PREVENTING THE COSTS OF INVASIVE ALIEN SPECIES (IAS) IN BARBADOS AND THE OECS COUNTRIES

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SUMMARY

Invasive species are one of the leading causes of biodiversity decline worldwide and can have severe, detrimental impacts on human health and the economy. We define invasive species here as any non-indigenous species that is brought by humans to a location where it has never occurred before and has substantial, negative impacts on native biodiversity and/or human systems. Prevention is by far the cheapest and most effective form of invasive species management. It is therefore not surprising that risk assessments are increasingly being used to identify high risk vectors and/or non-native species that should be prioritized for management.

Over 100 exotic marine species have been introduced to the wider Caribbean region. It is likely that many of these species will, at some point, enter Barbados and the Organization of Eastern Caribbean States (OECS) countries (i.e., the subregion) either by natural dispersal or via similar major transport vectors. Given the above, in this report we first conducted a retrospective relative risk assessment of vectors for the wider Caribbean. The findings from this assessment were subsequently used to predict the relative importance of major transport vectors to the subregion in the short to medium term. We also used the retrospective assessment to identify potential non-native species that could become invasive in the subregion. In this latter instance, we paired stratified, random sampling with an internationally recognized, semi-quantitative species risk assessment approach.

Several major findings emerged from our analysis. We found that, similar to the regional retrospective assessment, the transport vectors that pose the most risk to the

subregion in the future are the aquarium trade, shipping (i.e., ballast water and biofouling) and fisheries (inclusive of aquaculture). Moreover, we discovered that a large percentage of species introduced to the region (and that can therefore potentially enter the subregion) could not be ascribed to any particular vector. Thirty-two species were assessed for their potential to become invasive in the subregion and were placed on one of three invasive species watch lists: red (high likelihood of becoming invasive), orange (medium likelihood of becoming invasive) and green (low likelihood of becoming invasive). The majority of species posed a medium risk of becoming invasive. However, four species were highly likely to become invasive if they should enter the subregion. These included (in descending order of risk): (1) the Giant tiger prawn, *Penaeus monodon*, (2) the Ribbon sea lettuce, *Ulva reticulata*, (3) the Spotted scat, *Scatophagus argus*, and (4) the Atlantic sea nettle, *Chrysaora quinquecirrha*. This report is a preliminary assessment of the key threats to the subregion and should be used as a guideline for more in-depth analyses.

INTRODUCTION

Risk assessments have been used for environmental contaminants for almost half a century (Landis et al. 2013), but only relatively recently (i.e., since the early 2000s) have they been applied to biological invasions (Davidson et al. 2017). Nevertheless, the usefulness of this approach for national and/or regional biosecurity is obvious. Prevention is by far the cheapest and most effective form of invasive species management (Lockwood et al. 2013; Lodge et al. 2016). Limited resources, however, mean that the need to prioritize which species and/or vectors require special regulations and monitoring to prevent future invasions is crucial. Risk assessments allow for this objective to be met.

There are generally three approaches to risk assessments, which can be undertaken singularly or in a hierarchical fashion: qualitative, semi-quantitative and quantitative. All involve ranking risks based on a variety of information and/or data sources along with a justification and measure of uncertainty (O 2015; Holsman 2017). Qualitative assessments involve the rapid evaluation of qualitative data (e.g., literature reviews) in which the analyst answers yes or no to a series of questions related to species traits, environmental characteristics and the ecological and sometimes, socioeconomic impacts associated the invasion process (Essl et al. 2011; O 2015; Holsman et al. 2017; e.g., Therriault & Herborg 2008). In comparison, although semi-quantitative assessments also involve answering yes or no to a series of questions, these responses are given a numerical value. Values to each question are subsequently summed and the total is used to determine species rank based on predetermined thresholds (Lockwood et al. 2013; Copp et al. 2016; e.g., Bilge et al. 2019; Uyan et al. 2020). Finally, quantitative assessments are the most data intensive of the three and use machine learning and statistical techniques to evaluate risks (Lodge et al. 2016; e.g., D'Amen & Azzurro 2020).

Numerous challenges are associated with conducting invasive species risk assessments, but this is particularly so when dealing with small island developing states like those in the Caribbean region. Data and knowledge gaps about a species and/or vector pose the greatest challenge, regardless of approach, taxonomic grouping, location, or ecosystem (Davidson et al. 2017). However, in the Caribbean these gaps are widened by restricted access to what little data and knowledge may already exist but are locked behind expensive journal paywalls. Indeed, this problem plagues the scientific enterprise as a whole (e.g., see Fuller et al. 2014; Giehl et al. 2017; Smith et al. 2017). Another important challenge is the limited opportunity for advanced technical training of analysts in the Caribbean. In addition to formal training in invasion biology and system specific knowledge, analysts can be required to possess sophisticated statistical skills and be familiar with specific modelling software, depending on the approach. Finally, conducting risk assessments is expensive. All approaches are time intensive, and some require software that may not necessarily be free (e.g., ArcGIS). These costs can quickly add up, particularly when there is a need to hire outside analysts due to lack of internal capacity.

We carefully considered all these challenges when selecting an approach and the associated tools for conducting an invasive species risk assessment for Barbados and the Organization of Eastern Caribbean States (OECS) countries. Our aim was to provide a method that could be easily implemented in regions where resources and technical expertise are limited. We determined that a semi-quantitative approach was most appropriate because in addition to the above, it allows for relatively complex modelling capabilities even when quantitative data are scarce. Moreover, internationally recognized, easy-to-use tools already exist for this approach, and some are freely available for download from the internet.

Here, we first evaluate the relative risks of transport vectors of marine invasive species to Barbados and the eastern Caribbean (i.e., the subregion). To do this, we performed a retrospective relative risk analysis of the wider Caribbean region, and then used these results to forecast vector relative risks in the short to medium term in the subregion. Second, we assess the risks that non-indigenous species introduced to the wider Caribbean region, but not (yet) present in the subregion, could become invasive in the subregion. In this latter instance, we used the Aquatic Species Invasiveness Screening Kit (AS-ISK v2.2; Copp et al. 2016; free for download at www.cefas.co.uk/nns/tools/) to develop watch lists to identify non-native, marine taxa that may require special regulations and/or monitoring to prevent future invasions. This study is not exhaustive and should be interpreted as a preliminary assessment of key threats.

METHODS

Risk assessment area

In this study, Wider Caribbean region (henceforth referred to as 'region') includes the marine waters surrounding Florida, the Caribbean Sea, and the Atlantic coasts of Central America, Colombia and Venezuela (Fig. 1). The eastern Caribbean (henceforth called 'subregion') refers to marine waters surrounding the countries that are the focus of our risk assessment (i.e., the 'risk assessment area'). These include: 1) Barbados, 2) Antigua and Barbuda, 3) Dominica, 4) Grenada, 5) St. Kitts and Nevis, 6) St. Lucia, and 7) St. Vincent and the Grenadines (Fig. 1).

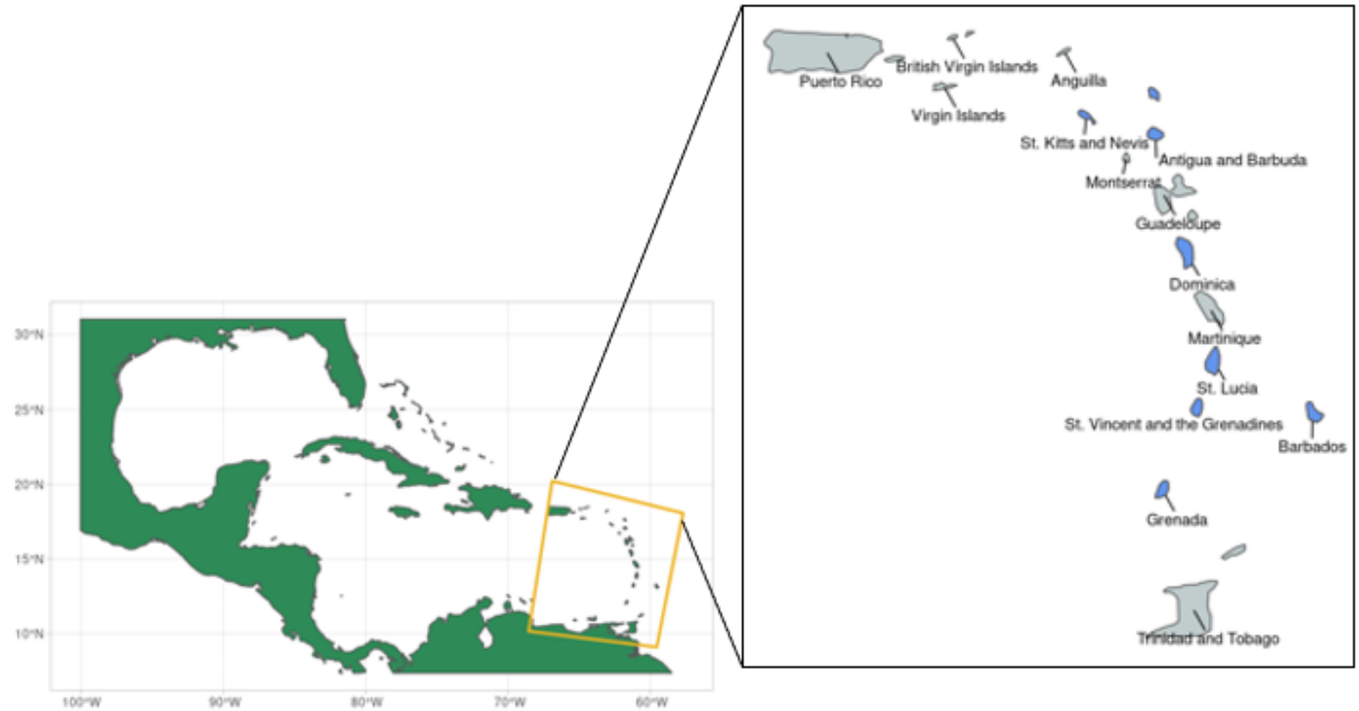

Fig. 1. Map of wider Caribbean region and study area. Image within the yellow box is enlarged. Islands included in the risk assessment area (i.e., Barbados and Organization of Eastern Caribbean States countries) are highlighted in blue.

Selection of species pools

Regional pool of introduced species

In addition to technical reports that were available online, we used a total of three databases to identify non-native species that were introduced to the region: 1) World Register of Introduced Marine Species (WRiMS), 2) IUCN Global Invasive Species Database, and 3) USGS Nonindigenous Aquatic Species (NAS) Database. Species were located by searching by country or region (e.g., Caribbean Sea). We recorded the place of introduction (country or region), both the scientific and common names of the species (where possible), the country or regional categorization of the species (cryptogenic, exotic, introduced, invasive, native transplant, or unknown), phylum, type of transport vector(s), and primary information source (Appendix 1).

Species that can potentially be introduced to the subregion

We compiled a list of species that can potentially be introduced to the subregion in the short to medium term by identifying those non-native species present in the region but currently absent from the subregion. We then assessed the risk posed to the subregion by approximately 25% (36 species) of these species. Specifically, we used stratified random sampling in which the number of species selected per phylum was proportional to the relative representation of this phylum in the regional species pool. For example, since chordates represented ~45% of all marine species introduced to the region (see Results), 45% of species chosen for assessment of risk to the subregion were also chordates. Two phyla were initially selected for inclusion in the subregional species pool but, in the end, were not included for a variety of reasons (see Results). This resulted in a total of 32 species selected for risk screening.

We used stratified random sampling to select a subset of species for assessment as opposed to expert opinion of species most likely to become invasive in the Caribbean for two reasons. First, insufficient background information was available on all 142 species prior to our in-depth assessment, which would be needed to make an informed, *a priori* judgement of risks. Second, given the diversity of taxa and places of origin of species on the regional list, it would be very difficult to compile a list of local experts that could address all 142 species.

Relative risk analysis of transport vectors

Retrospective relative risk analysis of vectors for the region

In keeping with previous studies (e.g., Williams et al. 2013), we tallied the number of species that had been introduced by each vector to determine the relative importance of each vector in introducing non-native species to the region in the past. Species that were introduced by more than one vector were counted separately for each vector, thus resulting in a sample size in the above analysis exceeding the total number of species in the regional pool (see Results). Additionally, some vectors are potentially represented twice in our list of major vectors and are not mutually exclusive because of insufficient data. For example, our category 'fisheries' contains species that were introduced into the subregion via the live seafood trade in which organisms are sometimes intentionally released into the environment, but may also contain species that were accidentally introduced via aquaculture but could not be placed into the latter category due to lack of detailed information.

Forecasting relative risks of vectors for the subregion

To determine and rank which vectors may become important for introducing non-native species to the subregion in the short to medium term, we examined the pool of species that could potentially be introduced to the subregion (i.e., species that are currently present in the region but absent in the subregion) and noted the vectors identified for each species at the regional scale (see above). As with the retrospective relative risk analysis of vectors, we tallied the number of species by vector to determine relative importance.

Species risk screening

We used the AS-ISK v2.2 (Copp et al. 2016) to screen 32 non-native species identified as having the potential to be introduced to the subregion (see above). Screening for each species was carried out independently by one or more authors of this report. When more than one assessment for a species was conducted, we present the mean.

The AS-ISK is a decision support tool that is an adaptation of the popular Weed Risk Assessment (Pheloung et al. 1999). It replaces five taxon-specific toolkits for amphibians, freshwater and marine fish and invertebrates (i.e., Amp-ISK, FISK, FI-ISK, MFISK, MI-ISK), and is applicable to virtually all climatic zones and all aquatic plants and animals, regardless of ecosystem (Copp et al. 2016). The AS-ISK consists of 49 questions focused on a species' biological and ecological characteristics, biogeographical and historical information, and its potential ecological and socio-economic impacts (Copp et al. 2016). Answers to these questions result in a Basic Risk Assessment (BRA) score ranging from -20 to 68, with higher scores indicating higher risks. An additional six questions allow the analyst to predict how climate change is likely to influence the risks of introduction, establishment, dispersal and impact, resulting in a combined BRA + CCA (climate change assessment) score (Copp et al. 2016). The BRA + CCA score ranges from -32 to 80.

All 55 responses are accompanied by a justification and a measure of uncertainty called a confidence level (CL), which is based on the Intergovernmental Programme for Climate Change (IPCC), and ranges from one to four where: 1 = low; 2 = medium; 3 = high; and 4 = very high confidence. A confidence factor (CF) for the BRA score and, separately, the BRA + CCA score is subsequently calculated from the confidence levels as follows:

$$CF = \sum (\mathrm{CLQi})/(4 \times n)\ (i = 1, \ldots, n)$$

where, CL_{Qi} is the analyst-assigned confidence level for each question and n is the number of questions in the assessment (i.e., 55) (Bilge et al. 2019; Lyons et al. 2020; Uyan et al. 2020). The CF for an assessment ranges from 0.25 (i.e., all 55 questions with a confidence level equal to 1) to 1.0 (i.e., all 55 questions with a confidence level equal to four) (Uyan et al. 2020).

Threshold values in the AS-ISK are used to determine whether a species is ranked as having a low, medium or high risk of becoming invasive. These values are typically calculated based on the results of a Receiver Operating Characteristic (ROC) curve analysis, which assesses the predictive ability of the AS-ISK to distinguish between high, medium and low risk taxa (Uyan et al. 2020). However, ROC analysis requires that species are categorized *a priori* for invasiveness (Uyan et al. 2020). Because relatively few non-native species have established in the eastern Caribbean, threshold values have not yet been determined for the subregion. We therefore used the high-risk BRA and BRA + CCA threshold values established by Bilge and colleagues (2019) for Lessepsian fishes in the eastern Mediterranean, which were 18.5 and 29.5, respectively. This substitution approach has been successfully used for other invasive species risk assessments in the western Atlantic (e.g., Lyons et al. 2020). Adhering to convention, we used the default threshold of 1.0 to distinguish between low and medium risk species (Copp et al. 2005; Uyan et al. 2020). We assigned species that obtained a high risk ranking to a 'red watch list', those that received a medium risk ranking to an 'orange watch list' and those that received a low risk ranking to a 'green watch list'.

RESULTS

Selection of species pool

Regional pool of introduced species

Searches for species that were previously introduced to the Caribbean region yielded a total of 142 species representing 15 phyla (Fig. 2; Appendix 1). The majority of introduced species were chordates (44%), followed by molluscs (16%), arthropods (9%), cnidarians (8%), algae from the phylum Rhodophyta (6 %), annelids (4%), and bryozoans (4%). The remaining phyla comprised fewer than five species (Fig. 2).

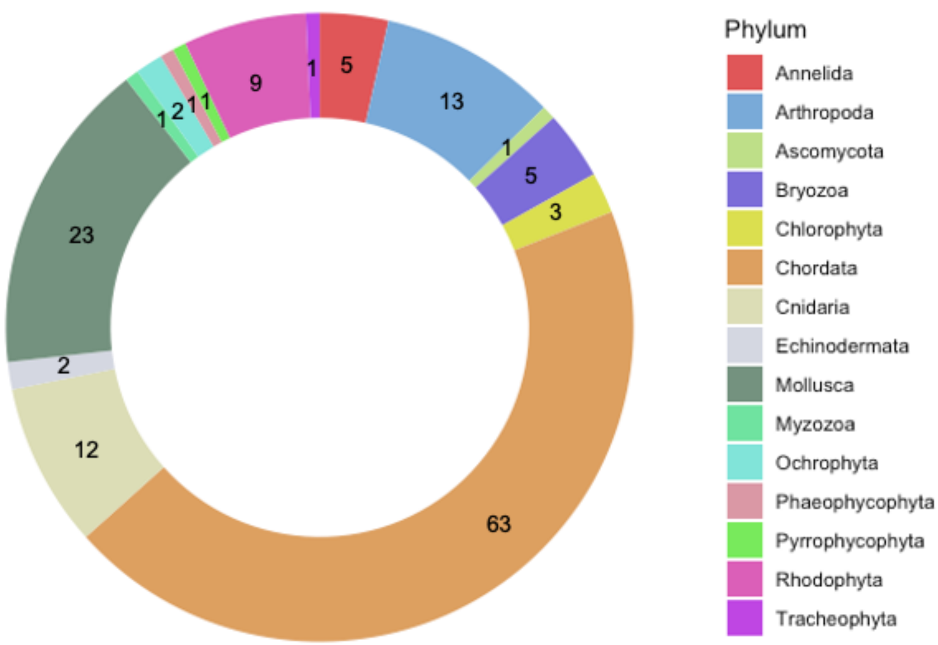

Fig. 2. Relative distribution of phyla introduced to the Caribbean region. Numbers indicate the number of species in each phylum.

Species that can potentially be introduced to the subregion

A total of 32 species that are currently present in the region but absent from the subregion were randomly selected for forecasting relative risks of vectors to the subregion (Appendix 2). These species include representatives from eight phyla. Our sample size is slightly less than 25%

of the regional species pool because: (1) although the phylum Annelida was selected, all members of this phylum except for one, whose vector was unascribed (i.e., *Alitta succinea*), had already been introduced to the subregion via shipping (Table 1), and (2) members of the phylum Ochrophyta were also omitted because all species that appeared in regional searches were either native to the subregion or were not exclusively marine (e.g., estuarine taxa).

As expected, chordates dominated the subregional species pool (17 species, or 53%), followed by species from the phyla Mollusca (6 species, or 19%), Arthropoda (3 species, or 9 %), Cnidaria (3 species, or 9%), and Rhodophyta (2 species, or 6%). The three remaining phyla were each represented by less than 3% (i.e., one species each) of the subregional species pool.

Table 1. List of introduced annelids that were already present in both the region and subregion.

Phylum	Species
Annelida	*Alitta succinea*
	Fycopomatus miamensis
	Hydroides dianthus
	Hydroides dirampha
	Hydroides elegans

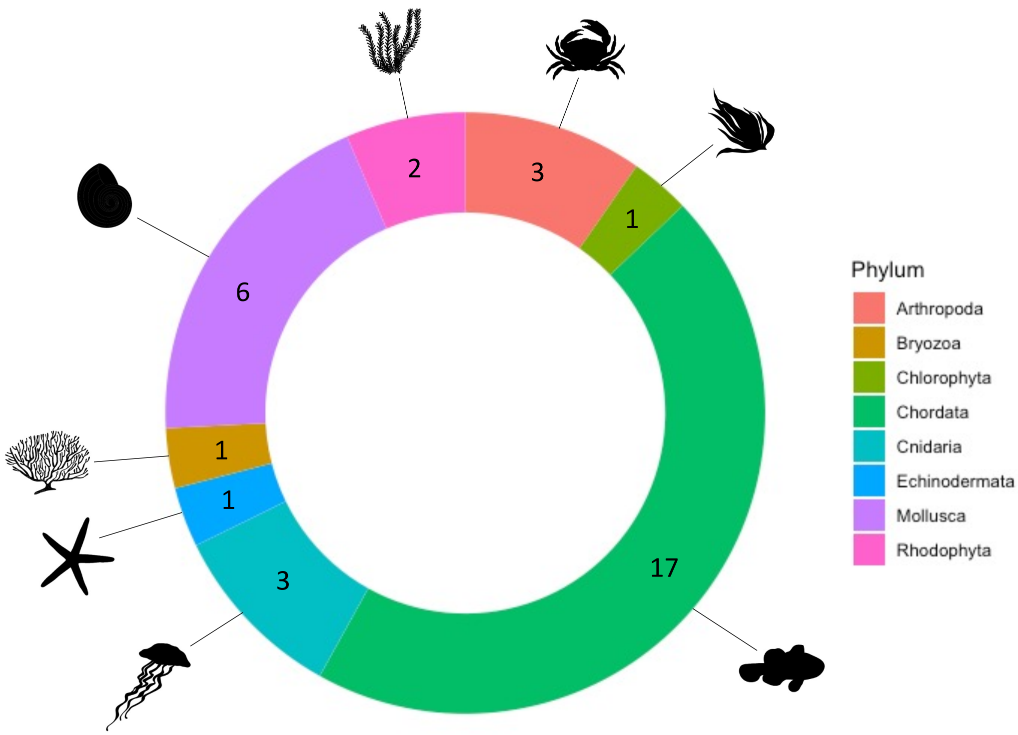

Fig. 3. Relative distribution of species in phyla that could be introduced into the subregion in the short to medium term given their presence in the regional species pool. Numbers indicate the number of species in each phylum.

Relative risk analysis of transport vectors

Retrospective relative risk analysis of vectors for the region

Aquarium releases have introduced the most species into the region in the past, with 41 species stemming from this vector alone (Fig. 4). The majority of species introduced by this vector were chordates (95%), in particular marine fishes, associated with the international aquarium trade in Florida. Other than chordates, only two species of Cnidaria were introduced by this vector, i.e., *Carijoa riisei* (the snowflake coral) and *Tubastraea coccinea* (the orange cup coral).

Of particular concern is the high number of introduced species in the region (31 species total) for which a vector cannot be ascribed. The number of species included in this latter category is second only to aquarium releases (Fig. 4). Almost two-thirds of introduced species with an unknown vector were chordates (39%) and molluscans (25%).

Biofouling and ballast water ranked third and fourth, respectively, for the greatest number of species introduced by a particular vector. Although both vectors originate from ships, which is also a separate category due to insufficient data (see Methods), it is important to note that the two are managed differently and are therefore analyzed separately here, as with other studies (e.g., Williams et al. 2013). While chordates accounted for a substantial percentage of species associated with biofouling (31%), they were a much smaller component of ballast water (13%), which was dominated instead by molluscs (30%) followed by cnidarians (17%) and arthropods (17%).

Aquaculture (21 species total) introduced slightly more species than fisheries as a whole (15 species total), which also potentially contained species that were introduced by aquaculture, while canals and natural dispersal accounted for the introduction of nine species to the region. In the past, oil rigs were the least important among the major categories of vectors, having introduced only four species to the region, three chordates and one cnidarian.

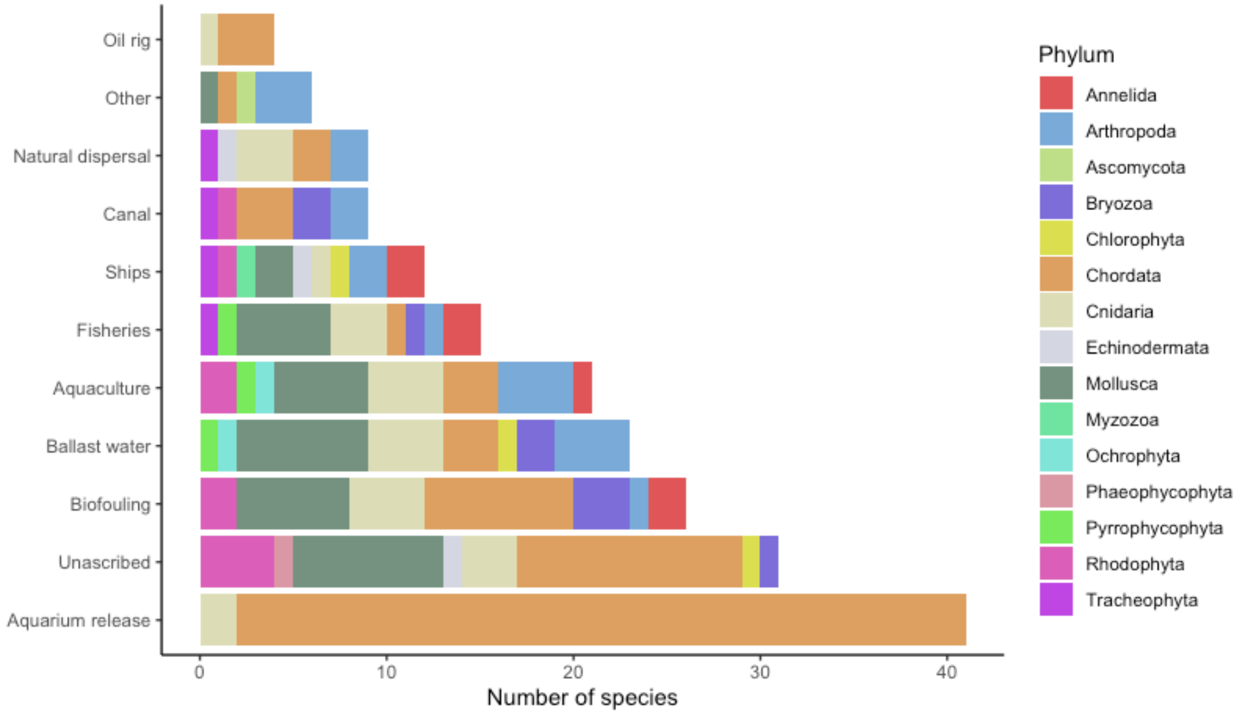

Fig. 4. Distribution of number of introduced marine species by phyla and their means of entry into the Caribbean region in the past.

Forecasting relative risks of vectors for the subregion

The greatest number of species are predicted to enter the subregion via the aquarium trade (15), all of which are chordates (marine fishes) (Fig. 5). As with the regional retrospective relative risk analysis of vectors, the second greatest number of species likely to be introduced to the subregion cannot be ascribed to any particular vector (8 species). This latter group comprised species from five phyla: (1) Chordata, (2) Cnidaria, (3) Mollusca, (4) Chlorophyta, and (5) Rhodophyta. Ballast water and biofouling were predicted to be the third and fourth most important vectors to the subregion, respectively. Surprisingly, no chordates are likely to be introduced via these latter two vectors. Although all species, in theory, are potentially able to enter the subregion via natural dispersal, fewer than five species are predicted to do so based on our analysis.

Aquaculture may introduce three species to the subregion while fisheries as a whole is predicted to introduce the same number, all of which are molluscs. Fewer than five species each are predicted to enter the subregion via ships in general, or other less common means. It is important to note that the two dominant phyla likely to enter the subregion, i.e., chordates and molluscans, are not predicted to be transported by biofouling, natural dispersal, or ships in general. Moreover, molluscs seem to be the most versatile phylum in terms of the number of vectors associated with it (i.e., five out of nine potential vectors). The absence of canals and oil and gas rigs as major vectors to the subregion is also notable.

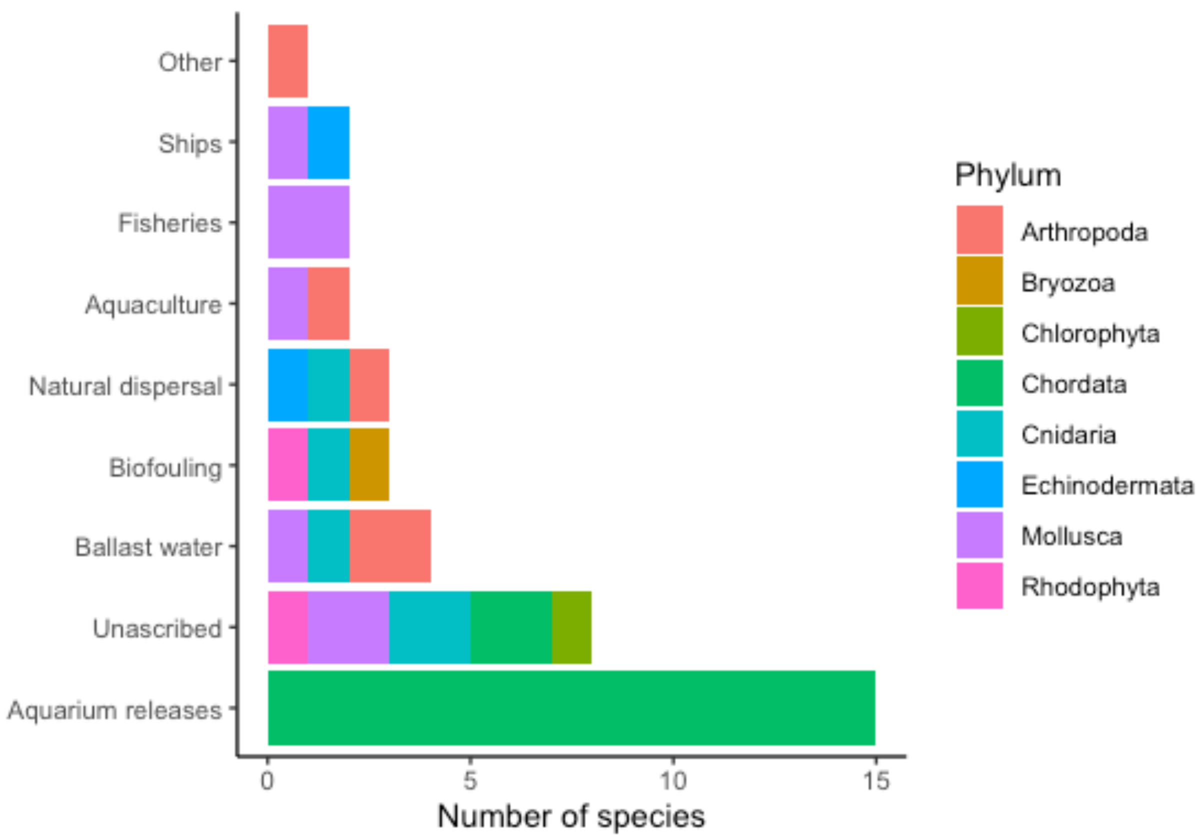

Fig. 5. Distribution of number of marine species by phyla forecasted to enter the subregion by various vectors.

Species risk screening

The majority of species we assessed (i.e., 24 out of 32) had a medium risk of becoming invasive in the subregion under current and future climates and was therefore placed on our orange watch list (Fig. 6; Tables 2 and 3). Four species, each representing a different phylum, were evaluated as having a high risk of becoming invasive in the subregion under current climatic conditions. These included (in descending order or risk): (1) the Giant tiger prawn, *Penaeus monodon*, (2) the Ribbon sea lettuce, *Ulva reticulata*, (3) the Spotted scat, *Scatophagus argus*, and (4) the Atlantic sea nettle, *Chrysaora quinquecirrha*. All were placed on our high management priority, red watch list (Table 3). Few species posed a low risk of becoming invasive under current climate, and were placed on our low priority, green watch list. These included (in descending order of risk): (1) Clown anemonefish, *Amphiprion ocellaris*, (2) Redrust bryozoan, *Watersipora subtorquata*, (3) Lesser girdled triton, *Gelagna succinta*, and (4) the sea hare, *Aplysia cervine* (Table 3).

In most instances, climate change scenarios either increased (e.g., Whitetail damselfish, *Dascyllus aruanus*) or did not affect (e.g., Mud or mangrove crab, *Scylla serrata*) a species' risk score compared to the risk scores under current climate conditions (Fig. 6). In one instance, assessment under a climate change scenario increased the threat category from low to medium risk of becoming invasive. This occurred for the Clown anemonefish, *Amphiprion ocellaris* (Fig. 6). There were also three rare instances in which a species' risk score decreased under a climate change scenario. Specifically, this occurred for the Crozier weed, *Hypnea musciformis*, the Erect sea moss, *Acanthophora spicifera*, and the Racoon butterflyfish, *Chaetodon lunula* (Fig. 6).

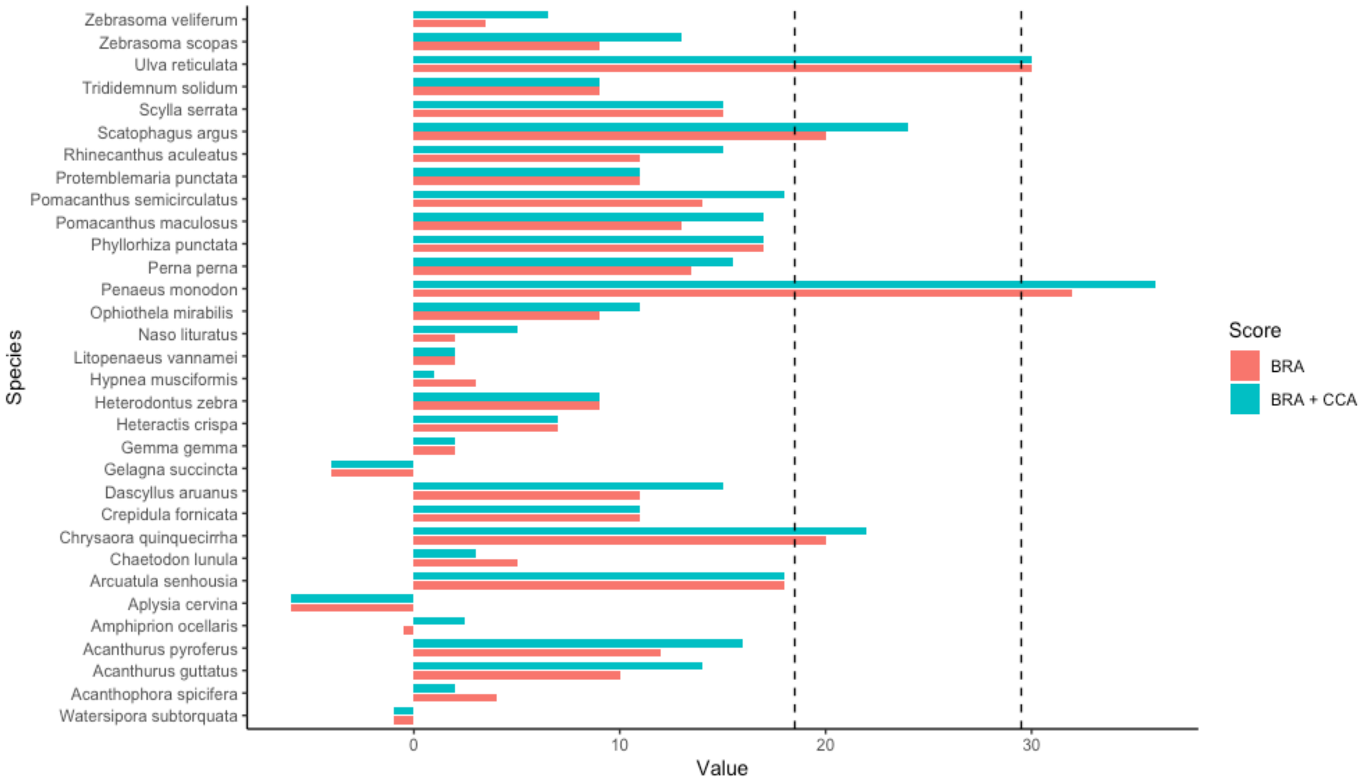

Fig. 6. Species risk screening. Species and their risk assessment score using the AS-ISK. BRA: basic risk assessment score; BRA + CCA: risk assessment score under climate change scenarios. Dashed lines represent the threshold values for species with a high likelihood of becoming invasive if they are introduced into the subregion under current (left line) and future (right line) climatic conditions, respectively.

Table 2. AS-ISK results for risk screening 32 species that may potentially enter the subregion

Species	Common Name	Phylum	BRA	BRA CF[1]	BRA + CCA	BRA + CCA CF[2]
Gelagna succincta	Lesser girgled triton	Arthropoda	-4	0.34	-4	0.33
Penaeus monodon	Giant tiger prawn		32	0.35	36	0.35
Scylla serrata	Mud crab		15	0.41	15	0.4
Watersipora subtorquata	Redrust bryozoan	Bryozoa	-1	0.38	-1	0.37
Ulva reticulata	Ribbon sea lettuce	Chlorophyta	30	0.57	30	0.56
Acanthurus guttatus	Whitespotted surgeonfish	Chordata	10	0.47	14	0.46
Acanthurus pyroferus	Chocolate surgeonfish		12	0.54	16	0.52
Amphiprion ocellaris	Clown anemonefish		-0.5	0.465	2.5	0.45
Chaetodon lunula	Racoon butterflyfish		5	0.62	3	0.56
Dascyllus aruanus	Whitetail damselfish		11	0.56	15	0.53
Heterodontus zebra	Zebra bullhead shark		9	0.62	9	0.61
Naso lituratus	Orangespine unicornfish		2	0.385	5	0.37
Pomacanthus maculosus	Yellowbar angelfish		13	0.54	17	0.52
Pomacanthus semicirculatus	Semicircle angelfish		14	0.57	18	0.56
Protemblemaria punctata	Warthead blenny		11	0.58	11	0.55
Rhinecanthus aculeatus	Lagoon triggerfish		11	0.45	15	0.44
Scatophagus argus	Spotted scat		20	0.4	24	0.38
Trididemnum solidum	Overgrowing mat tunicate		9	0.44	9	0.42
Zebrasoma scopas	Twotone tange		9	0.4	13	0.38
Zebrasoma veliferum	Sailfin tang		3.5	0.44	6.5	0.425
Chrysaora quinquecirrha	Sea nettle	Cnidaria	20	0.41	22	0.39
Heteractis crispa	Leathery sea anemone		7	0.34	7	0.33
Phyllorhiza punctata	Australian spotted jellyfish		17	0.41	17	0.4
Ophiothela mirabilis	Brittle star	Echinodermata	9	0.4	11	0.38
Aplysia cervina	Sea hare	Mollusca	-6	0.32	-6	0.31
Arcuatula senhousia	Asian date mussel		18	0.51	18	0.48
Crepidula fornicata	Slipper limpet		11	0.41	11	0.39
Gemma gemma	Amethyst gem clam		2	0.54	2	0.5
Litopenaeus vannamei	Whiteleg shrimp		2	0.38	2	0.37

Perna perna	Brown mussel		13.5	0.515	15.5	0.49
Acanthophora spicifera	Erect sea moss	Rhodophyta	4	0.41	2	0.4
Hypnea musciformis	Crozier weed		3	0.4	1	0.38

BRA CF[1]: Confidence Factor associated with the Basic Risk Assessment Score. BRA + CCA CF[2]: Confidence Factor associated with the risk assessment score under climate change scenarios.

Table 3. Species watch lists

Red list	Species	Common name
	Chrysaora quinquecirrha	Atlantic sea nettle
	Penaeus monodon	Giant tiger prawn
	Scatophagus argus	Spotted scat
	Ulva reticulata	Ribbon sea lettuce
Orange list	*Acanthophora spicifera*	Erect sea moss[1]
	Acanthurus guttatus	Whitespotted surgeonfish
	Acanthurus pyroferus	Chocolate surgeonfish
	Arcuatula senhousia	Asian date mussel
	Chaetodon lunula	Racoon butterflyfish
	Crepidula fornicata	Slipper limpet
	Dascyllus aruanus	Whitetail damselfish
	Gemma gemma	Amethyst gem clam
	Heteractis crispa	Leathery sea anemone
	Heterodontus zebra	Zebra bullhead shark
	Hypnea musciformis	Crozier weed
	Litopenaeus vannamei	Whiteleg shrimp
	Naso lituratus	Orangespine unicornfish
	Ophiothela mirabilis	Brittle star
	Perna perna	Brown mussel
	Phyllorhiza punctata	Australian spotted jellyfish
	Pomacanthus maculosus	Yellowbar angelfish
	Pomacanthus semicirculatus	Semicircle angelfish
	Protemblemaria punctata	Warthead blenny
	Rhinecanthus aculeatus	Lagoon triggerfish
	Scylla serrata	Mud crab
	Trididemnum solidum	Overgrowing mat tunicate
	Zebrasoma scopas	Twotone tange
	Zebrasoma veliferum	Sailfin tang
Green list	*Amphiprion ocellaris*	Clown anemonefish
	Aplysia cervina	Sea hare
	Gelagna succincta	Lesser girgled triton
	Watersipora subtorquata	Redrust bryozoan

[1] This species is native to some parts of the Caribbean, but it is not clear that its native range also includes the subregion.

DISCUSSION

We relied heavily on past patterns of non-native species introductions to the wider Caribbean region to identify transport vectors and non-indigenous marine species that could represent high risks to Barbados and the Organization of Eastern Caribbean States (OECS) countries in the future. Our retrospective relative risk analysis of vectors highlighted the importance of the aquarium trade, shipping (i.e., ballast water and biofouling), and fisheries (mainly aquaculture) in bringing exotic species into regional waters. Critically, it underscored a knowledge gap for a substantial number of introduced taxa (31 species out of 142) that could not be linked to any specific vector. Not surprisingly, findings from our forecasting relative risks of vectors to the subregion were similar to those of the retrospective regional analysis. However, the complete absence of canals and oil and gas rigs as future threats to the subregion was notable but should be interpreted with caution (also see Appendix VII). Using a semi-quantitative approach, we created watch lists of non-native species likely to enter the subregion. The majority of species had a medium risk of becoming invasive under current and future climatic conditions and were therefore placed on our orange watch list (Table 3). Four species presented a high risk of becoming invasive under current climate: (1) the Giant tiger prawn, *Penaeus monodon*, (2) the Ribbon sea lettuce, *Ulva reticulata*, (3) the Spotted scat, *Scatophagus argus*, and (4) the Atlantic sea nettle, *Chrysaora quinquecirrha*. These species were placed on our red watch list. Few species (13% of those examined) were added to our green list of taxa, which have a low probability of becoming invasive if introduced to the subregion.

The relative risks of marine transport vectors vary with geographic scale and location (e.g., Molnar et al. 2008). Globally, the most important vector in terms of number of marine exotic species introduced is shipping (i.e., ballast water and biofouling) (Molnar et al. 2008). Marine traffic was also recently identified as the main conveyor of non-indigenous species to the Galapagos Marine Reserve (Keith et al. 2016). In contrast, for most of the Pacific Northwest (i.e., Oregon, Washington, and British Columbia) aquaculture is the dominant vector while in the Levant Sea, canal construction poses the greatest threat (Molnar et al. 2008). We found that the aquarium trade has introduced the most species to the wider Caribbean region in the past (Fig. 4) and is predicted to be the dominant means by which non-native species enter the subregion in the future (Fig. 5). Indeed, the recent invasion of the western Atlantic and Caribbean by Indo-Pacific lionfish (*Pterois volitans* and *P. miles*), a product of aquarium releases, has drawn increased attention to this growing, multi-billion dollar global industry (Semmens et al. 2004; Côté & Smith 2018). It is important to note, however, that the threats from this vector stem almost exclusively from the importation of exotic marine fishes in Florida. Lack of data makes it difficult to determine the direct risks posed by this industry from countries within the subregion, but it is clear that without stricter regulations and/or education programs on invasive species in Florida, the aquarium trade is likely to remain the dominant source of non-native marine species in the region, and by extension, in the subregion.

Similar to some regional studies in the past (e.g., see Molnar et al. 2008), we found that shipping (i.e., ballast water and biofouling) poses the second greatest known risk to the subregion in the future (Fig. 5). With the global expansion of trade in goods and services and the subsequent recognition of this threat, the International Maritime Organization adopted the Ballast Water Management Convention (BWM) that came into force in 2017 and to which all nations in the subregion, except Dominica and St Vincent and the Grenadines, are signatories (https://treaties.un.org/Pages/showDetails.aspx?objid=080000028053b465). The BWM is a treaty that serves to prevent the spread of non-indigenous, aquatic organisms and pathogens through a ship's ballast water (www.imo.org). It is too early to evaluate the effectiveness of this new measure, but it may decrease the significance of this threat to the subregion in the long term.

Fisheries, inclusive of aquaculture, poses the third greatest threat to the subregion in the future. This pattern is consistent with past trends in the wider Caribbean region (Fig. 4). Fisheries can introduce non-native species into the subregion via the live seafood trade in which organisms are sometimes intentionally released into the environment while pathogens and other biological 'hitchhikers' can be introduced in the holding waters or other materials used during transport (Chapman et al. 2003; Minchin 2007). A more significant way in which fisheries acts as a transport vector, however, is via aquaculture. According to the United Nations Food and Agriculture Organization (FAO), aquaculture is the fastest growing food production sector (FAO 2016; but see Edwards et al. 2019). During aquaculture operations, non-native species may escape confinement in the ocean, or their larvae and nonindigenous live foods may be released in discharges. Primarily because of growing global interests in aquaculture, fisheries may become an increasingly important means by which exotic species are introduced into the subregion in the future.

There are some caveats to our method for forecasting relative risks of vectors in the subregion. First, it is not possible to predict vectors that currently do not exist, or the impacts of recent regulations, policies and/or developments on existing vectors. For example, neither canals nor oil and gas rigs are forecasted to be important means for introducing non-indigenous species to the subregion. However, a recent commentary warns of the increased likelihood of marine fish invasions through the Panama Canal due to expansions to the structure in 2016 that include construction of new, larger locks that permit the transit of large, NeoPanamax vessels (Castellanos-Galindo et al. 2020; but see Appendix VII). Likewise, the search for marine sources of fossil fuels in the Caribbean has increased in recent years, with the new deployment of oil rigs in Cuba and The Bahamas, and the rapidly increasing number of rigs in the nearby Guyana-Suriname Basin as cases in point (Beckman 2019; Vyawahare 2021; Whitfield 2021). These two vectors may therefore pose emerging threats to the region. Second, our method considers only the number of species introduced by a vector but does not account for the level of threat posed by different taxa. For instance, although the aquarium trade introduced the most non-native species into the region in the past and is predicted to be a major vector in the subregion in the future, only one of the four species (i.e., the Spotted scat, *Scatophagus argus*) assessed here as having a high likelihood of becoming invasive is ascribed to this vector. In contrast, two out of the four red watch list species (i.e., the Giant tiger prawn, *Penaeus monodon*, and the Ribbon sea lettuce, *Ulva reticulata*) are associated with both aquaculture and shipping. Third, our findings are sensitive to biases in data availability. For example, in general, it is easier to observe and subsequently report relatively large, charismatic fauna such as marine fishes often associated with the aquarium trade than it is to detect small, fouling organisms like bryozoans that are frequently introduced via biofouling on ship hulls. The finding that the aquarium trade poses a higher risk than biofouling to the region may therefore be influenced by data availability bias.

We created three watch lists in our study: red (high likelihood of becoming invasive), orange (medium likelihood of becoming invasive) and green (low likelihood of becoming invasive). Invasive species watch lists disaggregate otherwise long and unwieldy catalogues of non-native species into smaller groups based on invasion risk (e.g., Bayón & Vilà 2019). This process allows for managers to efficiently use limited resources by prioritizing groups most likely to cause harm. However, watch lists should be used with caution for at least two reasons. First, although a level of uncertainty is typically provided with an individual species risk assessment (e.g., Copp et al. 2016; Table 2), this uncertainty is currently not captured overall in watch lists. This omission could result in managers being overly confident in a list. Second, watch lists are meant to be dynamic, but they are not always treated this way. Watch lists need to be continuously updated as new data and/or technology become available. This dynamism requires an ongoing source of resources that is not always possible, particularly in small island states.

Various factors contributed to four non-native species being placed on our red watch list for species that are highly likely to become invasive if introduced to the subregion under current climate (Fig. 7). These species included: (1) the Giant tiger prawn, *Penaeus monodon*, (2) the Ribbon sea lettuce, *Ulva reticulata*, (3) the Spotted scat, *Scatophagus argus*, and (4) the Atlantic sea nettle, *Chrysaora quinquecirrha*. The AS-ISK scores species based on nine categories, with higher scores indicating a higher risk of becoming invasive: (1) undesirable traits, (2) tolerance attributes, (3) resource exploitation, (4) reproduction, (5) invasive elsewhere, (6) domestication or cultivation, (7) dispersal mechanisms, (8) climate change, and (9) climate and distribution. All red list species with the exception of the Ribbon sea lettuce scored roughly similarly among most categories (Fig. 7). However, the Ribbon sea lettuce had an exceptionally high score for being invasive elsewhere (Fig. 7). According to the World Register for Introduced Species, the Ribbon sea lettuce has been introduced to six countries, including the Caribbean Sea off the Venezuelan coast, which is in close proximity to the subregion. Unfortunately, the vector for this species is currently unascribed, but it is hypothesized that it can be introduced via ballast water (CABI Invasive Species Compendium 2021). The high-risk score under the AS-ISK 'invasive elsewhere' category is attributed to the fact that the Ribbon sea lettuce received a 'yes' response for all five questions in this category, which were related to whether a species had become naturalised outside of its native range and its adverse impacts on ecosystem services and social-economic systems.

Out of all red list species, the Ribbon sea lettuce has the largest, negative socio-economic impacts. This is because the Ribbon sea lettuce forms massive algal blooms or 'green tides' in high nutrient waters due to eutrophication from human caused factors such as untreated sewage (CABI Invasive Species Compendium 2021). These blooms have, in turn, negatively impacted tourism in many parts of the world where visitors expect sandy beaches and clear water. For example, in the Philippines, decreasing aesthetic value of beaches caused by green tide resulted in a decline in tourist arrivals in the early 2000s (CABI Invasive Species Compendium 2021). Likewise, a sailing event for the 29th Olympic Games held in Qingdao, China, was jeopardized by green tide, which occurred shortly before the competition. In this latter instance, it is reported that more than 10,000 people and 1,400 boats were needed to clean up the massive algal bloom covering 13,000 km^2 of ocean (CABI Invasive Species Compendium 2021). Tourism is a major industry in all countries in the subregion, making the socio-economic effects of this species particularly worrisome.

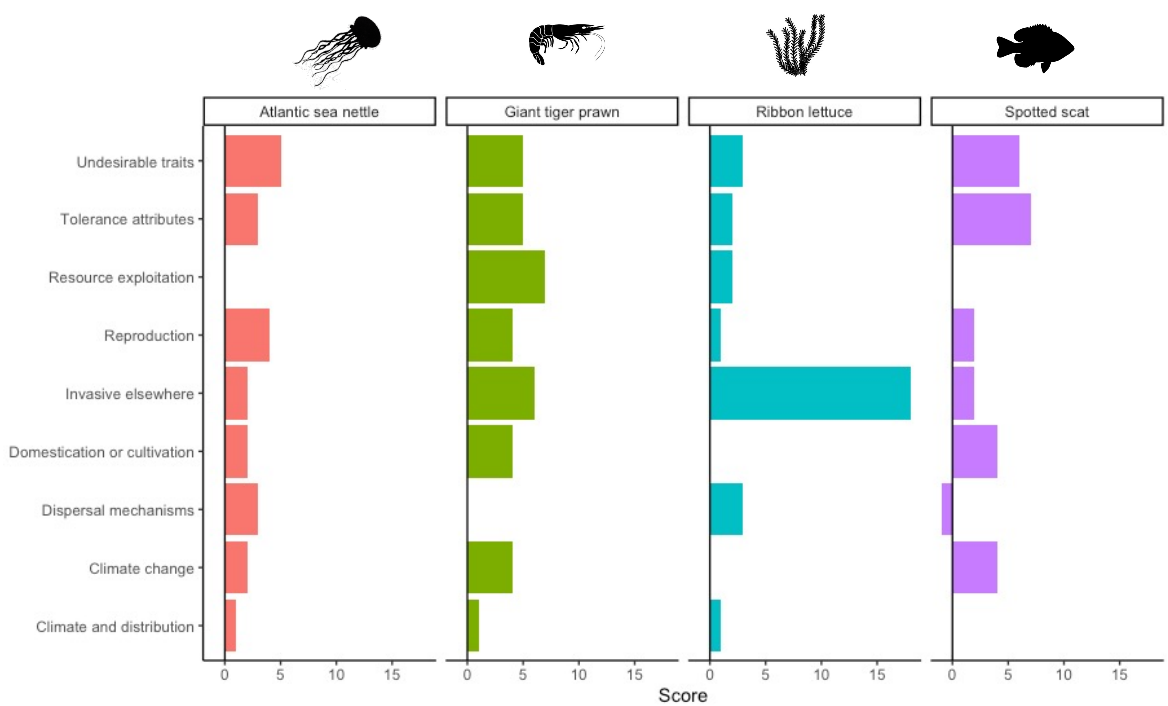

Fig. 7. AS-ISK score partitioning for red list species

MANAGEMENT RECOMMENDATIONS

Transport vectors

Three transport vectors emerged as the likely dominant means of non-native species introductions to the subregion in the future: the aquarium trade, shipping, and fisheries (including aquaculture). Each of these can be managed to limit the risk of marine introductions.

The size of the marine aquarium industry in the subregion is difficult to estimate, but fragmented live fish import statistics give an idea. In Barbados alone, more than 5,000 kg of live ornamental fishes are imported each year, although this statistic includes both marine and freshwater species (https://www.tilasto.com/en/country/barbados/handel/ornamental-fish-live-import-weight). Two key management actions have been proposed to reduce the overall risk of invasion via the aquarium trade (Chang et al. 2009, Walters et al. 2011, Azevedo-Santos et al. 2015). The first is to implement programs to increase awareness of invasive species among both sellers, especially in managerial positions, and hobbyists. Education initiatives targeting the former would increase the ability of store employees to advise the latter on the risks of their purchases and on options for responsible disposal of unwanted pets, and could complement general consumer education programs regarding invasive species. Education has been shown to encourage the adoption of risk-lowering behaviour in other consumer-based industries that can be vectors of introductions (e.g., horticulture, Burt et al. 2007). The second is improving labeling practices. Accurate identification of marine species for sale, as well as information on life-history and behavioural traits (maximum size, growth rate, aggressiveness, etc.), would inform consumers about the potential risks of their purchases and reduce the risk of release of unwanted pets into the wild.

A key management strategy to minimise the risk of shipping as a vector of marine introductions is the treatment of ballast water. As stated above, all nations in the subregion, with the exception of Dominica and St Vincent and the Grenadines, have already signed onto the Ballast Water Management Convention of the International Maritime Organization, which means that all ships registered under the flags of these nations must manage their ballast water so that aquatic organisms and pathogens are removed or rendered harmless before the ballast water is released into a new location (https://www.imo.org/). In addition, states that are parties to the Convention can, and should, expect ships registered under a flag that has not ratified the Convention, to comply with the requirements of the Convention. An essential tool to ensure the effectiveness of ballast management measures is regular checks of ship compliance (e.g., by sampling of ballast water) by port authorities.

Finally, mitigating the risk of introductions from aquaculture is difficult because many species translocated through this vector arrive as cryptic hitchhikers on the species targeted for farming. One strategy is to place aquaculture facilities far from shore, but this can result in economic costs if growth conditions are suboptimal and access to facilities becomes constrained. Distance from shore also does not always prevent spread to natural habitats. Instead, aquaculture as a vector of introduction should be managed by (1) careful placement of aquaculture facilities away from protected areas or otherwise ecologically valuable or vulnerable areas, and (2) strict controls and monitoring of aquaculture transfers and practices. The latter should include the use of risk assessments prior to transfers as well as quarantines. In addition, farm infrastructure should be maintained and cleaned, and measures taken to limit the dispersal of detached farm materials (e.g., rope and buoys).

High-risk species

The risk assessment performed here allowed a prioritisation of marine species already introduced to the Caribbean that can potentially become invasive in the subregion. The categorisation of species onto green, orange or red watch lists is preliminary and could change with more data. Nevertheless, on the basis of the information currently available, four species (the Giant tiger prawn, *Penaeus monodon*, the Ribbon sea lettuce, *Ulva reticulata*, the Spotted scat, *Scatophagus argus*, and the Atlantic sea nettle, *Chrysaora quinquecirrha*) present an elevated risk of becoming invasive in the subregion, and as such, deserve special attention.

These four species have, between them, been introduced by at least the three transport vectors discussed in the section above. Management of these vectors will help to delay, if not prevent, the arrival of these species into the subregion. However, to help their early detection, these species should also be the subject of agency-led formal surveillance as well as the target of general awareness campaigns to engage the public to recognise and report local occurrences (e.g., Larson et al. 2020, Epanchin-Niell et al. 2021). Early detection helps to increase the chance of eradication and/or minimise impact.

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Appendix I. Search results for regional species pool

Country	Common name	Species name	Country/Regional categorization	Phylum	Vectors	Primary information source
Anguilla	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Aruba	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Bahamas		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Bahamas		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Bahamas	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Bahamas		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Bahamas	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Barbados		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Barbados	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Barbados		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Bermuda		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Bermuda		*Bugula neritina*	Invasive	Bryozoa	fisheries; ships/ballast water; ships/fouling	Global invasive species database
Bermuda		*Caulerpa taxifolia*	Invasive	Chlorophyta	fisheries (boat anchors and fishing nets); ornamental trade	Global invasive species database

Bermuda		*Hypnea musciformis*	Invasive	Rhodophycota	unascribed	Global invasive species database
Bermuda	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Bermuda		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Bermuda		*Styela plicata*	Invasive	Chordata	ships/fouling; fisheries; ships/ballast water	Global invasive species database
Bermuda		*Trididemnum solidum*	Invasive	Chordata	unascribed	Global invasive species database
Bermuda		*Watersipora subtorquata*	Invasive	Bryozoa	ships/fouling	Global invasive species database
Cayman Islands	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Cayman Islands		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Cayman Islands		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Cayman Islands	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Cuba		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Cuba		*Gymnodinium catenatum*	Invasive	Pyrrophycophyta	ship/ballast water; aquaculture; fisheries	Global invasive species database
Cuba	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Cuba		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database

Cuba	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Dominica	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Dominican Republic	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Dominican Republic	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Dominican Republic		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Guadeloupe	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Haiti	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Haiti		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Jamaica		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Jamaica		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Jamaica	Asian green mussel	*Perna viridis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Global invasive species database
Jamaica	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Jamaica		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Jamaica	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database

Netherlands Antilles	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Netherlands Antilles		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Netherlands Antilles		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Netherlands Antilles	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Puerto Rico	Australian spotted jellyfish	*Phyllorhiza punctata*	Invasive	Cnidaria	ships/fouling; ships/ballast water; natural dispersal	Global invasive species database
Puerto Rico		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Puerto Rico		*Bugula neritina*	Invasive	Bryozoa	ships/fouling; ships; aquaculture accidental; ships/ballast water; fisheries/accidental	Global invasive species database
Puerto Rico		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Puerto Rico	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Puerto Rico	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
St. Lucia		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Trinidad and Tobago		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Trinidad and Tobago		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Trinidad and Tobago	Asian green mussel	*Perna viridis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Global invasive species database

Turks and Caicos Islands		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Turks and Caicos Islands		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Turks and Caicos Islands	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Turks and Caicos Islands	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
British Virgin Islands		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
British Virgin Islands		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
British Virgin Islands	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
US Virgin Islands	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
US Virgin Islands		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
US Virgin Islands		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
US Virgin Islands		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
US Virgin Islands	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Mexico	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Mexico	Wedge clam	*Rangia cuneata*	Invasive	Mollusca	unascribed	Global invasive species database

Mexico		*Gemma gemma*	Invasive	Mollusca	accidentally introduced along with Atlantic oyster	Global invasive species database
Mexico		*Kappaphycus spp.*	Invasive	Rhodophyta	aquaculture deliberate	Global invasive species database
Mexico		*Gymnodinium catenatum*	Invasive	Pyrrophycophyta	ship/ballast water; aquaculture; fisheries	Global invasive species database
Mexico		*Mytilopsis sallei*	Invasive	Mollusca	ship/fouling	Global invasive species database
Mexico		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Mexico		*Boonea bisuturalis*	Invasive	Mollusca	contaminated oyster stock	Global invasive species database
Mexico		*Bugula neritina*	Invasive	Bryozoa	ships/fouling; ships; aquaculture accidental; ships/ballast water; fisheries/accidental	Global invasive species database
Mexico		*Crepidula fornicata*	Invasive	Mollusca	unascribed	Global invasive species database
Mexico		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Mexico		*Mytilus galloprovincialis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Global invasive species database
Mexico	Brown mussel	*Perna perna*	Invasive	Mollusca	ship/ballast water	Global invasive species database
Mexico	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Mexico		*Watersipora subtorquata*	Invasive	Bryozoa	unascribed	Global invasive species database
Mexico		*Geukensia demissa*	Invasive	Mollusca	ship/ballast water; ships/fouling; legs of migratory birds	Global invasive species database
Belize		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Belize		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database

Belize	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Belize		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Belize	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Honduras	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Honduras	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Nicaragua	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Costa Rica	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Costa Rica		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Costa Rica	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Costa Rica		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Costa Rica		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Costa Rica		*Acanthaster planci*	Invasive	Echinodermata	unascribed	Global invasive species database

Panama		*Bugula neritina*	Invasive	Bryozoa	ships/fouling; ships; aquaculture accidental; ships/ballast water; fisheries/accidental	Global invasive species database
Panama		*Acanthaster planci*	Invasive	Echinodermata	unascribed	Global invasive species database
Panama		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Panama		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Panama	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Panama		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Panama	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Colombia		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Colombia		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Colombia	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Colombia	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Colombia		*Alitta succinea*	Invasive	Annelida	Unascribed	Global invasive species database
Venezuela		*Kappaphycus spp.*	Invasive	Rhodophyta	aquaculture deliberate	Global invasive species database
Venezuela	Brown mussel	*Perna perna*	Invasive	Mollusca	ship/ballast water	Global invasive species database
Venezuela		*Acanthophora spicifera*	Invasive	Rhodophyta	ships/fouling	Global invasive species database

Venezuela	Asian green mussel	*Perna viridis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Global invasive species database
Venezuela		*Geukensia demissa*	Invasive	Mollusca	ship/ballast water; ships/fouling; legs of migratory birds	Global invasive species database
Venezuela		*Gymnodinium catenatum*	Invasive	Pyrrophycophyta	ships/ballast water; aquaculture; fisheries	Global invasive species database
Venezuela		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Venezuela	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Global invasive species database
Venezuela	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Global invasive species database
Venezuela		*Watersipora subtorquata*	Invasive	Bryozoa	unascribed	Global invasive species database
Guyana		*Hypnea musciformis*	Invasive	Rhodophyta	ships/fouling	Global invasive species database
Florida USA	Australian spotted jellyfish	*Phyllorhiza punctata*	Exotic	Cnidaria	ships/fouling; ships/ballast water; natural dispersal	USGS Non-indigenous aquatic species database
Florida USA (but native to caribbean)	Bocourt swimming crab	*Callinectes bocourti*	Native transplant	Arthropoda	natural dispersal; ships/ballast water	USGS Non-indigenous aquatic species database
Florida USA	Indo-Pacific swimming crab	*Charybdis hellerii*	Exotic	Arthropoda	ships/ballast water; natural dispersal	USGS Non-indigenous aquatic species database
Florida USA	Asian tiger shrimp	*Penaeus monodon*	Exotic	Arthropoda	aquaculture; natural dispersal, ships/ballast water	USGS Non-indigenous aquatic species database
Florida USA	Climbing perch	*Anabas testudineus*	Exotic	Chordata	escape from aquarium fish farms	USGS Non-indigenous aquatic species database
Florida USA	Whitespotted surgeonfish	*Acanthurus guttatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database

Florida USA	Chocolate surgeonfish	*Acanthurus pyroferus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Red Sea surgeonfish	*Acanthurus sohal*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Orangespine unicornfish	*Naso lituratus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Palette surgeonfish	*Paracanthurus hepatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Sailfin tang	*Zebrasoma desjardinii*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Yellow tang	*Zebrasoma flavescens*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Brown Tang	*Zebrasoma scopas*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Sailfin tang	*Zebrasoma veliferum*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Yellowtail tang	*Zebrasoma xanthurum*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Clown triggerfish	*Balistoides conspicillum*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Lagoon Triggerfish	*Rhinecanthus aculeatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Bursa triggerfish	*Rhinecanthus verrucosus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA(native range is Lesser Antilles, Venezuela, Colombia and Brazil)	Tessellated Blenny	*Hypsoblennius invemar*	Unknown	Chordata	ships/fouling; ships/ballast; oil rigs	USGS Non-indigenous aquatic species database

Florida USA	Warthead Blenny	*Protemblemaria punctata*	Exotic	Chordata	hithiker on oil rigs	USGS Non-indigenous aquatic species database
Florida USA	Raccoon butterflyfish	*Chaetodon lunula*	Native transplant	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Pennant coralfish	*Heniochus acuminatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Pennant coralfish	*Heniochus diphreutes*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Red Sea bannerfish	*Heniochus intermedius*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Bannerfish	*Heniochus sp.*	Exotic	Chordata	unascribed	USGS Non-indigenous aquatic species database
Florida USA	Orbicular batfish	*Platax orbicularis*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA (but native to caribbean)	Fairy basslet	*Gramma loreto*	Exotic	Chordata	aquarium release; natural range expansion	USGS Non-indigenous aquatic species database
Florida USA	Brownbanded bambooshark	*Chiloscyllium punctatum*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	blue ringed angelfish	*Pomacanthus annularis*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Arabian angel	*Pomacanthus asfur*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	emperor angelfish	*Pomacanthus imperator*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	yellowbar angelfish	*Pomacanthus maculosus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	semicircle angelfish	*Pomacanthus semicirculatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	bluefaced angel	*Pomacanthus xanthometopon*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database

Florida USA	spiny chromis damselfish	*Acanthochromis polyacanthus*	Exotic	Chordata	unascribed	USGS Non-indigenous aquatic species database
Florida USA	clown anemonefish	*Amphiprion ocellaris*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	whitetail damselfish	*Dascyllus aruanus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	three spot damselfish	*Dascyllus trimaculatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Regal Demoiselle	*Neopomacentrus cyanomos*	Exotic	Chordata	hithiker on oil rigs; ship/ballast water	USGS Non-indigenous aquatic species database
Florida USA	scat	*Scatophagus argus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Red lionfish	*Pterois volitans*	Exotic	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	USGS Non-indigenous aquatic species database
Florida USA	peacock hind	*Cephalopholis argus*	Exotic	Chordata	intentionally stocked as food/sport in Hawaii; aquarium release in Florida	USGS Non-indigenous aquatic species database
Florida USA	panther grouper	*Chromileptes altivelis*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	blotched foxface	*Siganus unimaculatus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	masked pufferfish	*Arothron diadematus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	Moorish Idol	*Zanclus cornutus*	Exotic	Chordata	aquarium release	USGS Non-indigenous aquatic species database
Florida USA	veined rapa whelk	*Rapana venosa*	Exotic	Mollusca	ship/ballast; fisheries	USGS Non-indigenous aquatic species database
Bahamas	Brine shrimp	*Artemia cysts*	Invasive	Arthropoda	aquaculture	Kairo et al. 2003

Bahamas	Sea nettle	*Chrysoara quinquechirra*	Invasive	Cnidaria	unascribed	Kairo et al. 2003
Bahamas	American oyster	*Crassostrea virgnica*	Invasive	Mollusca	unascribed	Kairo et al. 2003
Curacao	Adam's dwarf triton	*Oenebra muricoides*	Invasive	Mollusca	unascribed	Kairo et al. 2003
Jamaica	Green mussel	*Perna viridis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Kairo et al. 2003
Trinidad	Green mussel	*Perna viridis*	Invasive	Mollusca	ship/ballast water; ship/fouling	Kairo et al. 2003
Curacao	Benthic colonial ascidian	*Trididemnum solidum*	Exotic	Chordata	unascribed	Kairo et al. 2003
Bonaire	Benthic colonial ascidian	*Trididemnum solidum*	Exotic	Chordata	unascribed	Kairo et al. 2003
Bahamas	Algae	*Nannochloropsis oculata*	Invasive	Ochrophyta	unascribed	Kairo et al. 2003
Bahamas	Blue crab	*Callinectes sapidus*	Invasive	Mollusca	unascribed	Kairo et al. 2003
Bahamas	Sea anemone	*Radianthus sp.*	Invasive	Cnidaria	unascribed	Kairo et al. 2003
Bahamas	Clown fish	*Amphiprion sp.*	Invasive	Chordata	aquarium release	Kairo et al. 2003
Bahamas	Dragonet	*Callionymus lyra*	Invasive	Chordata	unascribed	Kairo et al. 2003
Bahamas	Banded shark	*Chiloscyllium punctatum*	Invasive	Chordata	aquarium release	Kairo et al. 2003
Bahamas	Queenland grouper;	*Epinephelus lanceolatus*	Invasive	Chordata	unascribed	Kairo et al. 2003
Bahamas	Blue-girded angelfish	*Euxiphipops navarchu*	Invasive	Chordata	unascribed	Kairo et al. 2003
Bahamas	Yellow-faced angelfish	*Euxiphipops xanthometopon*	Invasive	Chordata	unascribed	Kairo et al. 2003
Bahamas	Bamboo shark	*Hemiscylliidae sp.*	Invasive	Chordata	unascribed	Kairo et al. 2003
Bahamas	Zebra bullhead shark	*Heterodontus zebra*	Invasive	Chordata	unascribed	Kairo et al. 2003
Aruba	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Debrot et al. 2011
Curacao	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases;	Debrot et al. 2011

					ornamental trade	
Bonaire	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal	Debrot et al. 2011
Bonaire	Cobia	*Rachycentron canadum*	Exotic	Chordata	aquaculture	Debrot et al. 2011
Curacao	Sea hares	*Aplysia cervina*	Cryptogenic	Mollusca	unascribed	Debrot et al. 2011
Netherlands Antilles	Sea hares	*Aplysia dactylomela*	Cryptogenic	Mollusca	unascribed	Debrot et al. 2011
Netherlands Antilles	Sea hares	*Aplysia parvula*	Cryptogenic	Mollusca	unascribed	Debrot et al. 2011
Bonaire	Giant clam	*Tridacna derasa*	Exotic	Mollusca	aquaculture	Debrot et al. 2011
Aruba	Ecuador white shrimp	*Peneaus vannamei*	Exotic	Arthropoda	aquaculture?	Debrot et al. 2011
Bonaire	Ecuador white shrimp	*Peneaus vannamei*	Exotic	Arthropoda	aquaculture?	Debrot et al. 2011
Curacao	Brown bryozoan	*Bugula neritina*	Exotic	Bryozoa	ships/fouling; ships; aquaculture accidental; ships/ballast water; fisheries/accidental	Debrot et al. 2011
Saba Bank	Brown alga	*Dictyota hamifera*	Cryptogenic	Ochrophyta	ship/ballast water	Debrot et al. 2011
Saba Bank	Green alga	*Caulerpa serrulata*	Cryptogenic	Chlorophyta	ship/ballast water	Debrot et al. 2011
St. Maarten	Guppy	*Poecilia reticulata*	Introduced	Chordata	aquarium release	Debrot et al. 2011
Curacao	Lesser grilled triton	*Gelagna succincta*	Introduced	Arthropoda	ship/ballast water	Debrot et al. 2011
Aruba	Whiteleg shrimp	*Litopenaeus vannamei*	Introduced	Mollusca	aquaculture	Debrot et al. 2011
Bonaire	Crustose coralline	*Ramicrusta sp.*	Cryptogenic	Rhodophyta	unascribed	Debrot et al. 2011
Curacao	NA	*Fycopomatus miamensis*	Cryptogenic	Annelida	ships/fouling	Debrot et al. 2011
Netherlands Antilles	NA	*Hydroides elegans*	Exotic	Annelida	ships	Debrot et al. 2011
Curacao	Slimy tubeworm	*Hydroides dianthus*	Cryptogenic	Annelida	ships/fouling	Debrot et al. 2011
Aruba	Didemnid colonial ascidian	*Trididemnum solidum*	NA	Chordata	unascribed	Debrot et al. 2011
Netherlands Antilles	Orange tube coral	*Tubastraea coccinea*	Exotic	Cnidaria	oil rigs	Debrot et al. 2011

Netherlands Antilles	Seafan disease	*Aspergillus syndowii*	Exotic	Ascomycota	terrestrial runoff	Debrot et al. 2011
St. Kitts	Red lionfish	*Pterois volitans*	Invasive	Chordata	natural dispersal; aquarium discards; individual releases; ornamental trade	Louis-Pierre Rich, personal communication
St. Kitts	Orange tube coral	*Tubastraea coccinea*	Invasive	Cnidaria	oil rigs	Louis-Pierre Rich, personal communication
St. Kitts	Brittle star	*Ophiothela mirabilis*	Exotic	Echinodermata	ships; natural dispersal	Rich et al. 2020
Caribbean Sea	Marine bristleworm	*Alitta succinea*	Introduced	Annelida	fisheries; aquaculture accidental	World Register of Introduced Marine Species
Caribbean Sea	Acorn barnacle	*Amphibalanus amphitrite*	Introduced	Arthropoda	ships/fouling	World Register of Introduced Marine Species
Trinidad and Tobago		*Amphibalanus reticulatus*	Introduced	Arthropoda	ships	World Register of Introduced Marine Species
Panama		*Amphibalanus reticulatus*	Introduced	Arthropoda	ships	World Register of Introduced Marine Species
Costa Rica		*Anadara transversa*	Introduced	Mollusca	ships/ballast water; aquaculture accidental	World Register of Introduced Marine Species
Jamaica		*Anadara transversa*	Introduced	Mollusca	ships/ballast water; aquaculture accidental	World Register of Introduced Marine Species
Panama		*Anomia peruviana*	Introduced	Mollusca	ships/fouling	World Register of Introduced Marine Species
Panama		*Arbopercula bengalensis*	Introduced	Bryozoa	canals/natural range expansion through canals	World Register of Introduced Marine Species
Puerto Rico		*Arbopercula bengalensis*	Introduced	Bryozoa	unascribed	World Register of Introduced Marine Species
Venezuela		*Arcuatula senhousia*	Introduced	Mollusca	fisheries accidental with deliberate translocations of fish or shellfish; ships	World Register of Introduced Marine Species

Colombia		*Arcuatula senhousia*	Introduced	Mollusca	fisheries accidental with deliberate translocations of fish or shellfish; ships	World Register of Introduced Marine Species
Caribbean Sea		*Ascidia sydneiensis*	Introduced	Chordata	ships/fouling	World Register of Introduced Marine Species
Caribbean Sea		*Asparagopsis taxiformis*	Introduced	Rhodophyta	ships; canals/natural range expansion	World Register of Introduced Marine Species
Caribbean Sea		*Balanus amphitrite; accepted as Amphibalanus amphitrite*	Introduced	Arthropoda	ships/fouling	World Register of Introduced Marine Species
Belize		*Botrylloides perspicuum; accepted as Botrylloides perspicuus*	Introduced	Chordata	ships/fouling	World Register of Introduced Marine Species
Caribbean Sea		*Bryopsis pennata*	Introduced	Chlorophyta	ships	World Register of Introduced Marine Species
Caribbean Sea		*Bugula neritina*	Introduced	Bryozoa	ships/fouling; ships; aquaculture accidental; ships/ballast water; fisheries/accidental	World Register of Introduced Marine Species
Caribbean Sea	European green crab	*Carcinus maenas*	Introduced	Arthropoda	natural dispersal on strong ocean currents associated with an unusually large El Nino; live-bait trade; ship/ballast water (less likely)	World Register of Introduced Marine Species
Caribbean Sea		*Carijoa riisei*	Introduced	Cnidaria	fouling; aquarium trade	World Register of Introduced Marine Species
Caribbean Sea		*Charybdis (Charybdis) hellerii*	Introduced	Arthropoda	ships/ballast water; canals/natural range expansion	World Register of Introduced Marine Species
Panama		*Cladonema pacificum*	Introduced	Cnidaria	aquaculture accidental	World Register of Introduced Marine Species

Puerto Rico	Medusae	*Clava multicornis*	Introduced	Cnidaria	aquaculture accidental; fisheries accidental; ships/ballast water	World Register of Introduced Marine Species
Caribbean Sea		*Cordylophora caspia*	Introduced	Cnidaria	ships; fisheries accidental; aquaculture accidental; ships/ballast water	World Register of Introduced Marine Species
Puerto Rico		*Diadumene leucolena*	Introduced	Cnidaria	ships/fouling; fisheries accidental; aquaculture accidental	World Register of Introduced Marine Species
Belize		*Didemnum psammatodes*	Introduced	Chordata	unascribed	World Register of Introduced Marine Species
Jamaica		*Didemnum psammatodes*	Introduced	Chordata	unascribed	World Register of Introduced Marine Species
Caribbean Sea		*Drymonema dalmatinum*	Introduced	Cnidaria	shipping; natural dispersal on ocean currents	World Register of Introduced Marine Species
Caribbean Sea		*Elasmopus pectenicrus*	Introduced	Arthropoda	canals/natural range expansion	World Register of Introduced Marine Species
Panama		*Eualetes tulipa*	Introduced	Mollusca	ships/ballast water; ships/fouling	World Register of Introduced Marine Species
Caribbean Sea		*Gammaropsis togoensis; accepted name Latigammaropsis togoensis*	Introduced	Arthropoda	ships	World Register of Introduced Marine Species
Caribbean Sea		*Garveia franciscana; accepted name Calyptospadix cerulea*	Introduced	Cnidaria	ships; ships/ballast water	World Register of Introduced Marine Species
Caribbean Sea		*Geukensia demissa*	Introduced	Mollusca	aquaculture accidental	World Register of Introduced Marine Species
Caribbean Sea		*Grateloupia filicina var. luxurians; accepted name Grateloupia filicina*	Introduced	Rhodophyta	unascribed	World Register of Introduced Marine Species

Colombia		*Griffithsia capitata*	Introduced	Rhodophyta	unascribed	World Register of Introduced Marine Species
Aruba		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Bonaire		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Curacao		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Dominica		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Grenada		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Guadeloupe		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
St. Maarten		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Puerto Rico		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
St. Lucia		*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species

St. Vincent and the Grenadines	*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
St. Eustatius	*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Venezuela	*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
British Virgin Islands	*Halophila stipulacea*	Introduced	Tracheophyta	canals/natural range expansion; ships; natural dispersal; fisheries	World Register of Introduced Marine Species
Belize	*Hippoporina indica*	Introduced	Bryozoa	unascribed	World Register of Introduced Marine Species
Panama	*Hippoporina indica*	Introduced	Bryozoa	unascribed	World Register of Introduced Marine Species
Caribbean Sea	*Hydroides dianthus*	Introduced	Annelida	ships; fisheries accidental	World Register of Introduced Marine Species
Caribbean Sea	*Hydroides dirampha*	Introduced	Annelida	ships	World Register of Introduced Marine Species
Caribbean Sea	*Hydroides elegans*	Introduced	Annelida	ships	World Register of Introduced Marine Species
Caribbean Sea	*Hypnea musciformis*	Introduced	Rhodophyta	ships/fouling	World Register of Introduced Marine Species
Panama	*Kappaphycus alvarezii*	Introduced	Rhodophyta	aquaculture deliberate	World Register of Introduced Marine Species
Caribbean Sea	*Monocorophium insidiosum*	Introduced	Arthropoda	ships/with solid ballast; fisheries accidental	World Register of Introduced Marine Species

Caribbean Sea		*Nannochloropsis oculata*	Introduced	Ochrophyta	aquaculture	World Register of Introduced Marine Species
Caribbean Sea		*Oreochromis mossambicus*	Introduced	Chordata	unascribed	World Register of Introduced Marine Species
Caribbean Sea		*Ostreopsis ovata*	Introduced	Myzozoa	ships	World Register of Introduced Marine Species
Caribbean Sea		*Pelamis platura; accepted as Hydrophis platurus*	Introduced	Chordata	unascribed	World Register of Introduced Marine Species
Colombia	Asian tiger shrimp	*Penaeus monodon*	Introduced	Arthropoda	ships/ballast water; natural dispersal; aquaculture; aquaculture accidental	World Register of Introduced Marine Species
Costa Rica	Asian tiger shrimp	*Penaeus monodon*	Introduced	Arthropoda	ships/ballast water; natural dispersal; aquaculture; aquaculture accidental	World Register of Introduced Marine Species
Caribbean Sea	Green mussel	*Perna viridis*	Introduced	Mollusca	ships/fouling; ships/ballast water; aquaculture accidental	World Register of Introduced Marine Species
Caribbean Sea		*Phallusia nigra*	Introduced	Chordata	ships; ships/fouling; canals natural range expansion	World Register of Introduced Marine Species
Caribbean Sea	Australian spotted jellyfish	*Phyllorhiza punctata*	Introduced	Cnidaria	ships/fouling; ships/ballast water; natural dispersal	World Register of Introduced Marine Species
Belize		*Procambarus clarkii*	Introduced	Arthropoda	aquaculture deliberate	World Register of Introduced Marine Species
Caribbean Sea		*Pterois miles*	Introduced	Chordata	canals/natural range expansion; individual deliberate release; aquarium discards	World Register of Introduced Marine Species
Colombia		*Scylla serrata*	Introduced	Arthropoda	accidental release by individuals	World Register of Introduced Marine Species

Panama		*Sinoflustra annae*	Introduced	Bryozoa	ships/fouling; ships/ballast; canals	World Register of Introduced Marine Species
Caribbean Sea		*Styela canopus*	Introduced	Chordata	ships/fouling	World Register of Introduced Marine Species
Caribbean Sea		*Styela plicata*	Introduced	Chordata	ships/fouling	World Register of Introduced Marine Species
Panama		*Symplegma brakenhielmi*	Introduced	Chordata	natural dispersal; ships/fouling; canal natural range expansion; aquaculture accidental	World Register of Introduced Marine Species
Caribbean Sea	Orange tube coral	*Tubastraea coccinea*	Introduced	Cnidaria	ships/fouling; natural dispersal; disposal by aquarists	World Register of Introduced Marine Species
Panama		*Turritopsis dohrnii*	Introduced	Cnidaria	unascribed	World Register of Introduced Marine Species
Venezuela		*Ulva reticulata*	Introduced	Chlorophyta	unascribed	World Register of Introduced Marine Species
Bahamas		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Costa Rica		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Dominican Republic		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Haiti		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Panama		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
St. Lucia		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
British Virgin Islands		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Bahamas		*Trididemnum solidum*	Invasive	Chordata	unascribed	Global invasive species database

Florida USA		*Trididemnum solidum*	Invasive	Chordata	unascribed	Global invasive species database
Venezuela		*Trididemnum solidum*	Invasive	Chordata	unascribed	Global invasive species database
Netherlands Antilles		*Trididemnum solidum*	Invasive	Chordata	unascribed	Global invasive species database
Mexico		*Watersipora subtorquata*	Invasive	Bryozoa	ships/fouling	Global invasive species database
Venezuela		*Watersipora subtorquata*	Invasive	Bryozoa	ships/fouling	Global invasive species database
Bonaire	Whiteleg shrimp	*Litopenaeus vannamei*	Introduced	Mollusca	aquaculture	Debrot et al. 2011
Belize		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Jamaica		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Panama		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Bermuda		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
El Salvador		*Sargassum fluitans*	Invasive	Phaeophycophyta	unascribed	Global invasive species database
Panama		*Arbopercula bengalensis*	Introduced	Bryozoa	canals: natural range expansion through canals	World Register of Introduced Marine Species
Puerto Rico		*Arbopercula bengalensis*	Introduced	Bryozoa	unascribed	World Register of Introduced Marine Species
Belize		*Hippoporina indica*	Introduced	Bryozoa	Unascribed	World Register of Introduced Marine Species
Panama		Sinoflustra annae	Introduced	Bryozoa	biofouling and ballast water through canal	World Register of Introduced Marine Species
Panama		*Hippoporina indica*	Introduced	Bryozoa	Unascribed	World Register of Introduced Marine Species

Appendix II. Subregional species pool

Species	Common Name	Phylum
Gelagna succincta	Lesser girgled triton	Arthropoda
Penaeus monodon	Giant tiger prawn	
Scylla serrata	Mud crab	
Watersipora subtorquata	Redrust bryozoan	Bryozoa
Ulva reticulata	Ribbon sea lettuce	Chlorophyta
Acanthurus guttatus	Whitespotted surgeonfish	Chordata
Acanthurus pyroferus	Chocolate surgeonfish	
Amphiprion ocellaris	Clown anemonefish	
Chaetodon lunula	Racoon butterflyfish	
Dascyllus aruanus	Whitetail damselfish	
Heterodontus zebra	Zebra bullhead shark	
Naso lituratus	Orangespine unicornfish	
Pomacanthus maculosus	Yellowbar angelfish	
Pomacanthus semicirculatus	Semicircle angelfish	
Protemblemaria punctata	Warthead blenny	
Rhinecanthus aculeatus	Lagoon triggerfish	
Scatophagus argus	Spotted scat	
Trididemnum solidum	Overgrowing mat tunicate	
Zebrasoma scopas	Twotone tange	
Zebrasoma veliferum	Sailfin tang	
Chrysaora quinquecirrha	Sea nettle	Cnidaria
Heteractis crispa	Leathery sea anemone	
Phyllorhiza punctata	Australian spotted jellyfish	
Ophiothela mirabilis	Brittle star	Echinodermata
Aplysia cervina	Sea hare	Mollusca
Arcuatula senhousia	Asian date mussel	
Crepidula fornicata	Slipper limpet	
Gemma gemma	Amethyst gem clam	
Litopenaeus vannamei	Whiteleg shrimp	
Perna perna	Brown mussel	
Acanthophora spicifera	Erect sea moss	Rhodophyta
Hypnea musciformis	Crozier weed	

Appendix III. Red watch list species fact sheets

ATLANTIC SEA NETTLE

Chrysaora quinquecirrha

Photo credit: Antoine Taveneaux

Invasive Species Profile

The Atlantic sea nettle is a species of jellyfish native to the Pacific, Atlantic, and Indian oceans, where it inhabits estuaries and coastal waters. This species is capable of tolerating a range of water salinities, and feeds on marine worms, plankton, and other species of jellyfish.

Introduced Range

The Atlantic sea nettle has been introduced to The Bahamas.

Life Cycle

The life cycle of the Atlantic sea nettle consists of several phases, and it starts with an immobile polyp stage that settles on hard substrate and reproduces asexually. The polyp then matures into a free-swimming larva called an ephyra, which eventually becomes a sexually-reproducing adult called a medusa. Spawning generally peaks in July and August, and fertilization of eggs can occur externally or internally in the gastrovascular cavity of the adult. Free-swimming larvae hatch from the eggs and grow into polyps, thus starting the cycle all over again.

Photo credit: Jarek Tuszyński, https://creativecommons.org/licenses/by-sa/3.0/deed.en

Description

On average, the Atlantic sea nettle measures 25cm wide and 50cm long, with adults being white in colour with red spots or stripes. The jellyfish's tentacles originate from 8 lobes located on its body and are lined with stinging structures called nematocysts.

Potential Impacts

The impacts of the Atlantic sea nettle in its introduced ranges are yet to be determined.

Photo credit: Jacob Drucker (licensed under http://creativecommons.org/licenses/by-nc/4.0/)

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GIANT TIGER PRAWN

Penaeus monodon

Photo credit: CSIRO

Invasive Species Profile

The giant tiger prawn is a marine crustacean native to the Indo-Pacific, including East Africa, South and Southeast Asia, and Australia. As larvae, they grow up in estuaries, lagoons, and mangroves before moving out to open waters as adults. They thrive in tropical climates with temperatures between 28-33°C, and feed on small invertebrates such as molluscs, gastropods, and crabs. When spawning, females can produce as many as 500,000 to 750,000 eggs.

Introduced Range

The giant tiger prawn has been introduced to the Atlantic Ocean along the southeastern coast of the United States and the west coast of Africa. Increased sightings and trawling catches of this species in these regions suggest that populations have become established.

Methods of Invasion

Accidental aquaculture releases and ballast water releases have allowed the giant tiger prawn to enter non-native regions.

Description

Giant tiger prawns are distinguished by their rust-coloured body with black and white banding along their back and tail.
They can reach up to approximately 30cm in length and weigh 320g, with females being larger than males.

Photo credit: Ranjith Chemmad

Commercial Significance

The giant tiger prawn plays a major role in the aquaculture industry, and research on breeding and raising these prawns for human consumption began in Taiwan in the early 1970's. In 1972, the first extensive farms were established for this species, and in 1974 semi-intensive farms were created. Since then, farming of the giant tiger prawn has spread through Southeast Asia, with some of the largest producers of this species being Taiwan, Thailand, Vietnam, Indonesia, and the Philippines.

Potential Impacts

The impacts that the giant tiger prawn may have in their introduced ranges is not yet fully understood. This species is known for being an aggressive predator in its native range and can reach a larger size than native crustaceans on the Atlantic coast of the United States, which suggests that it may outcompete native species for food resources. The giant tiger prawn is also known for carrying several harmful pathogens including White Spot Syndrome Virus, which can be transmitted to wild crustacean populations. In addition, this prawn can contract Acute Hepatopancreatic Necrosis Syndrome, which has had a large impact on farmed giant tiger prawn populations in southeast Asia.

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RIBBON SEA LETTUCE

Ulva reticulata

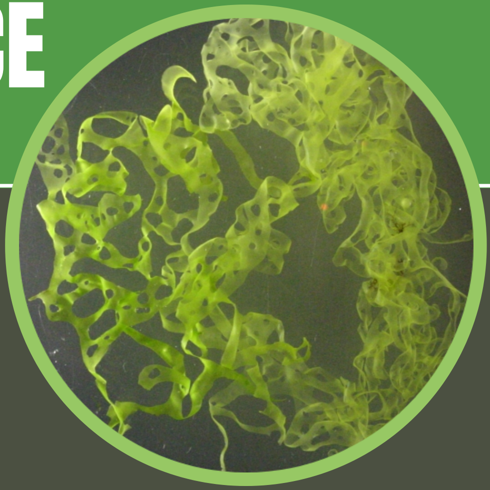

Photo credit: http://www2.bishopmuseum.org/algae/results3.asp?search=Ulva_reticula

Invasive Species Profile

The ribbon sea lettuce is a species of tropical green algae that is native to the Pacific and Western Indian oceans. Its distribution is largely dictated by water temperature, and it prefers to settle on hard substrate in shallow waters.

Introduced Range

This species is thought to have established itself off the coast of Venezuela, and has also been reported in Chile.

Methods of Invasion

Ribbon sea lettuce spores can hitch a ride on ship hulls or in ballast water, and can also be transported along with aquaculture stock or other algae species being used for commercial purposes.

Description

The ribbon sea lettuce has green, asymmetrical blades called thalli. This species is known to respond rapidly to increased nutrient levels, and will bloom and compete with other organisms on the ocean bottom for resources and space.

Life Cycle and Commercial Significance

The life cycle of the ribbon sea lettuce involves an alternation between forms of the organism with one or two sets of chromosomes. This begins with a spore-producing form called the sporophyte, which has two sets of chromosomes and releases spores with only one set. Each spore becomes a germling which later grows into a gamete-producing form called the gametophyte. The gametes will later fuse to form zygotes, which will grow into sporophytes again and restore the complete set of chromosomes.

The ribbon sea lettuce has been used in animal feed, biofuels, and in human consumption. This species of green algae is known for its high protein and high caloric content, and is used in Southeast Asian cuisine. It is also known for having certain medicinal properties, and could potentially be used in the production of pharmaceuticals.

Potential Impacts

When enough nutrients are present, blooms of the ribbon sea lettuce can occur which slow water flow and increase sedimentation rate, which causes a build-up of organic matter to settle. This increased organic material raises the activity of microbes which are involved in the decomposition process, which can deplete oxygen in the water to dangerous levels. Algal blooms can also impact tourism by making beaches less attractive to visitors.

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SPOTTED SCAT

Scatophagus argus

Photo credit: Jack Randall

Invasive Species Profile

The spotted scat is native to the coastal waters of the Indo-Pacific, including the southern tip of India, Indonesia, the Philippines, southern Japan, Tahiti, as well as the north coast of Australia. They inhabit estuaries and mangroves, and feed on a wide range of organisms such as insects, algae, worms, crustaceans, and organic matter. Female spotted scats reach a larger size than males at sexual maturity, and in the Philippines, spawning coincides with the heavy rains associated with the monsoon season.

Introduced Range

This fish species has established itself in the Maltese part of the Mediterranean Sea, and has also been reported in Cedar Key, Levy County as well as the St. Lucie inlet in Florida.

Methods of Invasion

The spotted scat has been introduced by aquarium releases, both accidental and deliberate.

Photo credit: Guérin Nicolas

Commerical Uses and Role in the Aquarium Trade

While the spotted scat is only of small commercial importance, it is a very popular aquarium fish and juveniles are taken from the wild for use in captivity. The spotted scat is valued in the aquarium trade for its attractive patterning, slow growth rate, hardiness, and good disposition. In addition, the spotted scat is sold in fish markets for human consumption in southeast Asia, and is known for being a nutrient-dense fish with good flavour.

Description

The spotted scat is a green and silver fish with brown spots, and has a rectangular body shape and a steep head profile. They can reach about 30cm in length from snout to tail, with some growing even larger. Juveniles are greenish-brown with large spots or stripes. This fish is also known for its venomous spines which can inflict painful wounds.

Potential Impacts

The impacts of the spotted scat in its introduced ranges are yet to be determined.

Photo credit: J. E. Randall

Draft by Amanda Gray

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Appendix III. Workshop summary

Three vector and invasive species risk assessment online training workshops, led by Dr. Nicola S. Smith, were held on the following dates via zoom:

1. June 8th, 2021
2. June 15th, 2021
3. June 22nd, 2021

Each workshop was approximately three hours long and consisted of a mixture of PowerPoint presentations, ice breakers, group activities, a homework exercise, and a hands-on demonstration in using invasive species risk assessment software. The overarching goals of the workshops were to familiarize participants with invasive species impacts, vectors, and management as well as to train participants to conduct invasive species risk assessments using a semi-quantitative approach (i.e., the Aquatic Species Invasiveness Screening Kit, AS-ISK).

Quite a diversity of professionals attended the workshops. The number of participants varied among workshop days but never exceeded 14 people on any given day, and included representatives from: (1) Antigua and Barbuda, (2) St. Kitts and Nevis, (3) The Bahamas, (4) Barbados, (5) St. Vincent and the Grenadines, and (6) Trinidad and Tobago. Members from a variety of organizations were present at the workshops including, members from national fisheries departments, customs and excise divisions, environmental awareness groups, ministries of environment, CAB International, and the ministry of agriculture and food security plant quarantine.

It is difficult to ascertain how effective the workshops were are meeting its goals because although 11 people answered the pre-workshop survey, only two individuals answered the post-workshop survey. Nevertheless, according to the pre-workshop survey, most people considered themselves to be moderately knowledgeable about marine invasive species and risk assessments. In contrast by the end of the workshops, participants stated that they now knew either “a lot” or “a great deal” about invasive species impacts, vectors, management, and risk assessments. Moreover, both respondents noted that they were “very confident” in using the AS-ISK decision support tool and were “likely” to use the AS-ISK tool in the future.

Appendix IV. Workshop flyer and agenda

Preventing the COST of Invasive Alien Species in Barbados and the OECS Countries

Vector & Species Risk Assessment Training for Marine Waters
. . . Because prevention is better than cure!

Workshop 1: 8th June 2021

Workshop 2: 15th June 2021

Workshop 3: 22nd June 2021

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Starting at 1PM (EST) on Zoom

Learn risk assessment techniques & tools

Workshop agenda

Workshop goals:
1. To foster an awareness of invasive species and the threats they pose
2. To develop a basic understanding of approaches to invasive species management
3. To become aware of the major transport vectors for non-native species in the region
4. To develop a basic understanding of invasive species risk assessment approaches
5. To become familiar with using the AS-ISK Decision Support Tool for invasive species risk assessments
6. To have a general understanding of project risk assessment process and results for the region

Workshop objectives:
1. To distinguish between native, naturalized, and non-native invasive species
2. To give an example of one of the threats posed by invasive species in the region
3. To appreciate that invasions are rare but detrimental when they do occur
4. To become familiar with the invasion process and how to manage non-native species at various stages of the process
5. To identify some of the major invasive species transport vectors in the region & be familiar with different ways to rank their risks
6. To identify the key elements of invasive species risk assessments and identify the various types (i.e., qualitative, semi-quantitative and quantitative)
7. To develop a basic proficiency in using the AS-ISK Decision Support Tool
8. To be able to give a broad overview of how the regional risk assessment was conducted and summarize its major findings

Workshop Agenda

Workshop 1 – Introduction to invasive species, their transport vectors and their management (2 hrs 15 mins total)
1. Participant introductions (15 mins)
2. Opening survey (10 mins)
3. Presentation on invasive species and the threats they pose (15 mins)
4. Break (5 mins)
5. Presentation on the invasion process & invasion management (10 mins)
6. Presentation on invasive species transport vectors (10 mins)
7. Break (5 mins)
8. Break out rooms – Rank invasive species transport vectors in the region by importance & state how you made your decisions (15 mins)
9. Group presentations on transport vector rankings (15 mins – 5 mins per group, 3 groups)
10. Break (5 mins)
11. Presentation revealing results from project vector risk analysis & group discussion of results (15 mins)
12. Group review of key concepts via a few multiple-choice questions (10 mins)
13. Closing questions (5 mins)

Workshop 2 – Introduction to invasive species risk assessments (2 hrs 45 mins total)

1. Ice breaker activity (15 mins)
2. Presentation giving an overview of the general principles of risk assessments & the different approaches (15 mins)
3. Break (5 mins)
4. Break out rooms – Determine how you would go about conducting an invasive species risk assessment for the region. Which approach would you use? How would you come up with a list of species to assess? (15 mins)
5. Group presentations on your approach to conducting an invasive species risk assessment for the region (15 mins - 5 mins per group, 3 groups)
6. Break (5 mins)
7. Presentation on the approach I used for conducting an invasive species risk assessment for the region and an overview on how to use the AS-ISK tool (15 mins)
8. Guided group exercise in using the AS-ISK tool (60 mins)
9. Break (5 mins)
10. Questions and explanation of homework assignment (15 mins)

Workshop 3 – Experiences using the AS-ISK Decision Support Tool (1 hr 50 mins total)
1. Ice breaker activity (15 mins)
2. Group 1 presentation on results from AS-ISK homework (10 mins)
3. Group 1 question-answer period (5 mins)
4. Break (5 mins)
5. Group 2 presentation on results from AS-ISK homework (10 mins)
6. Group 2 question-answer period (5 mins)
7. Group 3 presentation on results from AS-ISK homework (10 mins)
8. Group 3 question-answer period (5 mins)
9. Break (5 mins)
10. Presentation on my results from regional invasive species risk assessment (15 mins)
11. Group discussion of regional risk assessment and closing questions (15 mins)
12. Closing survey (10 mins)

Dates:
Workshop #1 – Tuesday 8th June 2021
Workshop #2 – Tuesday 15th June 2021
Workshop #3 – Tuesday 22nd June 2021

Appendix V. Pre-workshop survey questions

Preventing the COSTS of Invasive Alien Species (IAS) in Barbados and the OECS Countries

Marine Invasive Species Risk Assessment Training Pre-Workshop Survey

The aim of this brief survey is to gauge your current knowledge of marine invasive species and risk assessments. Another aim is to understand participant expectations of the workshop. This survey should take about 5 minutes to complete.

1. What is your job title?

2. What organization do you represent?

3. What country do you represent?

* 4. How knowledgeable do you consider yourself to be about marine invasive species?

This topic is brand new to me | I know enough to get by | Expert

5. How knowledgeable do you consider yourself to be about risk assessments?

This topic is brand new to me | I know enough to get by | Expert

1

6. Which statement best describes the current state of invasive species globally?

- ◯ The rate and magnitude of biological invasions are increasing
- ◯ The rate and magnitude of biological invasions are unchanged
- ◯ The rate and magnitude of biological invasions are decreasing

7. List a marine invasive species in the wider Caribbean other than Lionfish

[ ]

8. A "naturalized species" is another term to describe a native species

- ◯ True
- ◯ False
- ◯ Not sure

9. There are currently no international regulations to prevent the introduction of marine invasive species

- ◯ True
- ◯ False
- ◯ Not sure

10. An invasive species transport vector is the specific route between the source region and recipient environment for an invasive species.

- ◯ True
- ◯ False
- ◯ Not sure

11. How strongly do you agree or disagree with the following statement? "There is no association between the likelihood that a non-native species spreads widely and the severity of its ecological impacts."

Strongly Agree — Neither Agree or Disagree — Strongly Disagree [ ]

12. What is the typical accuracy rate of risk assessments at correctly identifying a species as invasive?

0% — 50% — 100% [ ]

13. What things need to be considered when selecting a risk assessment approach? Select all that apply.

- ☐ Available funding
- ☐ The question(s) being asked
- ☐ The technical training level of the analyst
- ☐ Data availability
- ☐ Time availability
- ☐ The level of perceived threats of the species being evaluated
- ☐ None of the above

14. A key benefit of quantitative risk assessments is that the models can be applied to different ecosystems and species that the assessment was not originally designed for?

- ○ True
- ○ False
- ○ Not sure

15. What are you hoping to gain from this workshop? Select all that apply.

- ☐ To become aware of invasive species and the threats they pose
- ☐ To become aware of the major transport vectors in the region
- ☐ To become aware of different management strategies for invasive species
- ☐ To be able to conduct a marine invasive species risk assessment
- ☐ To understand the process and results of the regional invasive species risk assessment
- ☐ Other (please specify)

Appendix VI. Post-workshop survey questions

Invasive Species Risk Assessment Post-Workshop Survey

The purpose of this survey is to gauge the success of the workshop. It should take about 15 minutes to complete.

1. How useful was the information provided during the presentations?
   - Extremely useful
   - Very useful
   - Somewhat useful
   - Not so useful
   - Not at all useful

2. How useful was the guided group exercise on using the AS-ISK?
   - Extremely useful
   - Very useful
   - Somewhat useful
   - Not so useful
   - Not at all useful

3. Did the workshop homework assignment increase your understanding of using the AS-ISK tool?
   - Yes
   - No

4. Did the workshop improve your understanding of invasive species impacts?
   - A great deal
   - A lot
   - A moderate amount
   - A little
   - None at all

5. Did the workshop increase your understanding of major transport vectors for invasive species in the subregion?
   - A great deal
   - A lot
   - A moderate amount
   - A little
   - None at all

1

6. Did the workshop increase your knowledge of different approaches to invasive species management?

- ◯ A great deal
- ◯ A lot
- ◯ A moderate amount
- ◯ A little
- ◯ None at all

7. How confident are you in using the AS-ISK tool?

- ◯ Extremely confident
- ◯ Very confident
- ◯ Somewhat confident
- ◯ Not so confident
- ◯ Not at all confident

8. How likely are you to use the AS-ISK tool in future?

- ◯ Very likely
- ◯ Likely
- ◯ Neither likely nor unlikely
- ◯ Unlikely
- ◯ Very unlikely

9. Did you have the opportunity to ask questions during the workshop?

- ◯ Yes
- ◯ No

10. Which aspect(s) of the workshop did you like? Select all that apply.

- ☐ Powerpoint presentations
- ☐ Group activities
- ☐ Guided group exercise in using the AS-ISK tool
- ☐ Icebreakers
- ☐ Homework assignment
- ☐ Other (please specify)

  ____

- ☐ None of the above

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11. Which aspect(s) of the workshop did you NOT like? Select all that apply.

- [ ] Powerpoint presentations
- [ ] Group activities
- [ ] Guided group exercise in using the AS-ISK tool
- [ ] Icebreakers
- [ ] Homework assignment
- [ ] Other (please specify)
- [ ] None of the above

12. How would you rate the workshop overall?

☆ ☆ ☆ ☆ ☆

13. How likely are you to recommend this workshop to colleagues?

- ○ Very likely
- ○ Likely
- ○ Neither likely nor unlikely
- ○ Unlikely
- ○ Very unlikely

14. Do you have any additional comments about the workshop?

15. Which statement best describes the current state of invasive species globally?

- ○ The rate and magnitude of biological invasions are increasing
- ○ The rate and magnitude of biological invasions are unchanged
- ○ The rate and magnitude of biological invasions are decreasing

16. List a marine invasive species in the wider Caribbean other than Lionfish

17. A "naturalized species" is another term to describe a native species

- ○ True
- ○ False
- ○ Not sure

3

18. There are currently no international regulations to prevent the introduction of marine invasive species

- True
- False
- Not sure

19. An invasive species transport vector is the specific route between the source region and recipient environment for an invasive species.

- True
- False
- Not sure

20. How strongly do you agree or disagree with the following statement? "There is no association between the likelihood that a non-native species spreads widely and the severity of its ecological impacts."

Strongly Agree | Neither Agree nor Disagree | Strongly Disagree

21. What is the typical accuracy rate of risk assessments at correctly identifying a species as invasive?

0 % | 50 % | 100 %

22. What things need to be considered when selecting a risk assessment approach? Select all that apply.

- Available funding
- The question(s) being asked
- The technical training level of the analyst
- Data availability
- Time availability
- The level of perceived threats of the species being evaluated
- None of the above

23. A key benefit of quantitative risk assessments is that the models can be applied to different ecosystems and species that the assessment was not originally designed for?

- True
- False
- Not sure

4

Appendix VII. Literature review: Risk assessment approaches & marine IAS transport vectors

Table of Contents

Summary

Invasive species are one of the leading causes of biodiversity loss worldwide and are major drivers of global change. Once established, it is difficult to impossible to eradicate most invasive species, particularly in marine systems. Hence, many environmental managers have focused on the prevention of invasions, which can be less costly and more effective. In these instances, risk assessments are used to predict which vectors are most likely to transport exotic species, or which introduced species are likely to become invasive. There are three main approaches to risk assessments (i.e., qualitative, semi-quantitative, and quantitative assessments), which can be used singularly or in a hierarchical fashion. However, the decision regarding which one, or all, of these approaches to use is often unclear because it depends on a variety of factors including: the questions being asked, data availability, time and funding considerations, and the technical training level of the analyst. In this review, we summarize the basic elements and underlying principles of risk assessments and compare the various approaches that are used to conduct one. We also provide examples of tools or protocols used in risk assessments along with a short list of studies that apply these approaches and tools specifically to marine invasive species risk assessments across the globe. A second aim of this report was to describe the various vectors used to transport nonindigenous species to new regions. We briefly discuss some of the most common sources of marine species introductions such as ballast water but also, we underscore some of the less common but emerging sources such as petroleum platforms and the rapidly growing mariculture industry. Finally, we conclude with a brief discussion of how climate change is likely to interact with the transport and introduction of invasive species, and how some risk assessment tools are being modified to accommodate these changes.

Introduction

Biological invasions are among the leading causes of biodiversity loss worldwide (Wilcove et al. 1998; Mckinney & Lockwood 1999; Sala et al. 2000; Bax et al. 2001). Some non-native species have caused considerable harm to local ecosystems (e.g., Shiganova 1998; Green et al. 2012), human health (e.g., Vetrano et al. 2002; Juliano & Lounibos 2005; Mazza et al. 2013), and national economies (Pimentel et al. 2000; 2005). Rising global trade and travel along with human alterations to land- and seascapes have accelerated the rate and magnitude of biological invasions (Cohen and Carlton 1998; Pimentel et al. 2000; Ricciardi & Atkinson 2004). Once established, it is difficult to impossible to eradicate most invasive species, particularly in marine systems (Molnar et al. 2008; Lockwood et al. 2013; Côté & Smith 2018). Hence, many environmental managers have focused on the prevention of invasions, which can be less costly and more effective (Bax et al. 2001; Leung & Dudgeon 2008; Lockwood et al, 2013). Despite the importance of invasion prevention, there are few, if any, comprehensive overviews of the different approaches, tools, and decisions involved in preventing the entry of invasive species to new areas, particularly those in marine environments. Identifying methods for assessing which species are likely to become invasive and which vectors are likely to introduce them to novel locations is paramount. This review aims to fill that gap. Specifically, we outline and compare the approaches used to predict which introduced species are likely to become invasive and provide examples of practical tools for conducting such assessments. We propose a decision tree to guide managers in determining the most appropriate approach. Additionally, we provide an overview of transport vectors that are most likely to be involved in the introduction of potentially invasive marine organisms. We conclude with a brief discussion of how climate change is likely to interact with the transport and introduction of invasive species, and how some risk assessment tools are being modified to accommodate these changes. This is not a systematic review. Our intent here is to select a few key papers from both the peer-reviewed and gray literature that we think best illustrate each point or demonstrate the practical applications of an approach or tool.

What is a risk assessment and what steps are involved in conducting one?

Risk assessments can be used to predict which vectors are most likely to transport exotic species or which introduced taxa are likely to become invasive. There are three aspects to risks: (1) the probability of an undesirable event occurring, (2) the consequences if the undesirable event occurs, and (3) uncertainty of outcome (Arthur 2008). The US National Research Council (2002) defines risk as the product of the likelihood of an event and its consequences. Risk analysis includes both risk assessment and risk management. Invasive species risk assessment is a component of risk analysis and involves evaluating the likelihood that an introduced species will become invasive (broadly defined here as a non-native species that arrives, establishes a self-sustaining population, and spreads widely in an area where it did not previously occur), and predicting the wide range of negative impacts that the species may have if this threat were realized (Richardson et al. 2000, 2007; Colautti et al. 2004; Molnar et al. 2008; Lockwood et al 2013; Arthur 2008).

Based on the US Environmental Protection Agency framework for ecological risk analysis (1992), there are three principal elements to invasive species risk assessments: (1) problem formulation, (2) analysis of exposure and effects, and (3) risk characterization (Andersen et al. 2004; Powell 2004; Stohlgren & Schnase 2006). *Problem formulation* involves specifying the scope of the risk assessment (Powell 2004; Stohlgren & Schnase 2006). This element entails identifying and describing known or potential invasive species, their source region, their relevant pathway(s) and/or vector(s), and the resources and/or values that are at risk (i.e., assessment end points) (Powell 2004). Making core values or assessment endpoints explicit in invasive species risk assessments is beneficial because it increases the transparency of decision making and helps to structure the numerous impacts that invasive species can have (Campbell 2010). However, the evaluation of multiple core values (i.e., ecological, economic, human health and social/cultural values) under one method is relatively new to invasive species risk assessments (Campbell 2010). In the past, these values have been assessed separately using tools such as environmental impact assessments (Thomas & Elliott 2005), economic valuation analyses (e.g., Pagiola 2004; Kalof & Satterfield 2005), and social impact assessments (e.g., Thomas & Elliott 2005; Campbell 2010). For example, Belgium (Branquart 2007), Germany/Austria (Essl et al. 2011) and Norway (Gederaas et al. 2007) evaluate only ecological impacts in their risk assessment protocol, while Australia (Bomford 2008) and the United States/Canada/Mexico (CEC 2009) incorporate a suite of values.

Analysis of exposure and effects typically follows problem formulation in a risk assessment. It includes: (1) the collection of information on species traits, (2) matching species traits to suitable climates and habitats, (3) determining propagule pressure (usually only possible for intentional introductions), (4) estimating the severity of environmental, human health, and/or socioeconomic impacts, (5) surveying the current distribution and abundance of potential invasive species, and (6) estimating the probability that a non-native species transits all stages of the invasion process, i.e., introduction, establishment and spread (Powell 2004; Stohlgren & Schnase 2006).

The final stage of risk assessment is *risk characterization*. This stage involves integrating and synthesizing the outcomes of problem formulation and analysis of exposure and effects to arrive at an overall conclusion of the risks, which includes ranking risks and takes into consideration all assumptions and uncertainties as well as the limitations of data sources (Powell 2004; Lockwood et al. 2013; Martone 2015). Sources of uncertainty in risk assessments include uncertainty of the process or methodology, uncertainty of the assessor (i.e., human error), and uncertainty about the organism (i.e., biological and environmental unknowns) (US Generic Non-indigenous Aquatic Organisms Risk Analysis Review Process, 1996; Verbrugge et al. 2010). During risk characterization, estimates of the potential distribution and abundance of non-indigenous species may also be presented along with estimates of their potential rate of spread (Stohlgren & Schnase 2006).

Principles of risk assessments

All risk assessments should ideally abide by an underlying set of principles. For some, this list is relatively short. The US National Research Council (2002), for instance, states three criteria. First, the assessment should be transparent, have undergone peer evaluation, and is accessible for further review. Second, the assessment should be logical, and incorporate independent factors that have been deemed important to the invasion process through critical observation and/or experimentation. Finally, the assessment should be reproducible: different analysts using the same risk assessment tool should come to the same conclusions (US National Research Council 2002). For others, this list is more extensive and includes applying concepts such as the 'precautionary principle' (Arthur 2008; Essl et al. 2011). Additional factors to consider may include whether the assessment is scalable to varying spatial scales, is easily updated, and is adaptable to data limitations (O 2015). However, few risk assessments abide by all principles for practical or legal reasons. For example, a zero-risk or 'precautionary approach' to the introduction of exotic diseases via trade in live organisms is not permitted under the Sanitary and Phytosanitary (SPS) agreement of the World Trade Organization (Peeler & Thrush 2004).

Challenges to invasive species risk assessments

It is important to note that few introduced species spread widely and become abundant, and even fewer have substantial, negative impacts in the invaded range (Williamson & Fitter 1996; Parker et al. 1999; Mack et al. 2000). Indeed, the above observation leads to the "base-rate effect" in which invasive species risk assessment tools with less than 100% accuracy decline in value as the frequency with which an introduced species becomes invasive declines (Keller et al. 2007). Furthermore, there is no correlation between the likelihood that a species spreads widely and the severity of its ecological impacts (Ricciardi & Cohen 2007). It is also difficult to predict if a non-indigenous species will adapt or evolve in new environments (Powell 2004). We lack basic natural history information for most species while traits that facilitate transition from one stage to another in the invasion process can also inhibit transitions at another stage (Kolar & Lodge 2001). All of the above present considerable challenges to risk assessments.

Nevertheless, invasive species risk assessment tools have been successful in two major ways. First, they can achieve remarkable accuracy. Some assessments have an accuracy rate of 90% or higher, including those that focused on fish in the Laurentian Great Lakes (Kolar & Lodge 2002), plants in Australia (Pheloung 1995), and plants in the USA (Reichard & Hamilton 1997). More typically, however, assessments predicting which species will successfully pass through all stages of the invasion process and have considerable, negative impacts have an accuracy ranging between 80% to 95% (Keller et al. 2007; e.g., Champion & Clayton 2000; Marchetti & Moyle 2004). Second, invasive species risk assessments can produce economic benefits despite relatively low base rates (see Keller et al. 2007).

Approaches to risk assessments

There are three different approaches to risk assessments, which may be undertaken singularly or in a hierarchical fashion: qualitative, semi-quantitative, and quantitative (O 2015; Holsman 2017; Table 1). A serial approach to risk assessments typically begins with a qualitative analysis that gradually progresses in quantitative complexity, thus allowing for prioritization of species selected for in-depth, quantitative assessments with high data demands (O 2015; Holsman 2017). When applying a hierarchical approach, risk scores (along with the sources and magnitude of uncertainty) are attached to each assessment, and typically only species identified as being a medium or high risk are selected for further evaluation (O 2015; Holsman 2017).The decision regarding which approach(es) to use will depend on the questions being asked, data availability, time and funding considerations, and the technical training level of the analyst (Campbell 2010; O 2015; Table 1 and Fig. 1).

Qualitative risk assessments

Qualitative risk assessments involve the rapid evaluation of qualitative data by experts and/or stakeholders who ultimately assign risk-ranking categories along with estimates of uncertainty (Mandrak & Cudmore 2004; Essl et al. 2011; O 2015; Holsman et al. 2017). Information sources include literature reviews and expert opinions solicited from surveys (e.g., Mandrak & Cudmore

2004; Therriault & Herborg 2008; Table 1). Typically, this assessment involves answering yes or no to a series of questions related to species traits and characteristics associated with the invasion process, and subsequently arriving at an assessment of the risk, ranging from high to medium to low, of the species transiting each stage of the invasion process (Lockwood et al. 2013; e.g., Mandrak & Cudmore 2004; Bomford et al. 2005; O 2015; Table 2). Experts also make qualitative judgements about the impacts of a species, which are ranked either as low, medium or high (Generic non-indigenous aquatic organisms risk analysis review process 1996; Lockwood et al. 2013; e.g., Mandrak & Cudmore 2004), or as “major”, “medium”, “minor” or “no known” effects (e.g., Sandvik et al. 2013). Each risk estimate is usually accompanied by a level of uncertainty specified by the expert reviewer, ranging from “very certain” (i.e., scientific basis), to “reasonably certain”, to “reasonably uncertain”, to “very uncertain” (i.e., best guess) (e.g., Mandrak & Cudmore 2004; Generic non-indigenous aquatic organisms risk analysis review process 1996). For example, in an invasive species risk assessment for Asian carps in Canada, the probability that the Grass carp, *Ctenopharyngodon idella*, would spread if it were to escape the area of introduction in the Great Lakes basin was assessed as “High, reasonably certain” (Mandrak & Cudmore 2004). A scientific justification along with references accompanies each ranking. Finally, the qualitative evaluation of the likelihood of an invasion is combined with the impact ranking of a potential invader to arrive at an overall categorical assessment of risk, where the highest level of uncertainty may be used (Lockwood et al. 2013). Expanding on the Grass carp invasion of the Great Lakes example, the probability of establishment was assessed as “High, reasonably certain” while the negative consequences of its establishment were assessed as “High, very certain”. The final estimate of risk was therefore assessed as “High, reasonably certain” (Mandrak & Cudmore 2004). Some protocols like the German-Austrian Black List

Information System (GABLIS) use a listing system instead of categorical ranks. The GABLIS assigns species to a Black ("negative impact confirmed, invasive"), White ("no negative impact, non-invasive") or Grey List ("impacts are uncertain") based on the severity of ecological impacts (Essl et al. 2011). The Black List is further separated into sub-lists based on species distribution and available eradication measures, while the Grey List is subdivided based on the certainty of the assessment (Essl et al. 2011). Table 2 presents examples of the application of a qualitative risk assessment for marine organisms.

Semi-quantitative risk assessments

Similar to qualitative assessments, semi-quantitative assessments involve answering yes or no to a series of questions related to species traits, characteristics, and impacts. The responses are then given a numerical value (Lockwood et al. 2013; e.g., Pheloung et al. 1999; Bomford et al. 2005; Sandvik et al. 2013; O 2015; Uyan et al. 2020). The values to each question are subsequently summed and the total is used to determine a recommendation or species rank based on predetermined thresholds (Pheloung et al. 1999; Lodge et al. 2016). For example, in the internationally recognized weed risk assessment tool used to screen potential plant invaders in Australia, recommendations include "accept the plant for importation", "further evaluate the plant" (e.g., obtain more data and re-run the model), or "reject the plant from entry into the country" (Pheloung et al. 1999). Importantly, one does not have to answer all questions - for example, if there are data limitations - to receive a recommendation. To generate an indicator of reliability, the recommendation is evaluated against the number of questions answered (Pheloung et al. 1999). Semi-quantitative assessment tools are calibrated using already-known invaders (e.g., Pheloung et al. 1999; Gordon et al. 2008). A popular, semi-quantitative risk assessment tool that is applicable to all aquatic plants and animals for any type of aquatic system (i.e., marine, brackish, or freshwater) is the Aquatic Species Invasiveness Screening Kit (AS-ISK), which is freely available at www.cefas.co.uk/nns/tools/ (Copp et al. 2016; Table 1).

Quantitative risk assessments

Quantitative risk assessments make use of machine learning and statistical techniques such as logistic regression and classification and regression trees (Lodge et al 2016; e.g., Kolar & Lodge 2002; Mandrake 1989; Keller et al. 2007). This approach is generally the most data intensive (in terms of model creation) and requires a reasonably high level of technical expertise by the analyst. The very nature of the approach lends itself to a high degree of transparency and reproducibility (Kolar 2004; Table 1). A variety of tools have been developed to screen quantitatively for invasive taxa using life history traits, species characteristics, aspects of invasion history, degree of association with humans, and environmental tolerances (e.g., Reichard & Hamilton 1997; Kolar & Lodge 2002; Daehler et al. 2004; D'Amen & Azzurro 2020; Table 1). For example, D'Amen and Azzurro (2020) assessed the susceptibility of 142 coastal Marine Protected Areas (MPAs) in the Mediterranean to invasion by Lessespsian fishes that had already invaded parts of the Mediterranean Sea. Specifically, they used ensemble modelling (i.e., generated several model predictions and then averaged them to obtain a final consensus) to predict suitable habitat within MPAs for the invaders in which environmental parameters for the models were calibrated using both the native and invaded ranges of the Lessespsian fishes (D'Amen & Azzurro 2020). They were then able to establish three invasion risk levels for Mediterranean MPAs under the assumption that more suitable habitat conditions make the MPA more vulnerable to invasion (D'Amen & Azzurro 2020). However, a key disadvantage to quantitative assessments like the one above is that models can only be used to make predictions for ecosystems or species in which the model was created (Kolar 2004). Moreover, as mentioned earlier, the accuracy of these models declines as the frequency of observing a successful invasion declines, i.e., the base-rate effect (Kolar 2004; Keller et al. 2007).

As a complement to statistical models, machine-learning algorithms can be used to generate maps of the potential geographic distribution of an invasive species. For instance, the General Algorithm for Rule-set Predictions (GARP) is used to predict species distributions from ecological and geographic data. Specifically, GARP combines species presence or absence data with environmental attributes such as precipitation and temperature (Kolar 2004). Through a series of iterations, GARP locates non-random associations between species presence or absence and ecological parameters. The resulting ecological niche model is then used to pinpoint areas where a non-indigenous species may become established or spread if it were introduced (e.g., Levine et al. 2004; Peterson et al. 2004).

Transport vectors for marine invasive species

In addition to determining whether or not a species is likely to become invasive, risk assessments can be used to evaluate the importance of a vector in transporting exotic species to new regions. This is useful as it is often easier to direct policy toward a specific industry than it is to protect against an unknown pool of potential invaders. The terms ‘transport vector’ and ‘pathway’ tend to be used interchangeably in the literature. However, there is a distinction between the two. While a transport vector is the means by which an organism is moved from one location to a new area, a transport pathway is the specific route between the source region and the recipient environment (Lockwood et al. 2013). Transport is the first phase in the invasion process, and considerable efforts have been directed to stymie the numbers of organisms entering new regions through various vectors like shipping and the aquarium trade. Below, we summarize some of the main transport vectors involved in marine invasions on a global scale. This list is not intended to be exhaustive but instead, gives an idea of the breadth of the problem.

Ballast water

Ballast water includes freshwater, brackish, or fully marine water, and is considered to be the single largest source of introduced aquatic species globally, responsible for the movement of thousands of species (Carlton and Geller 1993; Carlton 1999; Drake and Lodge 2004; Carlton 2011; Bailey 2015). Cruise and commercial ships, and naval vessels require ballast water to adjust buoyancy, provide stability, and enhance maneuverability in lieu of passengers, fuel, or cargo (Minchin et al. 2010). Marine organisms attach themselves to ship hulls, small pieces of floating wood, seaweed, seagrass, plastic, and other material, or float around in ballast water as plankton (Carlton and Geller 1993). Ballast water collected from one port is subsequently discharged at another port-of-call when the vessel takes on cargo or passengers, thus inadvertently transporting organisms ranging from viruses and bacterial pathogens to fishes and plants to novel locations (Carlton and Geller 1993). Ports with a large volume of ship traffic engaged in global commerce are both the most common sources and recipients of introduced species (Drake and Lodge 2004). Global hotspots for marine invasions via ballast water include large regions of Southeast Asia, northern Europe, and the Mediterranean Sea (Drake and Lodge 2004). One example of a marine invasive species that was introduced by ballast water is the comb jellyfish, *Mnemiopsis leidyi*. *Mnemiopsis leidyi* is a rapidly reproducing, self-fertilizing hermaphrodite that was introduced to the Black Sea in the early 1980s in the ballast water of ships from the northwestern Atlantic Ocean (Shiganova 1998). As a generalist predator of zooplankton, and fish eggs and larvae, *Mnemiopsis leidyi* is responsible for a dramatic decline in the abundance and species diversity of these prey groups (Shiganova 1998). Moreover, the population explosion of the comb jellyfish is linked with subsequent declines in the catch of planktivorous fishes that would, as adults, have consumed comb jellyfish prey (Shiganova 1998).

Recreational and commercial boating

All watercraft that lack ballast capabilities are classified as recreational or commercial boating (Canadian Action Plan to Address the Threat of Aquatic Invasive Species, 2004). This category includes powerboats, yachts, sailboats, floatplanes, research vessels, charter boats etc., and associated gear (e.g., trailers, fishing equipment). Marine organisms attach to the hull, motor, anchor, and other hard substrates affiliated with the watercraft, or enter the watercraft via bilge water, live wells, etc. Organisms are thus transferred from one area to another with the watercraft during in-water use or overland transportation (Canadian Action Plan to Address the Threat of Aquatic Invasive Species, 2004). Unlike shipping, which introduces non-native species into novel locations, the recreational/commercial watercraft pathway typically accelerates the spread of a non-indigenous species that is already present in the environment (i.e., secondary spread) (Bax et al. 2003). This is typically the case in freshwater systems (e.g., Johnson et al. 2001; Zanden & Olden 2008), but there are also instances involving marine environments (Bax et al. 2003; Darbyson et al. 2009). For example, although the invasive green alga, *Caulerpa taxifolia*, was likely introduced off the coast of Monaco via releases from public aquaria, its spread throughout the Mediterranean Sea was enhanced by cuttings that were transported on fishing nets, anchors and other gear (Meinsez et al. 2001).

Live bait

Recreational anglers either purchase or collect their own live bait. Typically, non-native fish, invertebrates, algae and other organisms are introduced into new environments through dumping the contents of bait buckets after fishing (Canadian Action Plan to Address the Threat of Aquatic Invasive Species, 2004; Michin et al. 2010; Keller et al. 2007). Live and dead bait can also become a vector for the introduction of non-native parasites and diseases when these organisms and pathogens are directly attached to the bait or are present in the carrying medium (Goodchild 2000; Michin et al. 2010; Haska et al. 2012). This vector for aquatic invasions is most prominent in freshwater systems. For example, the live bait industry is implicated in the introduction of 47 non-native freshwater species in the US Mid-Atlantic slope drainage alone, which is more than all other live trades combined (Kilian et al. 2012). However, live bait introductions are a concern for marine systems as well. Marine bait worm packaging, for instance, has been identified as a vector for invasive species into coastal ecosystems (Carlton 2001; Cohen et al. 2001; Haska et al. 2012). Bait worms are typically packaged in seaweed to reduce thermal stress and the threat of desiccation, but seaweed can also harbour and enable the survival of non-indigenous species (Haska et al. 2012). Some 13 species of macroalgae and 23 invertebrate species were associated with seaweed in bait boxes for the worm, *Nereis virens* (Haska et al. 2012).

Aquarium trade

Purchasing exotic marine organisms for public and private aquaria can result in the long-distance movement of vertebrates, invertebrates, plants and microbes over long distances where they can be intentionally or unintentionally released into the wild (Padilla and Williams 2004; Minchin et al. 2010). Indeed, the global aquarium trade is massive, generating $25 billion USD annually (Kay and Hoyle 2001). Because aquarium species are typically large and traded as adults, escapees have a high probability of surviving and establishing in the wild (Padilla and Williams 2004). Their likelihood of survival is also increased by the fact that aquarium species are placed under extreme artificial selection, with 75-85% of individuals dying during collection and transportation; the survivors are therefore typically robust individuals (Wabnitz et al. 2003). A number of recent marine introductions have been linked to the aquarium trade, most notably the Indo-Pacific lionfish, *Pterois volitans/miles*, invasion of the western Atlantic Ocean (Côté & Smith 2018). Likewise, the establishment of the invasive alga, *Caulerpa taxifolia*, in the Mediterranean Sea (Meinesz et al. 2001), southern California (Jousson et al. 2000), and Australia (Schaffelke et al. 2002) has been linked to releases from public aquaria.

Live seafood trade

Non-indigenous species can be introduced into a new area via the importation of live fish, shellfish and other marine organisms intended for sale and human consumption on the global market (Chapman et al. 2003). Non-native species may be intentionally released into the environment while pathogens and other biological 'hitchhikers' can be introduced in the shipping waters or materials used during transport. A notorious example is the European green crab, *Carcinus maenus*, which was likely introduced to the Pacific coast from the Atlantic coast of the

USA in the packaging of live foodfish (Canadian Action Plan to Address the Threat of Aquatic Invasive Species, 2004). Similarly, the virus *Bonamia ostreae* was introduced from Washington State, USA, to France in 1979 in shipments of the European oyster, *Ostrea edulis*. *Bonamia ostreae* subsequently destroyed stocks of native French oysters (Farley 1992).

Mariculture

Mariculture is the farming of fish, shellfish, and aquatic plants in the ocean. The rapid, global expansion of the mariculture industry, particularly in Asia, raises the risk of exotic species introductions through inadequate rules and regulations related to imported organisms (Naylor et al. 2001; Seo and Lee 2010). Non-native species may escape confinement in the ocean, or their larvae and nonindigenous live foods may be released in discharges (Michin 2007). The Japanese oyster, *Crassostrea gigas*, for example, is cultured in many countries, but is now established on almost all Northern Hemisphere coastlines (Shatkin et al. 1997). Mariculture species and their associated equipment can also be hosts to a variety of pests, parasites and diseases, all of which can escape into the wild and become associated with native species (Michin et al. 2010). For instance, numerous biota associated with mollusc mariculture have become invasive such as the Japanese oyster drill, *Ocinebrellus inornatus* (Shatkin et al. 1997), Asian eelgrass, *Zostera japonica*, (Thom 1990), and the Oyster thief, *Codium fragile* (Trowbridge 1999).

Canals

The creation of shipping canals permits the movement of species across otherwise natural, physical barriers. Non-indigenous species can migrate across entire biogeographic regions by passing through canals. For example, the Suez Canal is responsible for hundreds of introductions of Red Sea flora and fauna into the eastern Mediterranean, many of which have become invasive (Rilov & Galil 2009; Edelist et al. 2013). Species movement through the Suez Canal is largely unidirectional, likely due to currents which flow predominantly from the Red Sea into the Mediterranean and increasing water temperatures in the Mediterranean which may increase the likelihood of successful recruitment and propagation of tropical Red Sea species (Coll et al. 2010; Madkour et al. 2007). By contrast, the Panama Canal has resulted in far fewer marine invasions between the Pacific Ocean and Caribbean Sea because the majority of the canal is freshwater and water flows from the lake in the center of the canal out to both marine water bodies (Bunch et al. 2013). Of the few invasions that have occurred through the Panama Canal, the majority have been attributed to transport in ship ballast water, though some species have survived the passage on the outer hulls of ships (Ros et al. 2014).

Petroleum platforms

Oil and gas exploration and development in the ocean is becoming increasingly popular, and these platforms are among the largest artificial structures in the sea (Hamzah 2003). More than 7,500 offshore oil platforms exist globally (Parente et al. 2006; Pradella et al. 2013), while 3,600 oil and/or gas platforms presently exist in the Gulf of Mexico alone (Sammarco et al. 2004; Sammarco et al. 2010). Petroleum platforms provide hard, complex substrate that can serve as habitat to a wide range of reef fishes and benthic organisms in areas where available habitat is otherwise limiting (Ferreira et al. 2006; Atchison et al. 2008; Friedlander et al. 2014; Pradella et al. 2014). The practice of using tugboats to drag petroleum platforms across long, ocean distances from where they were originally constructed or stationed makes platforms a vector for marine invasive species. A recent example is the introduction of the Indo-West Pacific coral-reef damselfish, *Neopomacentrus cyanomos*, to the Southwest Gulf of Mexico (González-Gándara and De la Cruz-Francisco 2014; Ross Robertson et al. 2018). First reported in the Southwest Gulf of Mexico in 2013, *Neopomacentrus cyanomos* is now established on petroleum platforms and on natural and artificial reefs throughout the northern Gulf of Mexico (González-Gándara and De la Cruz-Francisco 2014; Schofield 2017). Although the cold waters off the southern tip of Africa likely prevent the survival of tropical fish from the Indian and Pacific Oceans to the Atlantic, it has been proposed that summer water temperatures and warmer waters during El Niño years are similar to the latitudinal range limits of fishes such as *Neopomacentrus cyanomos*, thus allowing the survival of some tropical species during transport (Ross Robertson et al. 2018).

The interaction between climate change and invasive species: What does this mean for non-native species transport vectors, introductions & risk assessments?

A changing climate is having numerous effects on global systems, including increased surface temperatures, ocean acidification, sea level rise, altered freshwater hydrological cycles, changes in ocean currents, and the intensification of storms (IPCC 2007). Another driver of global change is invasive species, which can lead to widescale biotic homogenization (Mckinney & Lockwood 1999) and the transformation of entire ecosystems (e.g., Vitousek et al. 1987; Vitousek et al. 1996; Strayer et al. 1999). What happens when these two forces come together? We are just beginning to understand some of the interactions between the many effects of climate change and invasive species, which are predicted to be pervasive and complex (Pyke et al. 2008; Lockwood et al. 2013).

One clear effect of climate change is that it will alter human transport and settlement patterns, which will subsequently affect the types of species that are transported across the planet, their propagule pressure (i.e., the quantity, quality and frequency of introduced species), as well as the location of transport vectors and associated pathways (Hellmann et al. 2008; Pyke et al. 2008; Lockwood et al. 2013). These changes will be most marked in polar regions such as the Arctic, where increasingly long, ice-free periods in the summer is providing alternative, shorter transport routes for commercial vessels, with associated increases in biotic introductions (Chan et al. 2019). Likewise, in Antarctica, recent increases in exploitation, research, and tourist activities in the area in concert with warming temperatures has resulted in a rise in species introductions (e.g., Avila et al. 2020; Chwedorzewska et al. 2020).

Climate change is also altering the abundance and distribution of both native and invasive species, whose ranges are contracting or expanding as they track changing environmental conditions. For example, we are witnessing the gradual northward expansion of Caribbean, marine tropical species and the southward expansion of Australian, marine tropical species into temperate areas (Canning-Clode et al. 2011; Booth et al. 2011). Of particular concern is the climate-change induced range expansion of invasive species known to negatively affect human health. The globally invasive Asian tiger mosquito (*Aedes albopictus*), for instance, is a vector for many viruses such as chikungunya, dengue and West Nile, and is predicted to expand its invaded range in the northeastern USA by 43% to 49% by the end of the century due to rising winter temperatures (Rochlin et al. 2013).

These novel interactions between climate change and invasive species are now being considered in some invasive species risk assessments (e.g., Mandrake 1989; Reimer et al. 2017; D'Amen & Azzurro 2020, Uyan et al. 2020). For example, using the Aquatic Species Invasiveness Screening Kit (AS-ISK) to identify potentially invasive marine fishes in South Korea, Uyan and colleagues (2020) conducted a semi-quantitative risk assessment, which resulted in a Basic Risk Assessment (BRA) score for each species. They then answered an additional six Climate Change Assessment (CCA) questions per species presented in the AS-ISK. These latter questions required the analyst to evaluate how future climatic conditions would affect a species' BRA score with regard to the risks associated with the various stages of the invasion process (i.e., introduction, establishment, spread and impact). The final score (i.e., the summation of the BRA score and the CCA score) is then compared against threshold values to determine the risk ranking of a species under a climate change scenario (Uyan et al. 2020).

Table 1. A comparison of the requirements and strengths of various approaches to risk assessments.

	Qualitative	*Semi-quantitative*	*Quantitative*
Cost	$	$$	$$$
Data needs	Low-Medium	Medium-High	High
Technical expertise	Low	Medium-High	High
Data type	Expert opinion; Literature review	Expert opinion; Experimental and/or observational	Experimental and/or observational
Accuracy	Low-Medium	Medium	High
Reproducibility	Low-Medium	Low-Medium	High
Strengths	Rapid; effective when data and technical expertise are low	Complex modeling capabilities when quantitative data are scarce	Accurate and highly reproducible models
[1]**Example tools or protocols**	ERAF (Level I) ERAEF (Level I) IEA (Level I) CARE GABLIS	AS-ISK; ERAF (Level II); ERAEF (Level II); IEA (Level II); BBN; QNM; FCM	EwE; Atlantis; Marxan; PVA; GARP

[1]ERAF: Ecological Risk Assessment Framework is a framework developed by scientists at the Department of Fisheries and Oceans Canada that uses categories of exposure and sensitivity to assess risk (O et al. 2015). Level I consists of a rapid qualitative assessment relying solely on expert opinion and literature review while Level II incorporates more spatial or organismal data.

ERAEF: Ecological Risk Assessment for the Effects of Fishing is a framework developed by Hobday and colleagues (2011) at the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) to assess risk to Australian fisheries. Level I is a rapid qualitative assessment based on expert opinion and literature review to score the likelihood of exposure and magnitude of effect of stressors on fisheries. Level II is a semi-quantitative productivity susceptibility analysis that incorporates more data on fish population and fishery productivity and on susceptibility to a given fishing method.

IEA: Integrated Ecosystem Assessment is a framework developed by Holsman and colleagues (2017) at the U.S. National Oceanic and Atmospheric Administration. This approach divides assessments into a matrix of levels, including rapid qualitative assessments using expert opinion (Level I), semi-quantitative vulnerability analyses using expert opinion and observational or experimental data (Level II), and fully quantitative methods (Level III), and classes, including one stressor-one organism (Class I), one stressor-multiple organisms (Class II), and multiple stressors-multiple organisms (Class III).

CARE: Comprehensive Assessment of Risk to Ecosystems was developed by Battista and colleagues (2017) with the Environmental Defense Fund. It modifies ERAEF and ERAF to include synergistic or antagonistic interactions among stressors based on expert opinion.

GABLIS: The German-Austrian Black List Information System is used in invasive species risk assessments and assigns non-native species to a Black ("negative impact confirmed, invasive"), White ("no negative impact, non invasive") or Grey List (impacts are uncertain) based on the severity of ecological impacts (Essl et al. 2011). The Black List is further separated into sub-lists based on species distribution and available eradication measures while the Grey List is subdivided based on the certainty of the assessment.

AS-ISK: The Aquatic Species Invasiveness Screening Kit is used in semi-quantitative, invasive species risk assessments and assesses the likelihood of any aquatic plant or animal becoming invasive and having strong, negative impacts. It is freely available at www.cefas.co.uk/nns/tools/ (Copp et al. 2016).

BBN: Bayesian Belief Networks are a semi-quantitative modeling approach in which experts construct conditional probability tables to parameterize pathways in causal networks (directed acyclic graphs) (see Ban et al. 2014).

QNM; Qualitative Network Models are causal networks that can include feed-back loops. Pathways are parameterized using the directionality of effect (positive, neutral, negative) (see Reum et al. 2015).

FCM: Fuzzy Cognitive Maps are based on causal networks that can include feed-back loops. Like QLN, pathways are parameterized using the directionality of effect weighted by the relative magnitude of the strength of the interaction (see Baker et al. 2018).

EwE: Ecopath with Ecosim is an open source quantitative food web modelling tool used most commonly for ecosystem-based management of fisheries, including invasive species (Christensen et al. 2005; e.g., Arias-González et al. 2011). Available at www.ecopath.org

Atlantis: Atlantis is a quantitative biophysical modelling tool for use in marine ecosystem-based fisheries management within an adaptive management framework (Fulton et al. 2004; e.g., Nyamweya et al. 2016). Available at research.csiro.au/atlantis

Marxan: Marxan is a suite of quantitative models used for spatial planning to maximize biodiversity protection given limited resources (Ball et al. 2009; e.g., Januchowski-Hartley et al. 2011). Available at http://marxan.org/

PVA: Population Viability Analysis is a statistical approach that uses demographic information to model extinction risk of a given species. It can also be used in invasive species risk assessments (see Andersen 2005).

GARP: The General Algorithm for Rule-set Predictions uses machine learning to predict invasive species distributions from ecological and geographic data (Kolar 2004).

Table 2. Examples of the application of different approaches to marine invasive species risk assessments.

Approach	Taxa	Region	Method or tool	Reference
Qualitative	*Ciona intestinalis* (vase tunicate)	Canada	Literature review & expert survey	Therriault & Herborg 2008
	Marine species in ballast water	Europe	Expert workshop	Gollasch and Leppäkoski 2007
Semi-Quantitative	*Littorina littorea* (Periwinkle), *Mya arenaria* (Soft shell clam), *Paralithodes camtschaticus* (Red king crab)	Canadian Arctic	Combination of techniques	Goldsmith et al. 2019
	Marine fishes	South Korea	AS-ISK	Uyan et al. 2020
	Marine fishes	Turkey	AS-ISK	Bilge et al. 2019
	Marine species	Bering Sea	Developed a new tool	Reimer et al. 2017
Quantitative	*Carcinus maenas* (European Green crab)	Washington, USA	A modified Relative Risk Model	Colnar & Landis 2007

	Pterois volitans/miles (Indo-Pacific lionfish)	Caribbean	Ecopath with Ecosim	Arias-Gonzlez et al. 2011
	Marine fishes	Mediteranean	Ensemble models	D’Amen & Azzurro 2020

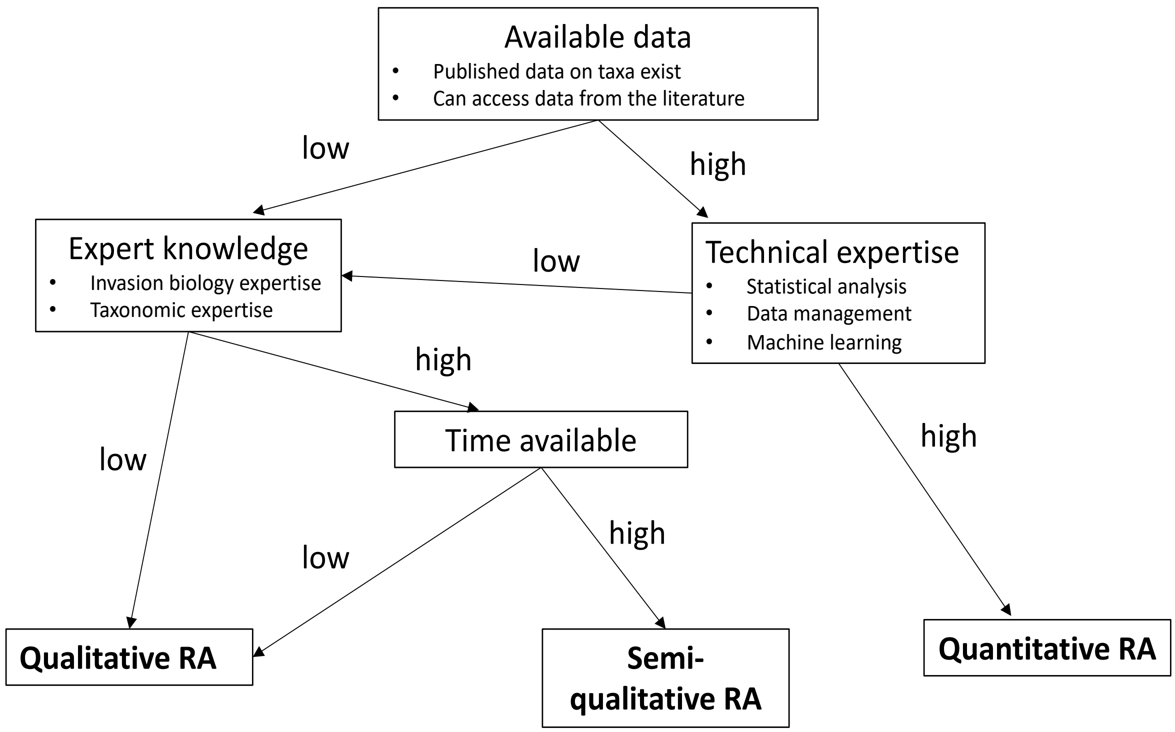

Figure 1. A decision tree to guide managers in determining the most appropriate approach to predict which species are likely to become invasive. RA: risk assessment.

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