costello (2013). "Marine biofouling on recreational boats on swing moorings and berths". In: *Management of Biological Invasions* 4.4, pp. 327–341. ISSN: 1989-8649.

Burgin, Shelley and Nigel Hardiman (2011). "The direct physical, chemical and biotic impacts on Australian coastal waters due to recreational boating". In: *Biodiversity and conservation* 20.4, pp. 683–701. ISSN: 0960-3115.

Buuren, Stef van and Karin Groothuis-Oudshoorn (2011). "mice: Multivariate Imputation by Chained Equations in R". In: *Journal of statistical software* 45.3, pp. 1–67. ISSN: 1548-7660.

Campbell, Marnie L and Chad L Hewitt (2011). "Assessing the port to port risk of vessel movements vectoring non-indigenous marine species within and across domestic Australian borders". In: *Biofouling* 27.6, pp. 631–644. ISSN: 0892-7014.

Carlton, J T and J B Geller (1993). "Ecological roulette: the global transport of non-indigenous marine organisms". In: *Science* 261.5117, pp. 78–82. ISSN: 0036-8075.

Clarke Murray, Cathryn, Evgeny A Pakhomov, and Thomas W Therriault (2011). "Recreational boating: a large unregulated vector transporting marine invasive species". In: *Diversity and Distributions* 17.6, pp. 1161–1172. ISSN: 1472-4642.

Clarke, Sandy, Tracey Hollings, Nianjun Liu, Greg Hood, and Andrew Robinson (2017). "Biosecurity risk factors presented by international vessels: a statistical analysis". en. In: *Biological invasions* 19.10, pp. 2837–2850. ISSN: 1387-3547, 1573-1464. DOI: 10.1007/s10530-017-1486-1.

Drake, John M and David M Lodge (2004). "Global hot spots of biological invasions: evaluating options for ballast–water management". In: *Proceedings of the Royal Society of London B: Biological Sciences* 271.1539, pp. 575–580. ISSN: 0962-8452.

Floerl, Oliver and Graeme J Inglis (2005). "Starting the invasion pathway: the interaction between source populations and human transport vectors". In: *Biological invasions* 7.4, pp. 589–606. ISSN: 1387-3547.

Floerl, Oliver, Graeme J Inglis, and Barbara J Hayden (2005). "A risk-based predictive tool to prevent accidental introductions of nonindigenous marine species". In: *Environmental management* 35.6, pp. 765–778. ISSN: 0364-152X.

Forrest, Barrie M and Grant A Hopkins (2013). "Population control to mitigate the spread of marine pests: insights from management of the Asian kelp Undaria pinnatifida and colonial ascidian Didemnum vexillum". In: *Management of Biological Invasions* 4.4, pp. 317–326. ISSN: 1989-8649.

Gelman, Andrew and Jennifer Hill (2007). *Data Analysis Using Regression and Multilevel/Hierarchical Models*. en. Cambridge: Cambridge University Press. ISBN: 9780511790942. DOI: 10.1017/CBO9780511790942.

Gelman, Andrew and Donald B Rubin (1992). "Inference from Iterative Simulation Using Multiple Sequences". In: *Statistical science: a review journal of the Institute of Mathematical Statistics* 7.4, pp. 457–472. ISSN: 0883-4237.

Hayes, Keith R, Rasanthi Gunasekera, Jawahar Patil, Cath Sliwa, Sasha Migus, Felicity McEnnulty, Piers Dunstan, Mark Green, and Caroline Sutton (2007). *Empirical validation: Small vessel translocation of key threatening species*. Australian Government Natural Heritage Trust Project 46630. CSIRO. ISBN: 9781921232534.

Hewitt, C, M Campbell, A Coutts, A Dahlstrom, D Shields, and J Valentine (2011). *Species Biofouling Risk Assessment*. Tech. rep. Australian Government Department of Agriculture Fisheries and Forestry.

Hewitt, Chad L, Marnie L Campbell, and Britta Schaffelke (2007). "Introductions of seaweeds: accidental transfer pathways and mechanisms". In: *Botanica marina* 50.5/6, pp. 326–337. ISSN: 0006-8055, 1437-4323.

Hewitt, Chad L, Marnie L Campbell, Ronald E Thresher, Richard B Martin, Sue Boyd, Brian F Cohen, David R Currie, Martin F Gomon, Michael J Keough, and John A Lewis (2004). "Introduced and cryptogenic species in Port Phillip Bay, Victoria, Australia". In: *Marine biology* 144.1, pp. 183–202. ISSN: 0025-3162.

Kauano, Rafael V, James J Roper, and Rosana M Rocha (2016). "Small boats as vectors of marine invasion: experimental test of velocity and desiccation as limits". In: *Marine biology* 1.164, pp. 1–10. ISSN: 0025-3162.

Lacoursière-Roussel, Anaïs, Dan G Bock, Melania E Cristescu, Frederic Guichard, Philippe Girard, Pierre Legendre, and Christopher W McKINDSEY (2012a). "Disentangling

invasion processes in a dynamic shipping–boating network". In: *Molecular ecology* 21.17, pp. 4227–4241. ISSN: 0962-1083, 1365-294X.

Lacoursière-Roussel, Anaïs, Barrie M Forrest, Frédéric Guichard, Richard F Piola, and Christopher W McKindsey (2012b). "Modeling biofouling from boat and source characteristics: a comparative study between Canada and New Zealand". In: *Biological invasions* 14.11, pp. 2301–2314. ISSN: 1387-3547.

Lott, M J and K Rose (2016). "Emerging threats to biosecurity in Australasia: the need for an integrated management strategy". en. In: *Pacific conservation biology: a journal devoted to conservation and land management in the Pacific region* 22.2, pp. 182–188. ISSN: 1038-2097, 2204-4604. DOI: 10.1071/PC15040.

Minchin, Dan, Oliver Floerl, Dario Savini, and Anna Occhipinti-Ambrogi (2006). "Small craft and the spread of exotic species". In: *The ecology of transportation: managing mobility for the environment*. Ed. by J Davenport and Davenport J.l. Dordrecht: Springer, pp. 99–118.

Molnar, Jennifer L, Rebecca L Gamboa, Carmen Revenga, and Mark D Spalding (2008). "Assessing the global threat of invasive species to marine biodiversity". In: *Frontiers in ecology and the environment* 6.9, pp. 485–492. ISSN: 1540-9295, 1540-9309. DOI: 10.1890/070064.

Paini, Dean R and Denys Yemshanov (2012). "Modelling the arrival of invasive organisms via the international marine shipping network: a Khapra beetle study". In: *PloS one* 7.9, e44589. ISSN: 1932-6203.

Pimentel, David (2011). *Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal, and Microbe Species*. Second. Hoboken: CRC Press, 2011.

Piola, Richard F and Justin I McDonald (2012). "Marine biosecurity: The importance of awareness, support and cooperation in managing a successful incursion response". In: *Marine pollution bulletin* 64.9, pp. 1766–1773. ISSN: 0025-326X.

R Core Team (2017). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.

Rubin, Donald B (1996). "Multiple Imputation after 18+ Years". In: *Journal of the American Statistical Association* 91.434, pp. 473–489. ISSN: 0162-1459. DOI: 10.1080/01621459.1996.10476908.

Ruiz, Gregory M, James T Carlton, Edwin D Grosholz, and Anson H Hines (1997). "Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences". In: *American zoologist* 37.6, pp. 621–632. ISSN: 0003-1569, 1540-7063.

Stan Development Team (2016). *Stan Modeling Language Users Guide and Reference Manual*.

Thresher, Ronald E (1999). "Diversity, impacts and options for managing invasive marine species in Australian waters". In: *Australian Journal of Environmental Management* 6.3, pp. 137–148. ISSN: 1322-1698.

Vehtari, Aki, Andrew Gelman, and Jonah Gabry (2016). "Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC". en. In: *Statistics and computing*, pp. 1–20. ISSN: 0960-3174, 1573-1375. DOI: 10.1007/s11222-016-9696-4.

Vitousek, Peter M, Carla M D'Antonio, Lloyd L Loope, and Randy Westbrooks (1996). "Biological invasions as global environmental change". In: *American scientist* 84.5, pp. 468–478. ISSN: 0003-0996.

Willan, Richard C, Barry C Russell, Nicolas B Murfet, Kirrily L Moore, Felicity R McEnnulty, Suzanne K Horner, Chad L Hewitt, Gavin M Dally, Marnie L Campbell, and Sean T Bourke (2000). "Outbreak of Mytilopsis sallei (Récluz, 1849) (Bivalvia: Dreissenidae) in Australia". In: *Molluscan research* 20.2, pp. 25–30. ISSN: 1323-5818. DOI: 10.1080/13235818.2000.10673730.

Zabin, Chela J, Gail V Ashton, Christopher W Brown, Ian C Davidson, Mark D Sytsma, and Gregory M Ruiz (2014). "Small boats provide connectivity for nonindigenous marine species between a highly invaded international port and nearby coastal harbors". In: *Manag Biol Invasions* 5.2, pp. 97–112.

Zhou, Xiang and Jerome P Reiter (2010). "A Note on Bayesian Inference After Multiple Imputation". In: *The American statistician* 64.2, pp. 159–163. ISSN: 0003-1305. DOI: 10.1198/tast.2010.09109. eprint: http://dx.doi.org/10.1198/tast.2010.09109.