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A Risk-Based Predictive Tool to Prevent Accidental Introductions of Nonindigenous Marine Species

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ABSTRACT / Preventing the introduction of nonindigenous species (NIS) is the most efficient way to avoid the costs and impacts of biological invasions. The transport of fouling species on ship hulls is an important vector for the introduction of marine NIS. We use quantitative risk screening techniques to develop a predictive tool of the abundance and variety of organisms being transported by ocean-going yachts. We developed and calibrated an ordinal rank scale of the abundance of fouling assemblages on the hulls of international yacht hulls arriving in New Zealand. Fouling ranks were allocated to 783 international yachts that arrived in New Zealand between 2002 and 2004. Classification tree analysis was used to identify relationships between the fouling ranks and predictor variables that described the maintenance and travel history of the yachts. The fouling ranks provided reliable indications of the actual abundance and variety of fouling assemblages on the yachts and identified most (60%) yachts that had fouling on their hulls. However, classification tree models explained comparatively little of the variation in the distribution of fouling ranks (22.1%), had high misclassification rates (~43%), and low predictive power. In agreement with other studies, the best model selected the age of the toxic antifouling paint on yacht hulls as the principal risk factor for hull fouling. Our study shows that the transport probability of fouling organisms is the result of a complex suite of interacting factors and that large sample sizes will be needed for calibration of robust risk models.

Preventing the introduction and establishment of nonindigenous species (NIS) is the safest and most efficient way to avoid the costs and impacts associated with biological invasions (Mack and others 2000, Rejmánek 2000, Leung and others 2002, Marchetti and others 2004). A major goal of research in this area, therefore, is to develop better ways of identifying the species that are likely to cause harm and the circumstances in which they are likely to be introduced, become established, and spread.

International trade and tourism are major pathways for the movement of species between countries and biogeographic ranges (Jenkins 1999, Levine and D'Antonio 2003). Interception systems that effectively identify high-risk species (those likely to cause harm if they become introduced and established) or transport vectors (those likely to carry nonindigenous species or their propagules) before they reach the country are important measures for preventing or minimizing new introductions. Many countries have now adopted risk-screening protocols to identify species whose importation should be restricted (so-called ''dirty lists'') or allowed (''clean lists'') (e.g., the Weed Risk Assessment of Australia (Steinke 1999) and the Ecological Risk Assessment Framework of the USA (Reichard and Hamilton 1997). Until recently, the development of these lists was based largely on expert opinion or qualitative assessments of putative invasive characteristics, and the predictive ability of the framework was uncertain. Increasingly, more sophisticated, quantitative predictive techniques such as Discriminant Analysis, Logistic Regression, and Classification and Regression Tree Analysis (CART) have been applied to develop more robust, defensible lists that have an estimated measure of prediction success (Reichard and Hamilton 1997, Kolar and Lodge 2002, Grigorovich and others 2003). For example, using classification and regression tree analysis, Kolar and Lodge (2002) categorized established, quickly spreading, and nuisance species of nonindigenous fish in the Great Lakes with 87% to 94% accuracy, and identified species that pose a high risk if introduced from unintentional or intentional pathways. Because they target particular species,

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such techniques hold considerable promise for controlling intentional introductions, but have had limited application in the management of accidental introductions. Variability in the probability of transportation (e.g., not all species in a port will be taken up with ships' ballast water) and survival within the transport pathway adds an extra dimension of stochasticity to the likelihood that any particular species will arrive in a given country (Smith and others 1999, Wonham and others 2000). In these circumstances, it is often more useful to treat all introductions as potentially harmful and to identify high-risk vectors that are likely to contain a large number of individuals or species (Wonham and others 2001).

Most introductions of nonindigenous marine species occur accidentally, through the transport of ballast water or fouling organisms on the hulls of ships and other ocean-going structures (Carlton 1985, Carlton and Geller 1993, Cranfield and others 1998, Hewitt and others 1999, Ruiz and others 2000). Risk-screening models developed for ballast-water transport, such as Australia's Ballast Water Decision Support System (BWDSS), aim to identify high-risk vectors as they arrive in port, but are based mostly on transport probabilities for particular target species (Hayes and Hewitt 2000, Hayes 2003). In this article, we use quantitative risk screening techniques to identify characteristics of vessels or their history that may be useful predictors of the total abundance or variety of fouling organisms being transported by them.

Fouling assemblages develop on the submerged surfaces of commercial and private vessels (for comprehensive reviews refer to AMOG Consulting 2002 and Marine Science and Ecology 2002). Most (60–69%) of the marine NIS recorded in Australia, New Zealand, and Hawaii are fouling organisms that are thought to have been introduced accidentally on the hulls of ships and other floating structures (Cranfield and others 1998, Thresher and others 1999, Eldredge and Carlton 2002). This vector is currently unregulated in most countries and continues to provide a means for unwanted species to be carried into new geographic areas (Gollasch 2002). Ocean-going yachts have been implicated in the introduction and spread of a number of well-known marine NIS worldwide, including the black striped mussel, *Mytilopsis sallei*, the Caribbean tubeworm, *Hydroides sanctaecrucis*, and the marine algae *Undaria pinnatifida* and *Codium fragile* spp. *tomentosoides* (Carlton and Scanlon 1985, Rao and others 1989, Hay 1990, Bird and others 1993, Fletcher and Farrell 1998, Field 1999, Neil 2002). The relative importance of yachts compared to commercial ships as transport vectors for marine NIS has so far not been assessed. However, a range of recent studies show that the relative extent of hull-fouling assemblages on yachts is usually greater than on commercial vessels (Coutts 1999, James and Hayden 2000, Floerl 2002).

The susceptibility of yachts to fouling is determined by how well they are maintained and how often they are used. Most yacht hulls are coated in toxic "antifouling" paint to prevent fouling by marine organisms. The performance of these paints is contingent on frequent use of the yachts, and most paints will only prevent fouling for 9–18 months. Generally, the abundance and diversity of hull fouling assemblages tend to be highest on yachts with old and ineffectual antifouling paint and/or yachts that have not been used (sailed) for extended periods (Hunter and Anderson 2001, Floerl 2002, Floerl and Inglis 2003). Because there is substantial variation in the frequency with which private owners maintain and use their vessels, there is likely to be similar variation in the frequency with which such yachts transport unwanted fouling species. Our aim was to develop a simple predictive tool, using descriptors of the recent travel and maintenance history of the yacht, which would allow authorities to identify high-risk yachts prior to or upon their arrival in a port. Predictive statistical modeling typically requires large samples to act as training and evaluation data sets (Breiman and others 1984, Hosmer and Lemeshow 1989, Guisan and Zimmermann 2000). Using 189 international yachts, we developed and calibrated a simple ordinal rank scale of fouling. This rank scale was used by quarantine inspectors to estimate the abundance of fouling assemblages on a further 594 yachts that arrived in New Zealand from overseas between 2002 and 2004. Characteristics of the maintenance and travel histories of the yachts were then modeled to identify useful predictors of fouling rank.

Materials and Methods

Developing a Fouling Index

Between 500 and 800 yachts enter New Zealand waters each year from overseas. Most arrive between November and January, and more than 95% enter the country through four designated arrival ports—Opua, Whangarei, Auckland, and Tauranga (Inglis 2001, New Zealand Customs Service, personal communication 2002)—where they are met by an officer of the New Zealand Ministry of Agriculture and Forestry (MAF) Quarantine Service. The yachts are generally 5–65 m in length, with a total submerged hull area of 25–1300 m^2 (mean length: 12 m; mean submerged area: 84 m^2)

Table 1. Ranks of the ordinal fouling scale that was used to quantify hull fouling on private yachts arriving in New Zealand

Rank	Description	Visual estimate of fouling cover
0	No visible fouling. Hull entirely clean, no biofilm[a] on visible submerged parts of the hull.	Nil
1	Slime fouling only. Submerged hull areas partially or entirely covered in biofilm, but absence of any macrofouling.	Nil
2	Light fouling. Hull covered in biofilm and 1–2 very small patches of macrofouling (only one taxon).	1–5 % of visible submerged surfaces
3	Considerable fouling. Presence of biofilm, and macrofouling still patchy but clearly visible and comprised of either one single or several different taxa.	6–15 % of visible submerged surfaces
4	Extensive fouling. Presence of biofilm and abundant fouling assemblages consisting of more than one taxon.	16–40 % of visible submerged surfaces
5	Very heavy fouling. Diverse assemblages covering most of visible hull surfaces.	41–100 % of visible submerged surfaces

[a]Biofilm: Thin layer of bacteria, microalgae, detritus and other particulates that is required for settlement of the larvae of many species of marine invertebrates. Refer to (Todd and Keough 1994, Keough and Raimondi 1995).

(Floerl and others 2003, New Zealand Customs Service, personal communication) We developed an ordinal rank scale of fouling intensity to allow MAF staff to estimate, from the surface, the level of fouling on the hulls of arriving yachts during their routine inspections. The scale was based on relative abundance (approximate percentage cover on hull surfaces visible from the surface) and number of different identifiable taxa of marine invertebrates and plants of fouling assemblages and ranged from 0 (no fouling) to 5 (very heavy fouling). It was designed to enable quarantine personnel to distinguish, from the surface, between yachts that carry no, sparse, or extensive fouling assemblages on their hulls. MAF officers were supplied with catalogues containing instructions on use of the scale and example pictures of hulls typical of each fouling rank. The officers allocated a rank to each yacht from the surface after a brief visual inspection of the submerged areas around the bow, waterline, and stern/rudder (Table 1). To ensure consistency in the allocation of fouling ranks, one of us (O.F.) visited approximately 50 yachts with all concerned MAF officers, and each observer independently allocated ranks to the yachts. Where the rankings were inconsistent between observers, the yacht was revisited and ranked again after discussion. This process was repeated until rank allocation was consistent among the various officers.

Calibration of the Ranks

Because the officers ranked fouling on the yachts from above the water surface, the ranks may not be a true indication of the degree of fouling on deeper, submerged surfaces of the hull. To test the utility of the ranks as an indicator of overall fouling intensity, we calibrated them against actual measures of the abundance and variety of fouling assemblages on the hulls of 189 vessels that had arrived in New Zealand between October and November 2002 (95 vessels), and in November 2003 (94 vessels). All vessels were sampled within two weeks of arrival in the Opua Marina, Whangarei Town Basin Marina, Westhaven Marina (Auckland), Bayswater Marina (Auckland), and Gulf Harbour Marina (Auckland) (Figure 1).

Fouling assemblages on the hulls were sampled using a remote-operated video camera (Deep Blue Pro, SplashCam Systems), with twin underwater lights, attached to a sampling frame. The sampling frame was mounted on soft wheels that allowed it to roll along or across a yacht hull while being steered from the surface using a telescopic arm with a single pivot link (see Floerl and others 2003 for details). Moving images from the camera were captured as digital video onto a recorder (Sony DCR-TRV900E) at the water surface.

Samples were taken along five haphazardly placed vertical transects (waterline to keel bottom) on the dockward side of each yacht. One still image (21×25 cm) was captured randomly from each of the video transects, and the average fouling cover across the hull was calculated from the five replicates. The percentage cover of broad taxonomic groups of fouling organisms (e.g., barnacles, colonial ascidians, etc.) was determined by projecting each image taken onto a screen and superimposing 64 randomly distributed dots on top of it. We chose this broad taxonomic resolution because our aim was to identify risk factors

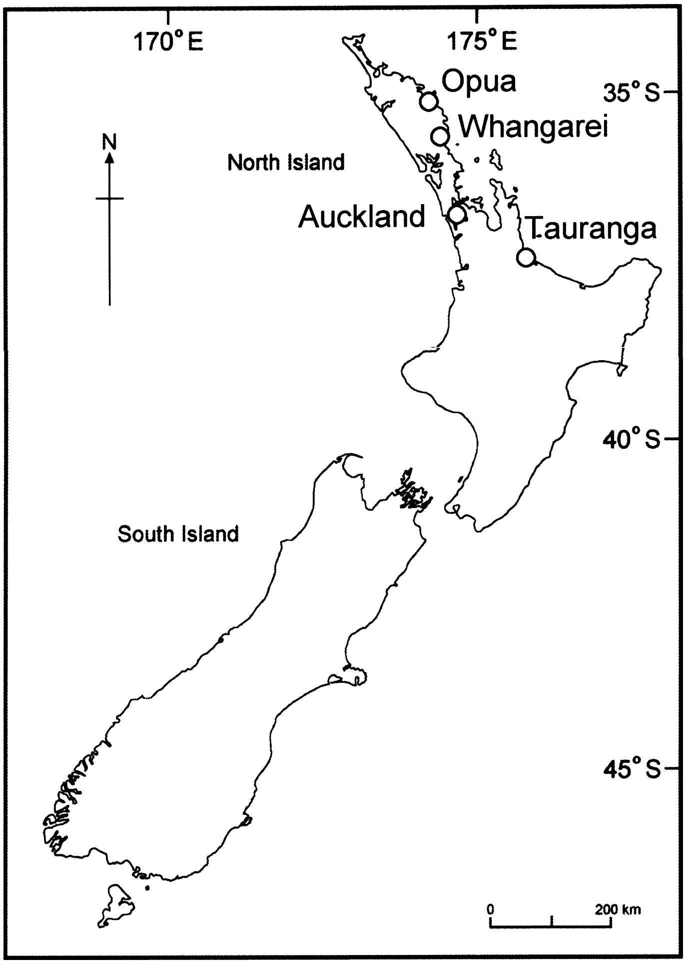

Figure 1. Sampling of international yachts was carried out in marinas of first-call in Opua, Whangarei, Auckland, and Tauranga.

that determine the presence of fouling organisms on the hulls of international yachts arriving in New Zealand. We anticipated a high variability in the species assemblages on arriving yacht hulls, with some species occurring on only one or a few yachts. The confidence intervals for the probability of presence of these species on a given yacht within each fouling rank would most likely have ranged from close to 0 to close to 1. Because the factors that determine the susceptibility of yacht hulls to colonization by sessile organisms are likely to be similar for species within broad taxonomic groups, more reliable probability estimates can be made by operating at higher taxonomic levels. The use of a relatively broad taxonomic level also allowed us to increase sampling effort and collect data on a large number of replicate yachts, which is a prerequisite for the development of a robust predictive model (Guisan and Zimmermann 2000). Pilot studies on 46 yachts showed that sampling using the surface-driven remote camera gave similar estimates of fouling percentage cover to those obtained by scuba divers using hand-held underwater video (percentage cover—analysis of variance (ANOVA): $F_{5,82} = 0.265$, $P = 0.931$; number of taxa—ANOVA: $F_{5,82} = 1.008$, $P = 0.419$; O.F. unpublished data). The remote camera was preferred because a larger number of yachts could be sampled at less cost. Scuba divers collected specimens of fouling organisms from a random subset of 25 yachts with visible fouling. These specimens were kept for taxonomic identification and assessment of their native origin.

We used binary logistic regression (LOGIT, Systat 10) to determine the relationship between the ranks and the probability of presence of different fouling taxa. For broad taxonomic groups (e.g., barnacles, erect bryozoans, tubiculous polychaetes), we first regressed the categorical ranks against the presence–absence of each group. Where the model was significant ($P < 0.05$), we also estimated the odds ratios and constructed a quantile table to estimate the probability of the organism being present on yachts of particular ranks. The odds ratio provides an

Table 2. Matrix of percentage cover of fouling organisms on 189 yacht hulls predicted by fouling rank vs. actual percentage cover observed from digital still images[a]

	Observed fouling cover (% of hull surface)				
Yachts sampled	0	1–5%	6–15%	16–40%	41–100%
Rank 0 (n = 20)	95.0	5.0	0	0	0
Rank 1 (n = 83)	90.4	9.6	0	0	0
Rank 2 (n = 34)	5.9	73.5	20.6	0	0
Rank 3 (n = 25)	0	28	48	24	0
Rank 4 (n = 19)	0	5.3	36.8	36.8	21.1
Rank 5 (n = 8)	0	0	0	37.5	62.5

[a]The numbers in the matrix represent the percentage of yachts within the different fouling ranks that were found to cover 0, 1–5%, 6–15%, 16–40% and 41–100% of submerged yacht hull surfaces. For example, 48% of yachts scored with fouling rank 3 had an actual fouling percentage cover of 6–15%.

Table 3. Predictor variables used to construct classification tree models for hull fouling on international yachts arriving in New Zealand

Predictor variables	Levels
1. General information and vessel maintenance	
Origin of yacht	International vessel; New Zealand yacht returning from overseas
Hull material	Fiberglass, steel, wood, concrete, aluminum
Age of current antifouling paint	No. months
Paint application	Private; by professional painter
Manual hull cleaning (scraping/brushing)	Yes/no
Time since last manual hull cleaning	No. months
2. Travel history (past 12 months):	
Last port-of-call	(location)
Time spent moored in last port-of-call	No. days
Longest period of stationary mooring	No. months
Activity	No. days spent sailing

average measure of the relative increase in the likelihood of the taxon being present with each increase of one unit in the fouling rank. The quantile table provides estimates of the probability (and 95 % confidence intervals) of the group being present for each level of the rank index (Hosmer and Lemeshow 1989).

Modeling Risk Characters of International Yachts

Between 2002 and 2004, a total of 783 yachts were sampled upon their arrival to New Zealand, which included the initial 189 yachts used to calibrate the fouling ranks. Sampling consisted of two components: (1) allocating a fouling rank to each yacht after visual assessment (see above), and (2) collection of data on the recent travel and maintenance history of each vessel, using a short questionnaire. The questionnaire asked owners of the vessel about (1) their recent use and application of antifouling paints, (2) whether they had cleaned the yacht manually (scrubbing/scraping) between consecutive antifouling paint treatments, and (3) the vessels' recent ports-of-calls and sailing activity (Table 3). All of the vessels sampled arrived in four first ports-of-call: Opua, Whangarei, Auckland, and Tauranga (Figure 1). CART was used to model the level of fouling (rank scale) on yachts from a set of predictor variables derived from the questionnaire. The predictor variables were selected on the basis of previous discussions with the yachting industry about likely direct and indirect influences on fouling (Table 3). The Gini-index is suitable for categorical data (Breiman and others 1984) and was used as the splits measure. Twenty iterations were run for each CART analysis. Misclassification rates were calculated using cross-validation by fitting the model to 90% of the data and predicting the remaining 10% with the model. This procedure was repeated 10 times, each time with a different 10% subset of the data. The classification tree size with the smallest cross-validation error was chosen as the ''best'' tree (Breiman and others 1984, De'ath and Fabricius 2000). Classification trees were constructed

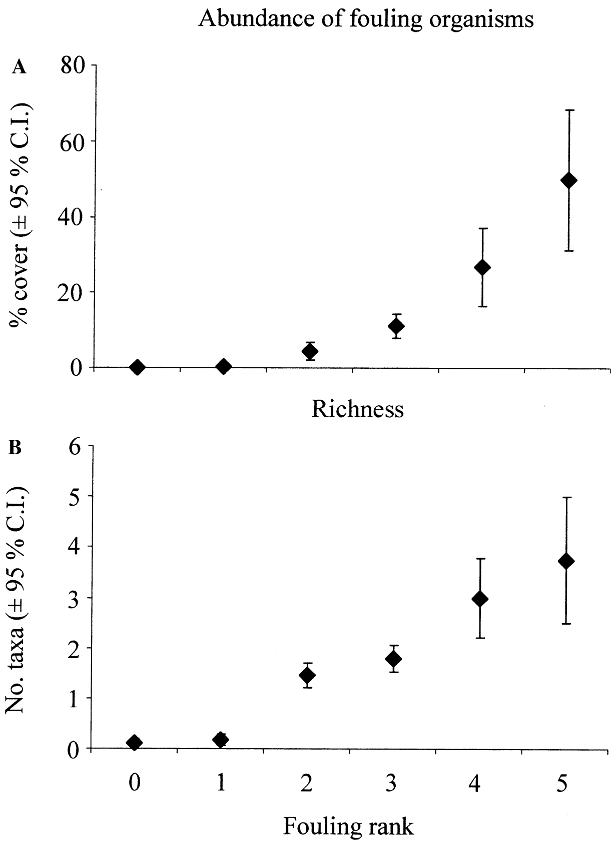

Figure 2. Mean abundance (percentage cover on submerged hull areas) (**a**) and taxonomic richness (number of broad taxonomic groups) (**b**) on hulls of the various fouling ranks (N = 189). Error bars depict the 95% confidence interval.

using the S-Plus routine "TreePlus" (De'ath and Fabricius 2000).

Results

Calibration of Fouling Ranks

Of the 189 yachts sampled *in situ*, 55% had been allocated fouling ranks 0 and 1 (i.e., clean of macrofouling) and 45% were given ranks 2, 3, 4, and 5 (presence of fouling assemblages). There was a strong correlation between the fouling ranks allocated by surface observation and the abundance and variety of hull-fouling assemblages determined *in situ*. Most yachts of ranks 0 and 1 (100% and 98.5%, respectively) were devoid of macrofouling, with an average percentage cover of fouling organisms of 0.1 ± 0.1% (mean ± 95% confidence intervals) (Table 2). As expected, fouling cover increased with fouling rank (rank 2: 4.35 ± 2.39%; rank 3: 11.11 ± 3.25%; rank 4: 26.76 ± 10.33%; rank 5: 49.88 ± 18.5%; (Pearson's r = 0.733, $P < 0.001$); Figure 2a). For some yachts, the percentage cover of fouling organisms derived from video analyses did not correspond to the fouling rank allocated by the surface observers (Table 2). Overall, 5% and 9.6% of vessels that had been allocated ranks 0 and 1, respectively, were found to carry small amounts of fouling (Table 2). Yachts scored with fouling rank 2 were found to be devoid of fouling in 6% of cases, when thick strands or layers of scuzz and slime were mistaken for macrofouling. Yachts scored with ranks 3, 4, and 5 had in 5% to 37% of cases a fouling percentage cover that corresponded not to the rank allocated (e.g., rank 4) but to an adjacent one (i.e., rank 3 or 5). However, importantly, none of the yachts scored with higher fouling ranks (3–5) were devoid of fouling (Table 2). Also the number of fouling taxa (e.g., erect bryozoans or barnacles) on the hulls increased with fouling rank, with 3.75 ± 1.2 (mean ± 95% confidence intervals) on hulls with a fouling rank of 5 (r = 0.794, $P < 0.001$; Figure 2b). Reference specimens collected from 25 yachts included a range of introduced species established or common in New Zealand, including the bryozoans *Bugula neritina* and *Watersipora subtorquata* and the tubeworm *Hydroides elegans* (Cranfield and others 1998). A bryozoan collected from one yacht hull represented a new record for New Zealand waters and was identified as *Scrupocellaria* cf. *diadema* (D. Gordon, unpublished data).

The relative abundance of most taxa (bivalves, colonial and solitary ascidians, encrusting and erect bryozoans, hydroids, tubiculous polychaetes, and sponges) on the hulls was on average highest for yachts of ranks 4 and 5 (Figure 3). The ranking scale was a highly significant predictor of the presence of all taxonomic groups except algae and encrusting bryozoans other than *Watersipora* sp. (binary logistic regression, $P < 0.05$; Table 4). The "odds ratio" calculated by logistic regression represents the multiplicative factor by which the probability of the presence of a taxon changes with a fouling rank increase of 1 (Steinberg and Colla 2000). The mean odds ratios for the taxa analyzed here ranged from 1.90 (barnacles) to 8.5 (sponges). For all groups with the exception of algae and encrusting bryozoans other than *Watersipora* sp., the lower 95% confidence interval of the odds ratio was >1, indicating that the fouling ranks represent a genuine risk scale for the presence of these taxa on international yacht hulls (Table 4). Fouling taxa varied widely in their probability of occurrence on yacht hulls of the same rank. Yachts with a fouling rank of 0 or 1 had a very low probability (0.001–0.05; 95% confidence interval) of carrying bivalves, colonial and solitary ascidians, hydroids, or sponges on their hulls, and a

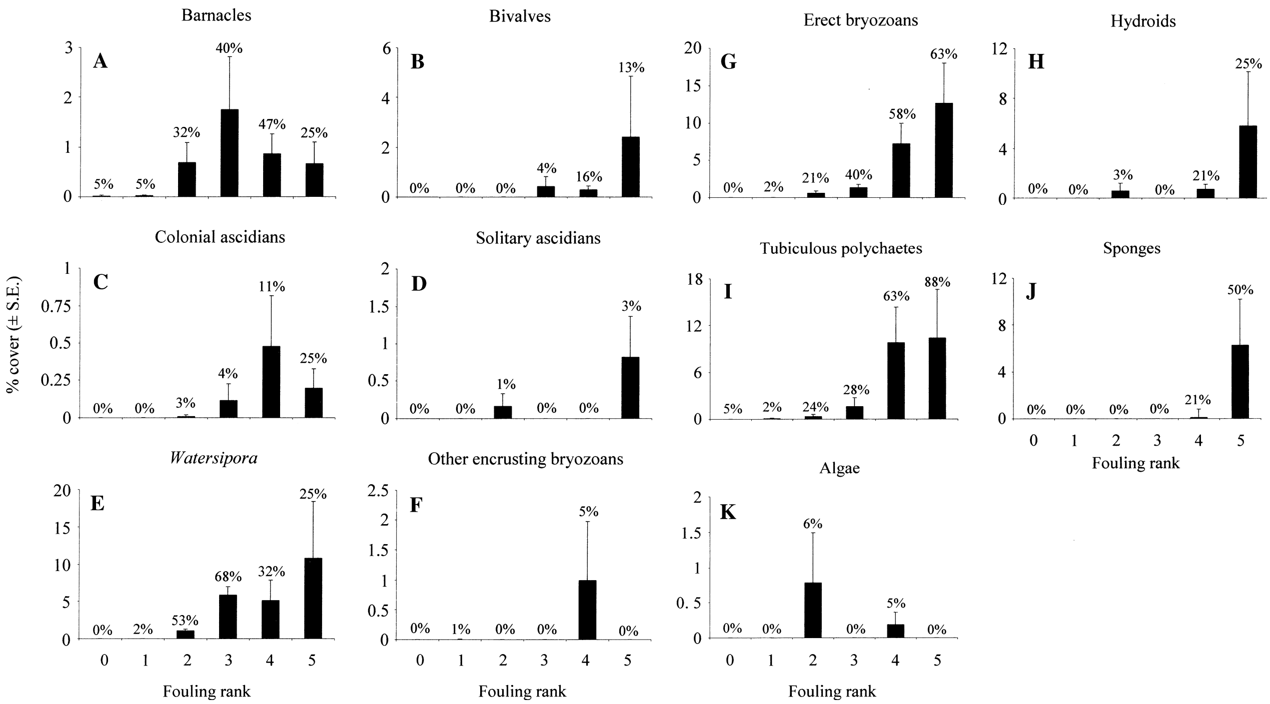

Figure 3. Relationships between the fouling ranks and mean abundances of different taxonomic groups. Annotations at the top of each bar depict the frequency of occurrence of the taxa on yachts (percentage of all yachts in that rank category).

Table 4. Results of logistic regression analysis[a]

	Barnacles	Bivalves	Colonial ascidians	Solitary ascidians	*Watersipora*	Other encrusting bryozoans
Rank 0	0.025 – 0.100	0.001 – 0.025	0.001 – 0.025	0.001 – 0.025	0.025 – 0.100	0.005
Rank 1	0.050 – 0.100	0.001 – 0.050	0.001 – 0.025	0.001 – 0.025	0.100	N/a
Rank 2	0.100 – 0.250	0.005 – 0.050	0.005 – 0.050	0.001 – 0.050	0.250 – 0.333	0.010
Rank 3	0.250 – 0.333	0.025 – 0.100	0.010 – 0.100	0.005 – 0.100	0.025 – 0.500	N/a
Rank 4	0.333 – 0.500	0.050 – 0.250	0.050 – 0.333	0.025 – 0.250	0.500 – 0.750	N/a
Rank 5	0.500 – 0.750	0.100 – 0.500	0.250 – 0.667	0.100 – 0.750	0.500 – 0.750	0.025
Odds ratio	1.90 (1.44, 2.51)	2.38 (1.28, 4.43)	2.98 (1.47, 6.1)	4.29 (1.44, 12.8)	1.99 (1.51, 2.61)	1.41 (0.56, 3.63)
Significance	$P < 0.001$	$P = 0.006$	$P = 0.002$	$P = 0.009$	$P < 0.001$	$P = 0.468$

	Erect bryozoans	Hydroids	Tubiculous polychaetes	Sponges	Algae
Rank 0	0.005 – 0.010	0.001 – 0.010	0.005 – 0.050	0.001 – 0.005	N/a
Rank 1	0.025 – 0.100	0.001 – 0.025	0.025 – 0.100	0.001 – 0.010	0.010
Rank 2	0.050 – 0.250	0.001 – 0.050	0.050 – 0.250	0.001 – 0.050	N/a
Rank 3	0.250 – 0.500	0.010 – 0.100	0.250 – 0.500	0.001 – 0.100	0.025
Rank 4	0.333 – 0.750	0.050 – 0.333	0.500 – 0.750	0.025 – 0.500	N/a
Rank 5	0.667 – 0.950	0.100 – 0.750	0.667 – 0.950	0.250 – 0.950	0.050
Odds ratio	2.99 (2.10, 4.26)	3.52 (1.69, 7.34)	3.12 (2.21, 4.53)	8.5 (2.54, 28.8)	1.53 (0.71, 3.3)
Significance	$P < 0.001$	$P = 0.001$	$P < 0.001$	$P = 0.001$	$P = 0.275$

[a]Shown are the 95 % confidence interval ranges associated with the probabilities of the various taxa to be present on hulls of the various fouling ranks. The "odds ratio" (shown with 95% confidence interval ranges in parentheses) represents the multiplicative factor by which the probability of the presence of a taxon changes with a fouling rank increase of one. P values denote the significance of the logit-model. For example, Barnacles had a probability between 0.25 and 0.333 to be present on a hull with a fouling rank of 3.

low probability (0.005–0.1) of carrying barnacles, *Watersipora*, erect bryozoans, and tubiculous polychaetes (Table 4). The latter four taxa were quite likely to occur on yachts of ranks 2 and 3 (probabilities of 0.05 to 0.50), whereas bivalves, colonial and solitary ascidians, hydroids, or sponges had consistently low

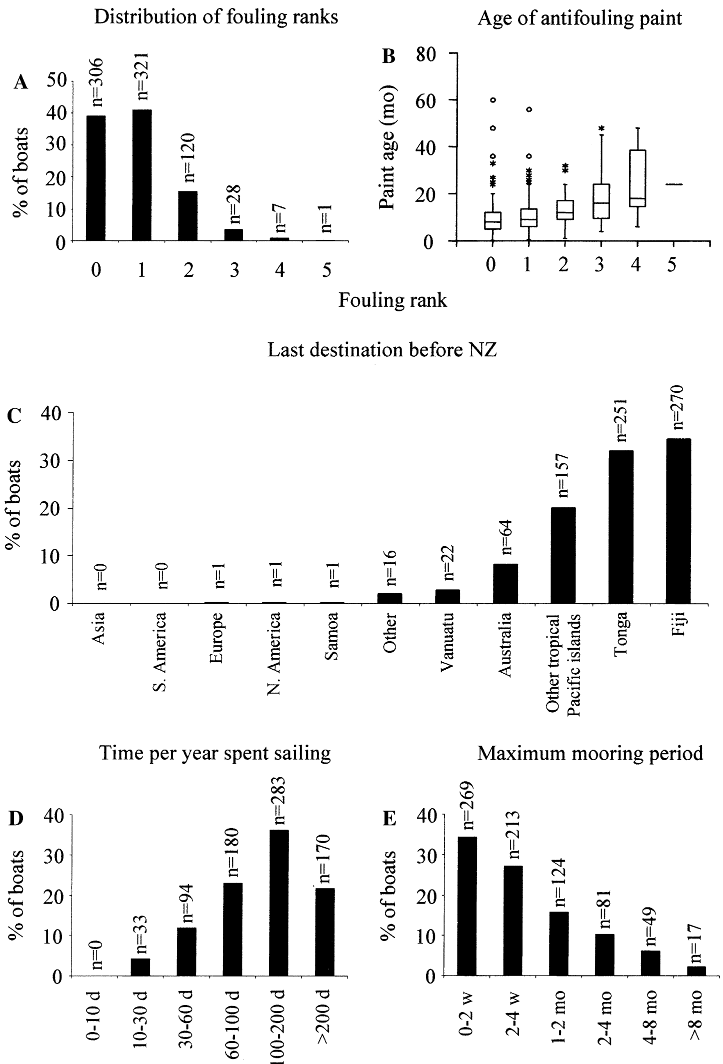

Figure 4. Summary plots showing the (**a**) frequency distribution of yachts in each rank class, (**b**) maintenance, and (**c**), (**d**), and (**e**) travel history of the 783 yachts sampled upon their arrival in New Zealand. The box plots in (b) depict the median paint age (horizontal lines), 25% quartiles (boxes), midrange (whiskers), and outliers (stars) and extreme values (circles) of observed paint ages.

probabilities (0.025–0.05) of occurring on hulls up to fouling rank 4 (Table 4). All taxa were very likely to occur on yachts of ranks 4 and 5, with cumulative probabilities ranging up to 0.95 (Table 4).

Risk Characterization and Predictive Modeling

Fouling ranks and questionnaire responses were obtained for a total of 783 yachts. Of these, 626 were international yachts and 157 were New Zealand yachts returning from overseas voyages. The majority of the yachts (85%; n = 666) had a fouling rank of 0 or 1 and carried no macrofouling on their hulls. However, 10% (n = 78), 4% (n = 31), 0.9% (n = 7), and 0.1% (n = 1) of the yachts had fouling ranks of 2, 3, 4, or 5, respectively, and had visible fouling on their hulls (Figure 4a). The yachts arrived from a total of 31 different destinations, most notably Fiji (34.5% of all arrivals), Tonga (32%), a range of tropical Pacific island nations (20%), Australia (8.2%), and Vanuatu (2.8%) (Figure 4c). The time the yachts had spent in these locations prior to leaving for New Zealand ranged from 1 day to 6 years (median: 21 days).

Almost all of the yachts (99.6%) had their hulls painted with toxic antifouling paint, which had been applied by the yacht's owner (57%) or a professional company (43%). The paint age at the time of sampling ranged from 1 week to 5 years, and was on average greater for yachts that carried visible fouling on their hulls (rank 2: 13.2 months mean paint age; rank 3: 17.3 months; rank 4: 25.4 months) than on those that did not (rank 0: 9.2 months; rank 1: 11.1 months). More than half of the yachts (54%) had their hull cleaned of fouling organisms by scraping or scrubbing since their last application of antifouling paint. This method is

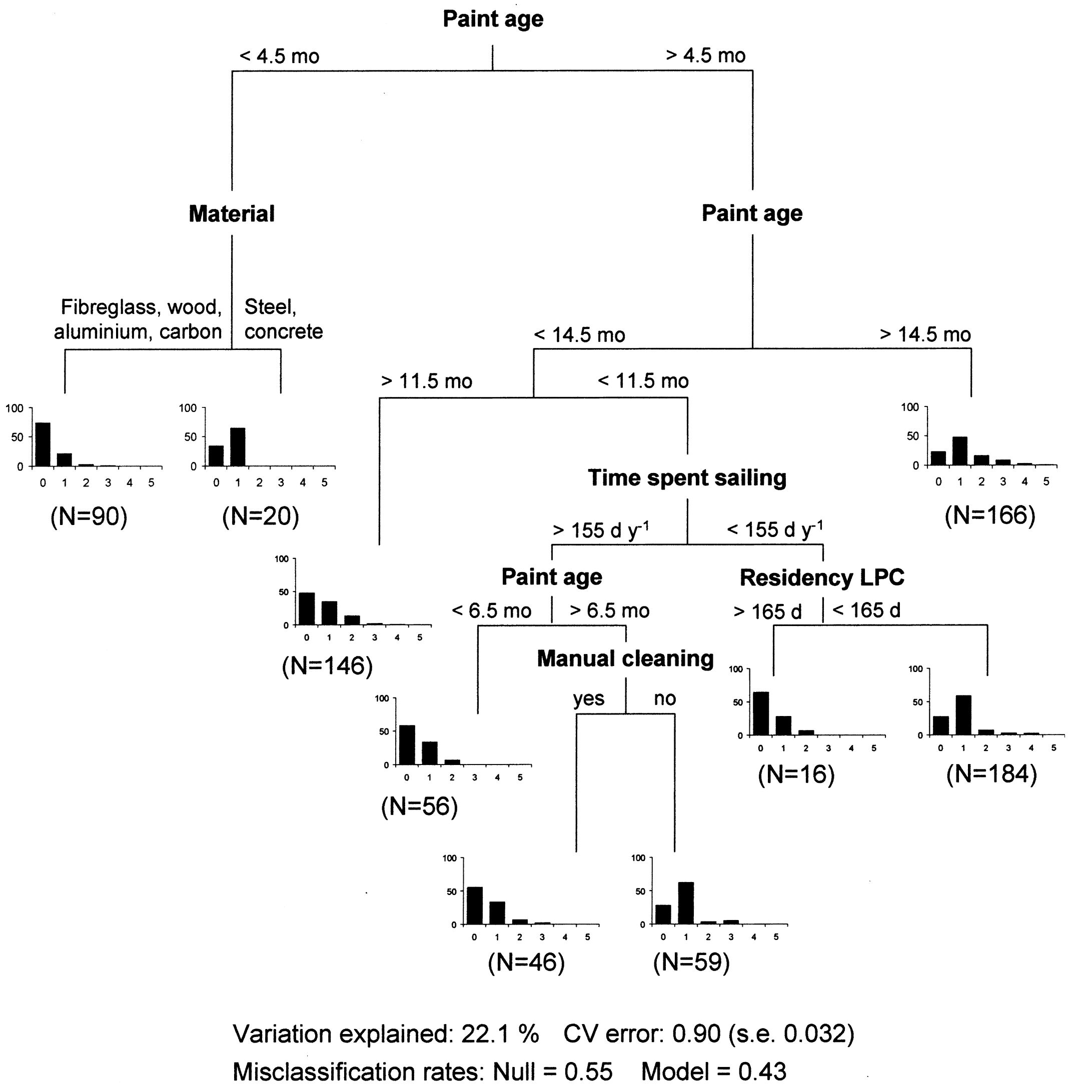

Figure 5. Classification tree for predicting fouling rank of the yachts. The proportional reduction in error (PRE) is calculated as (1 – relative error), and explains the proportion of the total variation explained by the model. The cross validation (CV) error and its standard error (s.e.) give an indication of the predictive power of the final model. The model also provides a comparison of rank misclassification rates if ranks were allocated at random (Null) and by the fitted model (Model). Splitting variables: Paint age = antifouling paint age; Material = outer hull material; Time spent sailing = no. of days spent sailing last year; Residency LPC = period of residency in the last port-of-call; Manual cleaning = manual removal of fouling assemblages from hull since last antifouling paint treatment.

often used to extend the service life of antifouling paints. On average, yachts that had been manually cleaned had an older antifouling paint age (12.8 ± 0.36, mean ± SE) than those that had not (8.6 ± 0.37) (ANOVA: Manual cleaning effect, $F_{1,4} = 5.3$; $p = 0.022$).

The majority of the yachts (58%) sampled had been in active use for more than 200 days in the past year. In contrast, only 4% had been actively sailing on 30 days or fewer (Figure 4d). Correspondingly, for most yachts (62%), the maximum time they had spent moored in ports or marinas since their last antifouling paint treatment was 4 weeks or less (Figure 4e). However, 10.3% of the yachts had been stationary for 2–4 months at a time, and 8.5% had not been in use for extensive periods ranging from 4 months to 5.5 years before sailing to New Zealand (Figure 4e).

The best classification tree model for the fouling ranks comprised nine splitting nodes with a cross-validation error of 0.90. The final model explained only 22.1% of the variation in fouling ranks among the 787 yachts and had a misclassification rate of 0.43, compared to 0.55 for the Null model based on randomized data (Figure 5). Application of antifouling paint (private or professional), maximum period of inactive mooring, and identity of the yachts' last port-of-call had no explanatory power and were excluded from the model. The age of the antifouling paint on yacht hulls explained the largest relative proportion of variation in fouling; four splits of the data were made on the basis of this variable, starting at an age of 4.5 months (Figure 5). The material the hull was constructed from, time spent sailing, manual cleaning, and period of residency in last port-of-call were also variables included in the model, but were of less relative importance in explaining variation in hull fouling. There was no clear pattern in the relative distribution of fouling ranks within the final nine groups of yachts created by CART (Figure 5). Yachts carrying fouling organisms (ranks 2, 3, 4, and, in a single case, 5) were present in all but one group (those with antifouling paint ages of <4.5 months). However, none of the groups contained exclusively yachts that carried fouling organisms: in all nine groups, the majority of yachts (70–100%) had fouling ranks of 0 or 1 (Figure 5).

Discussion

Human-mediated biotic invasions are a process that consists of several successive stages: (1) engagement of propagules with a transport vector in a source location, (2) transport from source to recipient location, (3) establishment of a self-sustaining population, and (4) spread through the new habitat (Mack and others 2000, Sakai and others 2001). Preventing the transport and release of NIS into native ecosystems are the only sure ways of avoiding the ecological and economic damage caused by invasive species (Leung and others 2002, Marchetti and others 2004). Our aim was to identify useful predictors of the abundance and composition of fouling organisms on international yachts that could be used to identify high-risk transport vectors before (if the relevant information is obtained while a yacht is on its way to New Zealand) or upon their arrival in New Zealand (if the information is obtained in the yacht's first port-of-call) and before they are able to reside in coastal waters for extended periods. The ordinal fouling rank we developed provided reliable indications of the actual abundance and variety of fouling assemblages on arriving yachts. Yachts with low ranks (0 and 1) were very unlikely to carry macrofouling on their hulls, whereas yachts of ranks 2–5 nearly always did. There was considerable variation in the probabilities of different taxa being present on hulls of the various ranks. However, for all taxa there was a positive relationship between fouling rank and probability of presence. One shortcoming of our sampling methodology during the rank calibration was that our remote-operated camera did not sample rudder and propeller surfaces, which are frequently occupied by fouling organisms. However, our personal observations suggest that fouling on propellers and rudders usually occurs in conjunction with fouling on hull and keel areas. This is supported by James and Hayden (2000), who sampled 26 yachts hulls in New Zealand marinas using a stratified approach. All of these yachts were found to carry fouling organisms on rudder and propeller, and in all instances fouling organisms were also encountered on hull and keel areas (James and Hayden 2000).

It has been argued that, from a precautionary perspective, all introductions should be treated as potentially harmful (Ruesink and others 1995) and to identify and target high-risk vectors that are likely to contain a large number of individuals or species (Wonham and others 2001). Although yachts of ranks 4 and 5 consistently harbored the largest number of fouling taxa, they only comprised a total of 7% of the yachts that arrived in New Zealand with fouling on their hulls in 2002–2004. Hulls of yachts with ranks 2 and 3 contained substantially (approximately 50%) fewer taxa, but comprised 93% of all ''fouled'' yachts. If the aim is to intercept a large proportion of the species that arrive in New Zealand on international yacht hulls, therefore, it may be inadvisable not to focus exclusively on yachts of the highest fouling ranks.

The observed abundance of fouling organisms on yacht hulls could not be reliably related to the yachts' travel or maintenance history or their owners' maintenance behavior. The models derived from CART analyses explained comparatively little variation in the distribution of fouling ranks (22.1%), had high misclassification rates (~43%) and, consequently, low predictive power. This was somewhat surprising, because we constructed the models using predictor variables associated with yacht maintenance and travel history that have repeatedly been demonstrated to influence hull fouling on commercial and private vessels (Coutts 1999, Floerl 2002). Antifouling paint age was the single most important risk factor for hull fouling on ocean-going yachts. Modern antifouling paints for yachts have a service life of 9–18 months given proper application and regular use of the vessels (Marine Science and Ecology 2002, J. Millett, personal communication 2001). In our sample, yachts lacking macrofouling (ranks 0 and 1) on average had a lower antifouling paint age (mean ± SE: 10.2 ± 0.28 months) than yachts with macrofouling (ranks 2–5; 15.1 ± 0.8

months). Also, the time a yacht had spent sailing was identified as a risk factor, and is indeed an important influencing factor on the performance and service life of modern antifouling paints (Christie and Dalley 1987, J. Millett, personal communication 2002). The recent travel history of the yachts was not identified as an important risk factor. We suspect this was because a potential influence of particular source locations on fouling abundance was masked by the overriding influence of antifouling paint age (yachts with low fouling ranks) or the lack of finer taxonomic resolution in the fouling data (yachts with high fouling ranks). The low predictive power of our model most likely reflects the complex suite of factors that determine the composition and abundance of fouling organisms in local ports, including variability in the composition of source populations of organisms (Floerl and Inglis in press) and the timing and intensity of recruitment at different phases of yacht maintenance (Floerl and Inglis 2003, Floerl and others in press). The various stages of biotic invasions—transport, introduction, establishment, spread and impact (Sakai and others 2001)—are each inherently idiosyncratic and of a highly multivariate nature (Marchetti and others 2004). Other, recent attempts to develop predictive models for the success of invaders have encountered similarly complex ecological determinants of invasion patterns. For example, Marchetti and others (2004) found that the model that best predicted establishment success of invasive fishes in California watersheds was the fully fitted model that used all eight available predictor variables. In our case, an additional complicating factor was the rarity of particularly high-risk cases (ranks 4 and 5) for model calibration. The development of robust predictive models relies upon relatively even numbers of cases across all sampling strata (Guisan and Zimmermann 2000). Although, during the timeframe of our study, we sampled *all* yachts arriving in New Zealand, only a small proportion of these (15%) had fouling ranks ≥2. Because CART uses 90% of the data as training sets to test the model, one or two cases from these rare ranks could produce comparatively high misclassification rates and poor performance of the model (Breiman and others 1984, Hosmer and Lemeshow 1989, De'ath and Fabricius 2000, S. Delean personal communication 2003).

Implications for Border Management and Prevention of NIS Introductions

Predictive modeling has had several applications in invasion science, including attempts to predict (a posteriori) successful invaders or their impacts, future invaders, and locations or habitats that are likely to be invaded (Rejmánek and Richardson 1996, Reichard and Hamilton 1997, Hengeveld 1999, Ricciardi and MacIsaac 2000, Kolar and Lodge 2002, Inglis unpublished data). In contrast to most of these studies, which focused on individual species with relatively fixed ecological and physiological traits and requirements, our model targets a whole transportation vector and incorporates the wide variation in maintenance and travel behavior of private yachts and their owners. Collection of data over a larger time frame, or simultaneous collection of standardized data in several locations worldwide would lead to a more comprehensive dataset that includes a large sample of yachts of all fouling ranks. If models with higher predictive power can be constructed from such data, they are likely to be robust and applicable for a wide range of geographic locations (Breiman and others 1984, De'ath and Fabricius 2000). The advantage of managing international yachts on the basis of risk-based predictive models is that these could be implemented at a pre-border stage, and allow yacht owners to assess and act on the condition and risk of their yacht prior to leaving their last port-of-call.

To our knowledge, few countries have implemented procedures to limit the accidental introduction of hull fouling organisms by ocean-going vessels. In Darwin, northern Australia, one of the only such cases known to us, management authorities have potentially prevented approximately 30 introductions of NIS as a result of the inspection of more than 700 international yachts since 1999 (A. Marshall, personal communication 2003). Our study shows that the use of the fouling rank scale proved to be an effective border-based observational technique to identify clean and fouled yachts after their arrival. The majority of yachts (90%) in this study arrived from tropical locations such as Fiji, Tonga, or French Polynesia. Many of the fouling organisms they carry are unlikely to survive in the colder waters of New Zealand. However, the NIS *Scrupocellaria* cf. *diadema* (not recorded in New Zealand before), *Bugula neritina*, *Watersipora subtorquata* and *Hydroides elegans* were collected from yachts whose last ports-of-call were in Noumea, Tonga, and Fiji, and all of the specimens were alive at the time of collection. Around 7% of the yachts we surveyed arrived from temperate Australian ports, most notably Hobart, Sydney, and Melbourne, which have a climate similar to that of northern New Zealand. In all of these ports, there are established populations of well-known NIS, including the crab *Carcinus maenas*, the seastar *Asterias amurensis*, the fanworm *Sabella spallanzanii*, the algae

Caulerpa taxifolia and *Undaria pinnatifida*, and other species (Hewitt and others 1999, Murphy and Schaffelke 2003). Considerable resources have been spent on eradication efforts and development of management tools for each of these species (Bax and others 2001, Secord 2003). A stronger commitment to the prevention of further NIS introductions and biological invasions will require appropriate attention to all vectors capable of transporting these and other high-risk species to new locations (Leung and others 2002), and the development and use of predictive tools may be a cost-effective way of achieving this (Mack and others 2000).

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