

# Hull fouling marine invasive species pose a very low, but plausible, risk of introduction to East Antarctica in climate change scenarios

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## Abstract

**Aims:** To identify potential hull fouling marine invasive species that could survive in East Antarctica presently and in the future.

**Location:** Australia's Antarctic continental stations: Davis, Mawson and Casey, East Antarctica; and subantarctic islands: Macquarie Island and Heard and McDonald Islands.

**Methods:** Our study uses a novel machine-learning algorithm to predict which currently known hull fouling MIS could survive in shallow benthic ecosystems adjacent to Australian Antarctic research stations and subantarctic islands, where ship traffic is present. We used gradient boosted machine learning (XGBoost) with four important environmental variables (sea surface temperature, salinity, nitrate and pH) to develop models of suitable environments for each potentially invasive species. We then used these models to determine if any of Australia's three Antarctic research stations and two subantarctic islands could be environmentally suitable for MIS now and under two future climate scenarios.

**Results:** Most of the species were predicted to be unable to survive at any location between now and the end of this century; however, four species were identified as potential current threats and five as threats under future climate change. *Asterias amurensis* was identified as a potential threat to all locations.

**Main conclusions:** This study suggests that the risks are very low, but plausible, that known hull fouling species could survive in the shallow benthic habitats near Australia's East Antarctica locations and suggest a precautionary approach is needed by way of surveillance and monitoring in this region, particularly if propagule pressure increases. While some species could survive as adults in the region, their ability to reach these locations and undergo successful reproduction is considered unlikely based on current knowledge.

## KEYWORDS

climate change, East Antarctica, gradient boosting, hull fouling, invasion biology, machine learning, Northern Pacific sea star, ports, subantarctic, XGBoost

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## 1 | INTRODUCTION

Ports worldwide are recognized as ecologically disturbed areas; most are heavily polluted, have undergone significant habitat modification and are repositories of marine invasive species (MIS). Many MIS have established populations in regions well beyond their original distributions and are now found in all oceans except the Southern Ocean (McCarthy et al., 2019; Ruiz et al., 1997). This region has thus far been protected from this threat by environmental barriers, such as extreme cold temperatures and other harsh environmental conditions, the physical barrier created by the Antarctic Circumpolar Current and its associated polar fronts, and the deep oceans around Antarctica (Aronson et al., 2009, 2011; Barnes et al., 2006). The Antarctic region also receives far less shipping traffic than other regions of the world, thereby limiting the propagule pressure exerted in this region (McCarthy et al., 2019). However, as the world's climate changes and human presence increases in the region, these barriers to invasion are breaking down or being bypassed (Cheung et al., 2009; Duffy et al., 2017).

Most Antarctic marine regions are experiencing gradual warming (Ducklow et al., 2007; Meredith & King, 2005). Coupled with changes in temperature are other environmental changes, such as a lowering of salinity; increased acidification; changes in productivity; and changes in the timing, extent and thickness of sea ice (Stark et al., 2019). There is limited understanding of how these changes could influence the ability of MIS to survive and establish in the Southern Ocean (though, see Aronson et al., 2009). While the threat of MIS in Arctic regions has been investigated (Ware et al., 2014), there has been a paucity of such research in the Antarctic, particularly in the East Antarctic and subantarctic regions (however, see Byrne et al., 2016; Lee & Chown, 2009; Lewis et al., 2005).

Antarctica is extremely remote in a global context. Non-anthropogenically assisted introductions of MIS are consequently limited to infrequent occurrences (Lewis et al., 2005); however, recent molecular work has shown that drifting species are able to cross the various oceanic fronts of the region to reach the continent (Fraser et al., 2018) and that non-native kelp rafts have carried invasive species as passengers to an West Antarctic island (Avila et al., 2020). Shallow coastal marine ecosystems along the Antarctic continental shelf are relatively uncommon, fragmented and separated by long distances (Clark et al., 2015). Corresponding ice-free coastal areas (within 5 km of the coast) are also rare, comprising approximately 0.06% of the continent (Brooks et al., 2019). This means there is limited habitat available for the establishment of shallow water MIS around the continent; nevertheless, the suitable habitat coincides with the locations of Antarctic research stations and their associated presence of ships (Stark et al., 2019). These small areas of habitat still have intrinsic biodiversity values as they support many endemic and novel species (Stark et al., 2019).

The presence of MIS in a novel ecosystem does not necessarily infer that an invasion has occurred, which is when a population becomes established and persistent (Arthur et al., 2015). Although no established populations of MIS have been found in the Antarctic region, five species of decapod MIS have been found free-living in the

Antarctic marine environment: *Emerita* sp.; *Hyas araneus*; *Rochinia gracilipes*; *Halicarcinus planatus*; and *Pinnotheres* sp. (Aronson et al., 2015; McCarthy et al., 2019; Tavares & De Melo, 2004; Thatje & Fuentes, 2003). Further, a settlement of the mussel *M. cf. platensis* was discovered in the shallow subtidal region of the South Shetland Islands; however, subsequent surveys indicate that this species no longer persists in the region (Cárdenas et al., 2020). Whether the presence of these species represents recent incursions or persistent populations is under debate, due mainly to the poor fossil record of the group and a lack of comprehensive biodiversity surveys in this region (Griffiths et al., 2013). While terrestrial invasions in the subantarctic region are relatively well documented and researched (Chown et al., 2012; Frenot et al., 2005; Shaw et al., 2010), the Antarctic region, and particularly the marine realm, has remained understudied to date (however, see Hughes et al., 2020). A better understanding of the present day and future threat of MIS that could affect this region is required (Hughes & Pertierra, 2016; McCarthy et al., 2019).

The international shipping network has been identified as the key driver of MIS transfer globally (Clarke et al., 2017; Molnar et al., 2008) with ports around the globe having established populations of MIS (Keller et al., 2011). Historically ship ballast had been the greatest contributor to ship-based MIS transfer, but this risk has declined with modern conventions and policies (Drake & Lodge, 2007). Hull fouling has received less attention as a source of MIS transfer, even though it likely poses a similar risk, if not greater, than ballast water (Drake & Lodge, 2007). Ships that travel to the Antarctic continent often have periods of passage through sea ice which acts as a natural hull cleaner, removing most attached fouling (Hughes & Ashton, 2017; Lee & Chown, 2009; Lewis et al., 2004). However, there are several protected niche areas in ships, such as sea-chests (a rectangular or cylindrical recess in the hull of a ship), which are not subject to sea ice scour and represent a potential pathway for MIS introductions to occur (Chan et al., 2015; Hughes & Ashton, 2017; Lee & Chown, 2007). Further, climate change is expected to alter sea ice distribution which could reduce the efficacy of ice scour to remove fouling from ship (Hughes & Ashton, 2017; Stammerjohn et al., 2012). Finally, travel to the subantarctic islands may have no preceding periods of sea ice traversal, increasing the risk of MIS introductions.

The arrival of MIS on the Antarctic continental shelf could be devastating to the endemic species which have been essentially isolated for the past 25 million years (Tavares & De Melo, 2004). It is well established that preventing incursions from occurring is more cost-effective than management of an introduced species (Finnoff et al., 2007; Hanley & Roberts, 2019; Leung et al., 2002). This is particularly true for remote locations where it may be more difficult or expensive to undertake surveillance and management of an invasive species, and the potential biodiversity impacts are greater (Rout et al., 2011). Successful eradications of MIS are rare, occurring only in spatially limited regions with ample access to resources after early detection (Giakoumi et al., 2019). Currently, there is no systematic MIS surveillance in the Antarctic region and the ability to detect and to act quickly is hindered by the isolation and harsh conditions, making eradication an unfeasible plan of action in this region.

This study explores how changes predicted to occur in the marine environment around Australia's Antarctic stations, in East Antarctica, and Australia's subantarctic islands could influence the vulnerability of these regions to hull fouling MIS establishment, both now and into the future. We use machine learning to develop models of known hull fouling marine invasive species presence and use these models to predict whether species could survive in the shallow benthic habitats adjacent to Australia's Antarctic research stations and subantarctic islands. This will offer insight into what species are threats for future invasions and a potential focus for management.

## 2 | METHODS

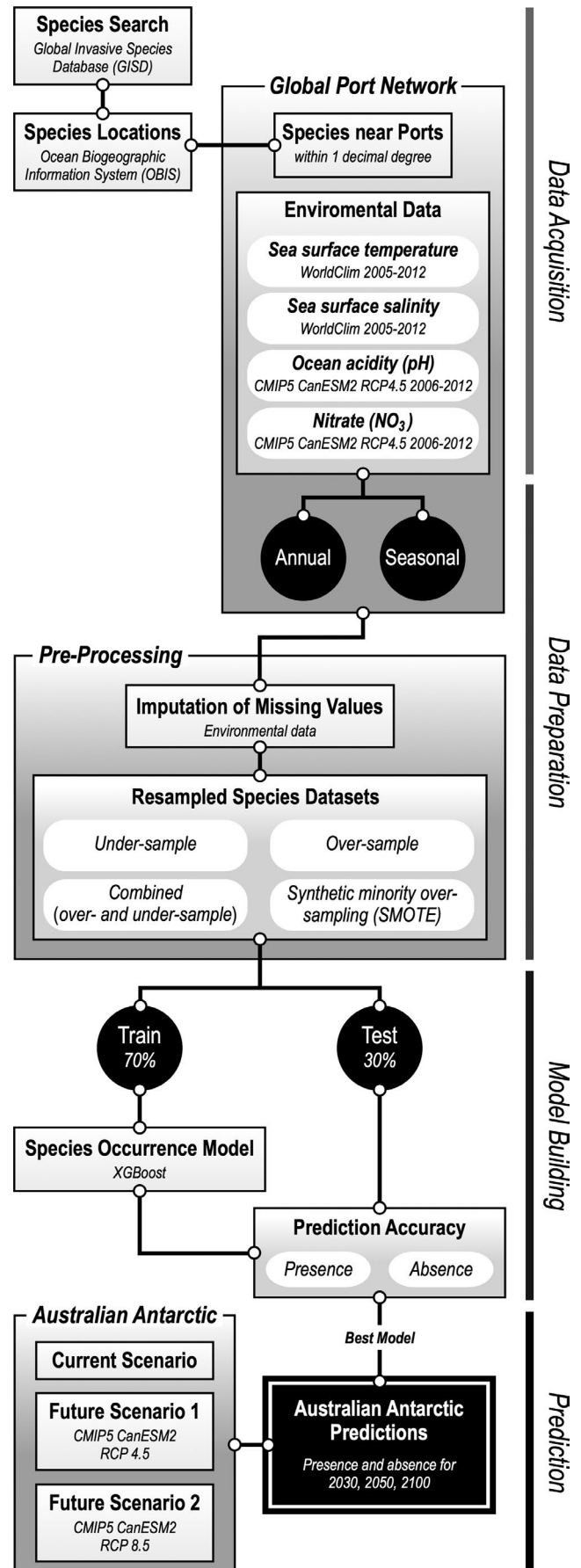
The methods for this study can be broken down into four key steps: (1) data acquisition; (2) data preparation; (3) model building; and (4) prediction. The flow and components of these steps are shown in Figure 1 and described in detail below.

### 2.1 | Study region

The Australian Antarctic research stations and subantarctic islands are located in the East Antarctic. There are three continental research stations: Davis (68° 34' 36" S, 77° 58' 03" E); Mawson (67° 36' 10" S, 62° 52' 26" E); and Casey (66° 16' 55" S, 110° 31' 39" E). Australia also manages two sub-Antarctic island groups: Heard and McDonald Islands (herein referred to as Heard Island due to their close proximity) group (53° 3' 0"S, 72° 37' 12"E); and Macquarie Island (54° 37' 12" S, 158° 51' 40" E) (Figure 2). This project is specifically focussed around these five discrete locations, as the logistic operations and science research are managed by the Australian Antarctic Division (under the Australian Government's Department of Agriculture, Water and the Environment).

### 2.2 | Global port network

As we were interested in hull fouling species, we used the global port network to build our model of environmental suitability for each species. The locations of ports worldwide are described in the World Port Index (National Geospatial-Intelligence Agency, 2017). There are 3,645 ports in the global port network, with most located in the Northern Hemisphere ( $n = 3,156$ ). Of these, 439 are located on freshwater lakes, or had insufficient data, and thus were excluded from further analysis. The total number of ports used for model building was 3,206; with 2,757 in the Northern Hemisphere compared with 449 in the Southern Hemisphere. Most global ports are located in temperate regions (65.22%,  $n = 2,091$ ), with less than half



**FIGURE 1** Methods flow chart of the four key steps of this study and the components that underpin each step



**FIGURE 2** Location of the Australian continental research stations: Mawson, Davis and Casey; and subantarctic islands: Heard and McDonald Islands and Macquarie Island. Adapted from the Quantarctica 3 dataset (Matsuoka et al., 2018)

appearing in tropical regions (31.07%,  $n = 996$ ), and relatively few ports in polar regions (3.71%,  $n = 119$ ) (Spalding et al., 2007). The location of the Australian Antarctic stations and sub-Antarctic islands were manually inputted using coordinates from Google Earth.

### 2.3 | Marine invasive species

A global list of known invasive species associated with marine and brackish habitats was obtained from the Global Invasive Species

Database (GISD—[iucngisd.org](http://iucngisd.org)). Using information from the GISD along with primary literature, species which did not have an association with fouling were removed from the list. This yielded a list of 160 species, with most ( $n = 112$ ) belonging to the *Didemnum spp.* group which was not resolved to species level within GISD. However, most *Didemnum spp.* show no conclusive evidence of being invasive in the literature; thus, we limited further investigation of this group to *D. vexillum*, which is known to be invasive.

We used the Ocean Biogeographic Information System mapper function (OBIS—<https://mapper.obis.org/>) to input the fouling

species to find occurrence data of their worldwide distribution. It is important to note that these records are likely incomplete records of the species' total distribution for reasons such as, but not limited to, biased global sampling (Phillips et al., 2009). The OBIS location data were overlaid with the location of world ports, and the Australian Antarctic stations and sub-Antarctic islands, and species were matched to ports where they occurred within 1.0 decimal degree of the port. Data were condensed by port, so that only one record per species per port was taken, to avoid spatial autocorrelation that would occur with heavily sampled species in specific regions (Assis et al., 2015; Elith & Leathwick, 2009). By limiting our pool of potential pseudo-absences to the global port network we, in effect, apply a similar bias to that observed in the presence data, which enhances the ability of our simulations to model the environmental conditions that are suitable for each of our species (Phillips et al., 2009). Where there were fewer than 10 occurrences of a species worldwide, that species was excluded from further analysis as there were insufficient points for gradient boosting analysis. Furthermore, we limited the species predictions for the three Antarctic sites to those species which had a recorded distribution that included subfreezing temperatures. Predictions for the subantarctic were limited to those species which had recorded distributions at a minimum temperature of 11°C or less to align with maximum temperatures expected in the subantarctic by the climate change scenarios. This resulted in a list of 33 species total, with a subset of 20 species which experience subfreezing temperatures somewhere in their current range (Table 1).

## 2.4 | Environmental variables for model building

Our study incorporates four environmental variables to determine habitat suitability for the suite of MIS, as discussed below. They are sea surface temperature (SST), sea surface salinity (SSS), nitrate ( $\text{NO}_3$ ) and ocean acidity (pH). These variables were aggregated into three sets: A—SST only; B—SST plus SSS and  $\text{NO}_3$ ; and C—all four variables. Where possible, it has been suggested to use multiple environmental variables with a statistical method that can adequately account for collinearity, such as regression trees (Hayes & Barry, 2008).

Sea surface temperature and sea surface salinity were selected for use as they are well known to influence species distributions (Barry et al., 2008; Ware et al., 2014). Present-day sea surface temperature and sea surface salinity data were obtained using the World Ocean Atlas version 2 (<http://www.nodc.noaa.gov/OC5/woa13/>) at 1° resolution using objectively analysed means. World Ocean Atlas environmental variables were monthly averages over the period 2005–2012.

Due to the nature of sea ice dynamics, associated under-ice algae and post-sea-ice breakout algal blooms, we could not adequately calculate present day and future predictions of chlorophyll. Instead, we used nitrate as a surrogate measure of productivity as it is often the limiting nutrient in coastal systems (Howarth & Marino, 2006). Nitrate has also been shown to be a stronger driver of species distributions than chlorophyll (Bosch et al., 2018). Ocean acidity (measured by pH) is known to have negative impacts on some species which rely on

calcium carbonate for skeleton and shell formation, particularly in the early stages of development (Guinotte & Fabry, 2008; Karelitz et al., 2017). Evidence that pH is becoming a key driver of marine species distributions is accumulating in the Southern Ocean region, where changes in acidification are occurring faster than originally predicted (Guinotte & Fabry, 2008; Hancock et al., 2020; Roden et al., 2013). Present-day data for nitrate and acidity were obtained from the CMIP5 (Coupled Model Intercomparison Project phase 5) CanESM2 (Canadian Earth System Model second generation) as monthly averages for the years 2006–2012 (Figure S1.1–S1.55).

Iron is the limiting nutrient in much of the greater Southern Ocean region yet is excluded from our set of environmental variables. Recent work has shown that iron is rarely limited in shallow ocean environments due to deposition from terrestrial regions, particularly where there are areas of ice-free land—typical of the subantarctic and areas in the Antarctic where research stations are located on the coast (Duprat et al., 2019; Stark et al., 2019).

## 2.5 | Environmental variables for predictions

Predictions for the present day for the five Australian Antarctic and subantarctic sites were made using the same data sources used for model building (see *Environmental variables for model building*). Future predictions were based on the CMIP5 CanESM2 future climate models for RCP 4.5 and RCP 8.5, which represent a curbing of emissions scenario and a business-as-usual scenario, respectively. The future projections were based on monthly predictions averaged for the years 2026–2030 (for 2030 predictions), 2046–2050 (for 2050 predictions), and 2096–2,100 (for 2,100 predictions). The RCP 8.5 models stop at October 2099; therefore, the months of November and December were averaged for the period 2096–2099 for RCP 8.5 2,100 predictions. The CMIP5 CanESM2 model has an oceanic resolution of 1.14° latitude and 1.4° longitude at the poles, with good spatial coverage of the Antarctic region and contains all environmental variables of interest, that is sea surface temperature, salinity, nitrate, and pH. We created two sets of environmental variables to explore the effect of seasonality on model outcomes: an annual model which used annual minimums, averages and maximums of each environmental variable; and a seasonal model where the data were collated into seasonal maximums, averages and minimums of each environmental variable (Figure S1.1–S1.5). All regions are expected to experience rises in temperature from ~ 0.5°C up to 4°C by the end of century. Conversely, all other environmental variables are expected to decrease by the end of the century. The Data S1 contains detailed environmental change information for each location.

## 2.6 | Data preparation

The dataset for each species was divided into “training” (70%) and “test” (30%) sets using the “createDataPartition” function in the R package “caret” (Kuhn, 2019) to ensure the ratio presences to

**TABLE 1** Hull fouling species considered for modelling for the two subantarctic or three Antarctic locations. Species appearing in bold are only considered for the subantarctic. Species indicated for modelling in the Antarctic region are species which currently have a part of their distribution in areas which experience subfreezing temperatures

Kingdom	Phylum	Class	Species		
Animalia	Annelida	Polychaeta	<i>Alitta succinea</i> (Leuckart, 1847)		
			<b><i>Ficopomatus enigmaticus</i> (Fauvel, 1923)</b>		
	Arthropoda	Malacostraca	<i>Sabella spallanzanii</i> (Gmelin, 1791)		
			<i>Carcinus maenas</i> (Linnaeus, 1758)		
			<i>Charybdis japonica</i> (A. Milne-Edwards, 1861)		
			<i>Hemigrapsus sanguineus</i> (De Haan, 1835)		
			<i>Rhithropanopeus harrisi</i> (Gould, 1841)		
			<b><i>Elminius modestus</i> (Darwin, 1854)</b>		
			Bryozoa	Gymnolaemata	<i>Bugula neritina</i> (Linnaeus, 1758)
					<b><i>Schizoporella errata</i> (Waters, 1878)</b>
					<i>Schizoporella unicornis</i> (Johnston in Wood, 1844)
			Chordata	Ascidiacea	<b><i>Watersipora subtorquata</i> (d'Orbigny, 1852)</b>
	<i>Ascidia aspersa</i> (Müller, 1776)				
	<i>Ciona intestinalis</i> (Linnaeus, 1767)				
	<b><i>Didemnum vexillum</i> (Kott, 2002)</b>				
	<i>Styela clava</i> (Herdman, 1881)				
	<b><i>Styela plicata</i> (Leseur, 1823)</b>				
	Echinodermata	Asteroidea			<i>Asterias amurensis</i> (Lutken, 1871)
			Mollusca	Bivalva	<i>Crassostrea gigas</i> (Thunberg, 1793)
	<i>Geukensia demissa</i> (Dillwyn, 1817)				
<b><i>Musculista senhousia</i> (Benson, 1842)</b>					
<i>Mya arenaria</i> (Linnaeus, 1758)					
<b><i>Mytilopsis leucophaea</i> (Conrad, 1831)</b>					
<b><i>Mytilus galloprovincialis</i> (Lamarck, 1819)</b>					
<b><i>Rangia cuneata</i> (G. B. Sowerby I, 1832)</b>					
Gastropoda		<i>Crepidula fornicata</i> (Linnaeus, 1758)			
		<i>Littorina littorea</i> (Linnaeus, 1758)			
		<i>Rapana venosa</i> (Valenciennes, 1846)			
Chromista	Ochrophyta	Phaeophyceae	<b><i>Undaria pinnatifida</i> ((Harvey) Suringar, 1873)</b>		
Plantae	Chlorophyta	Ulvothamniophyceae	<i>Codium fragile</i> ((Suringar) Hariot, 1867)		
	Rhodophytina	Florideophyceae	<b><i>Gracilaria vermiculophylla</i> ((Ohmi) Papenfuss, 1967)</b>		
			<i>Hypnea musciformis</i> ((Wulfen) J. V. Lamouroux, 1813)		
			<b><i>Polysiphonia brodiei</i> ((Dillwyn) Sprengel, 1827)</b>		

absences was maintained in the “training” and “test” datasets. The “class” of interest, in our case the presence of a MIS at a port, was the minority class in a highly imbalanced dataset. This can lead to high levels of classification accuracy due to the majority class being predicted in most cases (Leevy et al., 2018).

As the minority class is often the class we are most interested in, methods have been developed to overcome this imbalanced data—at the data level and at the algorithm level (Leevy et al., 2018). These methods can then be used independently; however, improved performance has been shown when data-level and algorithm-level methods are combined (Díez-Pastor et al., 2015). Resampling of the data is a common method for dealing with imbalanced data at the

data level (Díez-Pastor et al., 2015; Leevy et al., 2018). This process improves the ratio between majority and minority classes and there are several methods of resampling available. The resampling methods used in our study include the following: a) oversampling; b) undersampling; c) both over- and undersampling; and d) synthetic minority oversampling (ROSE) using the R packages, “caret” and “ROSE” (Kuhn, 2019; Lunardon et al., 2015). A more detailed explanation of the resampling techniques and their performance in this study is found in the Data S7 of this paper and the associated references. As the ratio of presence to absence data is unique for each species, the resampling was performed for each species, resulting in eight “training” datasets for each species.

## 2.7 | Gradient boosting analysis

Extreme gradient boosting is an ensemble machine-learning technique that makes predictions based on combinations of multivariate predictor data producing a specific outcome. For this study, we elected to use environmental variables at ports (the predictor variables) to predict the presence or absence of a MIS (the response variable). This method creates an ensemble of decision trees to create a strong classification (or regression) model based on a set of “weak” classifiers of the response variable. Here, we use the “xgboost” in R (Chen et al., 2019; Kuhn, 2019). This is the first study to use the extreme gradient boosting system to model MIS, and only the second to use it to model any invasive species (Sandino et al., 2018). Despite the paucity of use in invasive species research, extreme gradient boosting is a popular modelling algorithm in many other fields, such as critical care management (Chang et al., 2019; Zhang et al., 2019); financial fraud detection (Zhou et al., 2018) and credit scoring (Munkhdalai et al., 2019); and satellite image (Just et al., 2018) and astronomical feature classification (Tamayo et al., 2016). XGBoost has consistently outperformed other machine-learning algorithms in data science competitions while being computational efficient through parallel processing (Chen & Guestrin, 2016). Additional benefits of this gradient boosted algorithm is that it is robust against overfitting, has customizable hyper-parameters and includes cross-validation, and its non-parametric nature makes it useful when working with correlated predictor variables (Shi et al., 2019).

We used the XGBoost algorithm to model the environmental suitability using each species “training” datasets. Model accuracy for each species’ eight “training” datasets was assessed against the “test” subset from the original dataset to determine the predictive capability of each of the four resampling techniques with each of the model types, with a confusion matrix showing the accuracy for each analysis. The resampling technique that was able to predict the presence of a species with highest accuracy, while also maintaining a high accuracy in predicting the absence of a species, was deemed the best model. Higher accuracy in predicting the presence of species was given a higher preference as it is likely that the presence data are accurate, whereas absence data are likely to be less accurate as species distribution data are prone to type II errors (Lobo et al., 2010). Environmental variable importance was recorded for each model to show which environmental variables contributed most to the model. The best model as described here was used to predict the presence of the species at the five Australian Antarctic and subantarctic locations currently, and at 2030, 2050 and 2,100 under the two representative concentration pathways RCP 4.5 and RCP 8.5.

An outline of the R code used is available in the Data S8.

## 3 | RESULTS

### 3.1 | Present-day invasive potential

Of the 33 species investigated, 29 were not predicted to be suited to the environment of any location at the present day, with only 4 out

of 33 species predicting current environmental suitability in at least one location. These were as follows: *Asterias amurensis* (Northern Pacific sea star); *Geukensia demissa* (ribbed mussel); *Hypnea musciformis* (red algae); and *Undaria pinnatifida* (brown algae) (Tables 2 and 3). The annual model predicted a higher number of species ( $n = 4$ ) when compared with the seasonal model ( $n = 2$ ). Further, the choice of variable aggregation strongly influenced the outcome of predictions, particularly in the seasonal model where only the aggregation of all four variables leads to predictions of environmental suitability for any species (Figure 3).

### 3.2 | Future invasive potential

Environmental suitability was predicted for 5 of the 33 species that were included in this study (Tables 2 and 3). Like the present-day predictions, the seasonal model only predicted environmental suitability for two species (*A. amurensis* and *U. pinnatifida*), and again, only when aggregating all four variables. Two of those species (*Charybdis japonica* (Asian paddle crab) and *H. musciformis*) were predicted to be environmentally suited to one location each and only at one time (2030), and in both cases, only by the aggregation of all four variables. Predictions of environmental suitability for all five species did not greatly differ between RCP 4.5 and RCP 8.5. Only one species (*A. amurensis*) was common between the five locations, with all three aggregations of variables predicting presence in the annual models at all locations, and only the aggregation of all four variables in the seasonal model at all locations (Figure 3). *G. demissa* was common to the continental locations using the annual model, and *U. pinnatifida* was common to the subantarctic locations under both the annual and seasonal models.

### 3.3 | Model performance

The accuracy to predict both presence and absence was very high for all species and models (Table 4). The seasonal models generally outperformed the annual models in accuracy for predicting both presence and absence of MIS. The type of variable aggregation also influenced the model's predictive performance, with aggregation of sea surface temperature, salinity, and nitrate performing best in predicting both presence and absence of the species. The full details of model accuracy for each species are included in the Data S2 and S3.

Oversampling of the minority class produced the most accurate results for the annual model when using the SST only aggregation ( $n = 21$ ), followed by both over- and undersampling ( $n = 9$ ) and undersampling ( $n = 3$ ). For the corresponding seasonal model, oversampling was the only resampling technique to produce the most accurate results ( $n = 33$ ) and was also the case for the seasonal model when using the 3-variable aggregation. The 3-variable annual model was split evenly between oversampling ( $n = 12$ ), both over- and undersampling ( $n = 12$ ) and undersampling ( $n = 9$ ). Undersampling of the majority class produced the most accurate annual and seasonal models in the 4-variable aggregation ( $n = 19$  and 23, respectively), followed by both over- and undersampling

**TABLE 2** Species which were predicted to be able to survive in the five Australian Antarctic and subantarctic locations using the annual model for the current day and at 2030, 2050 and 2100. A is the sea surface temperature only variable aggregation; B is the sea surface temperature, salinity and nitrate aggregation; and C is the sea surface temperature, salinity, nitrate and pH aggregation. The environmental variable which contributed most to the model is listed for each species and variable aggregation

Species	Current day	RCP 4.5			RCP 8.5			Most important variable		
		2030	2050	2100	2030	2050	2100	A	B	C
Mawson										
<i>Asterias amurensis</i>	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	Avg SST	Min SST	Max Nitrate
<i>Geukensia demissa</i>	A, B	A, B	A, B	A, B	A, B	A, B	A, B	Avg SST	Avg Nitrate	-
Davis										
<i>Asterias amurensis</i>	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	Avg SST	Min SST	Max Nitrate
<i>Geukensia demissa</i>	A, C	A, B	A	A, B	A, B	A	A	Avg SST	Avg Nitrate	Max Nitrate
<i>Hypnea musciformis</i>	C	C	-	-	C	-	-	-	-	Avg pH
Casey										
<i>Asterias amurensis</i>	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	Avg SST	Min SST	Max Nitrate
<i>Charybdis japonica</i>	-	-	-	-	C	-	-	-	-	Avg pH
<i>Geukensia demissa</i>	A, B	A, B	A	A	A	A	-	Avg SST	Avg Nitrate	-
Macquarie Island										
<i>Asterias amurensis</i>	B, C	A, B, C	B, C	B, C	A, B, C	A, B, C	C	Avg SST	Min SST	Max Nitrate
<i>Undaria pinnatifida</i>	B	B	B	-	B	-	-	-	Avg SST	Avg SST
Heard and McDonald Islands										
<i>Asterias amurensis</i>	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	Avg SST	Min SST	Max Nitrate
<i>Undaria pinnatifida</i>	B	B	B	-	B	-	-	-	Avg SST	-

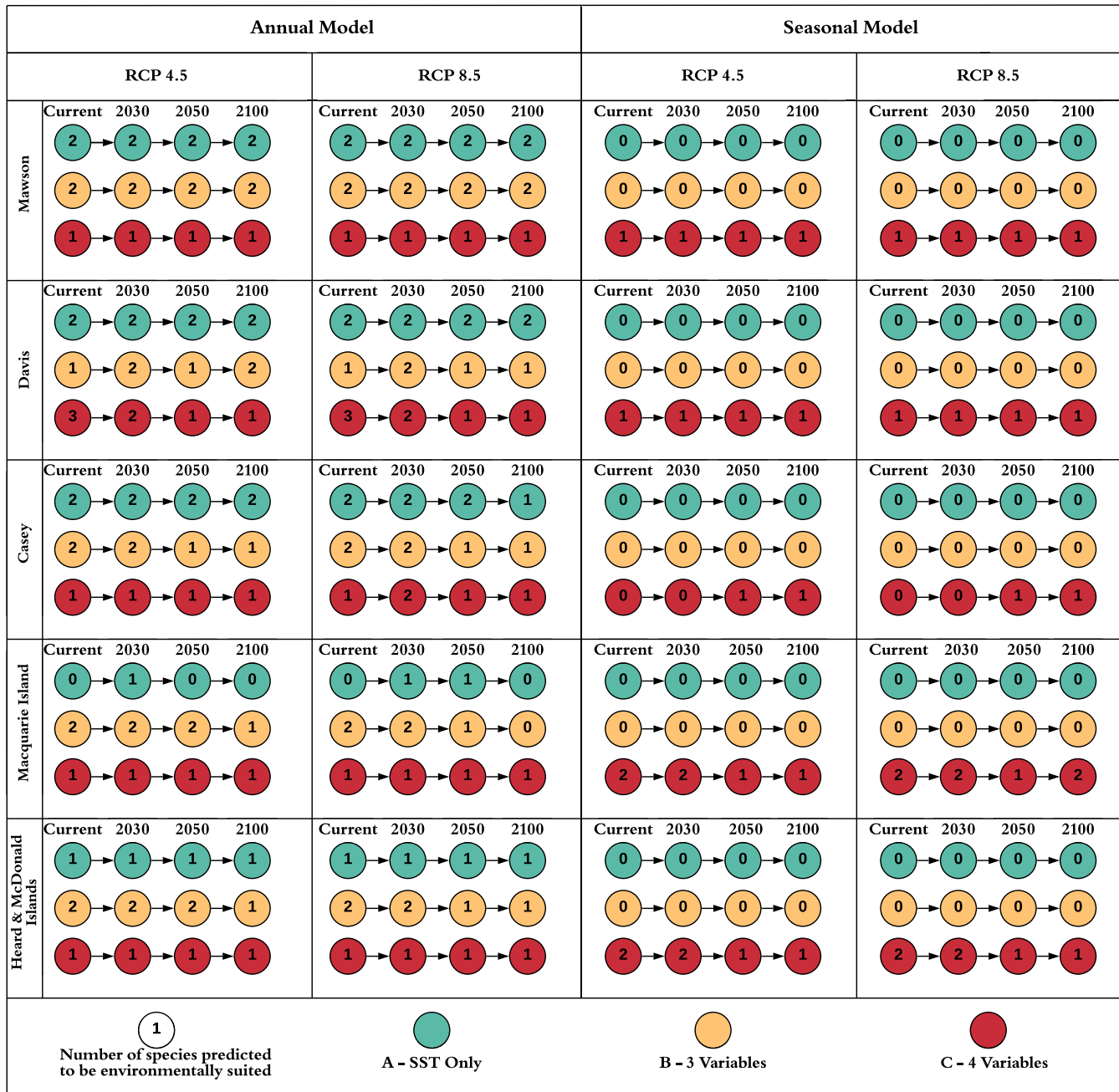
**TABLE 3** Species which were predicted to be able to survive in the five Australian Antarctic and subantarctic locations using the seasonal model. A is the sea surface temperature only variable aggregation; B is the sea surface temperature, salinity and nitrate aggregation; and C is the sea surface temperature, salinity, nitrate and pH aggregation. The environmental variable which contributed most to the model is listed for each species and variable aggregation

Species	Current day	RCP 4.5			RCP 8.5			Most important variable		
		2030	2050	2100	2030	2050	2100	A	B	C
Mawson										
<i>Asterias amurensis</i>	C	C	C	C	C	C	C	-	-	Winter Nitrate
Davis										
<i>Asterias amurensis</i>	C	C	C	C	C	C	C	-	-	Winter Nitrate
Casey										
<i>Asterias amurensis</i>	-	-	C	C	-	C	C	-	-	Winter Nitrate
Macquarie Island										
<i>Asterias amurensis</i>	C	C	C	C	C	C	C	-	-	Winter Nitrate
<i>Undaria pinnatifida</i>	C	C	-	-	C	-	C	-	-	Spring SST
Heard and McDonald Islands										
<i>Asterias amurensis</i>	C	C	C	C	C	C	C	-	-	Winter Nitrate
<i>Undaria pinnatifida</i>	C	C	-	-	C	-	-	-	-	Spring SST

( $n = 8$  and  $6$ , respectively) and oversampling ( $n = 6$  and  $4$ , respectively). There was no case where the ROSE resampling technique resulted in the most accurate results and often leads to overfitting of the presence class with low classification accuracy for the absence class. The best resampling technique for each species can be found in the Data S2 and S3.

### 3.4 | Variable importance

Average sea surface temperature was the most important variable for the annual model (Table 5). For the seasonal model, in all aggregated variable sets, average autumn sea surface temperature was the most important variable for the greatest number of species.



**FIGURE 3** Number of species predicted to survive the environmental conditions at each of the five Australian Antarctic and subantarctic locations by model type and environmental variable aggregation. A (blue) is the sea surface temperature only variable aggregation; B (orange) is the sea surface temperature, salinity and nitrate aggregation; and C (red) is the sea surface temperature, salinity, nitrate and pH aggregation

## 4 | DISCUSSION

We explored the environmental suitability of the Australian Antarctic region and subantarctic regions for MIS. Our models indicate that up to five of the species examined are or will be able to survive in at least some locations by the end of the century. Two of these species were predicted to be able to survive in only one or a couple of the four time periods we examined and show different patterns of predicted survival for different regions. These predictions could

be indicative of errors in the model predictions or perhaps that the environment is only borderline suitable for the species and warrant further investigation. In any case, a precautionary approach should be used due to the potential, as yet unknown, impacts of MIS in the East Antarctic region (Ojaveer et al., 2014). Further, all governance and management prescriptions for these areas aim to ensure that non-native species do not establish, in order to protect the wilderness values and natural ecosystems (Committee for Environmental Protection, 2017; Commonwealth of Australia, 2014; Parks &

**TABLE 4** The mean accuracy of model predictions for all species by model type and variable aggregation. Standard error is provided in brackets after mean, with the range provided in square brackets below

Variable Aggregation	Annual Model Mean		Seasonal Model Mean	
	Presence	Absence	Presence	Absence
A—Sea surface temperature only	90.48% ( $\pm 0.48$ ) [79.41% - 98.41%]	95.84% ( $\pm 0.95$ ) [86.88% - 99.89%]	99.42% ( $\pm 0.11$ ) [97.88% - 100%]	97.48% ( $\pm 0.23$ ) [94.36% - 99.85%]
B—SST, Salinity & Nitrate	92.97% ( $\pm 0.92$ ) [79.41% - 100%]	96.09% ( $\pm 0.44$ ) [88.62% - 99.19%]	99.58% ( $\pm 0.08$ ) [98.45% - 100%]	98.49% ( $\pm 0.14$ ) [96.94% - 99.90%]
C—SST, Salinity, Nitrate & pH	91.40% ( $\pm 0.01$ ) [71.79% - 97.95%]	93.87% ( $\pm 0.01$ ) [81.84% - 99.43%]	92.72% ( $\pm 0.01$ ) [73.68% - 100%]	93.17% ( $\pm 0.01$ ) [85.73% - 99.68%]

**TABLE 5** Number of species (total  $n = 33$ ) for which a variable is the most important variable in model building, by model type and variable aggregation set. Most important variable for each species is listed in the Data S2 and S3

ANNUAL		SEASONAL	
Variable	No. of species	Variable	No. of Species
A—Sea surface temperature only			
Average SST	18	Autumn SST	13
Maximum SST	8	Summer SST	8
Minimum SST	7	Spring SST	8
		Winter SST	4
B—SST, Salinity and Nitrate			
Average SST	12	Autumn SST	13
Maximum Salinity	6	Spring SST	5
Minimum SST	5	Winter SST	5
Maximum SST	4	Summer SST	4
Average Salinity	2	Winter Nitrate	3
Maximum Nitrate	2	Summer Salinity	1
Average Nitrate	1	Autumn Salinity	1
Minimum Salinity	1	Winter Salinity	1
C—SST, Salinity, Nitrate and pH			
Average SST	9	Autumn SST	7
Maximum SST	8	Spring pH	6
Minimum SST	5	Summer SST	5
Average Nitrate	3	Winter SST	4
Maximum pH	3	Spring SST	3
Maximum Nitrate	2	Winter Nitrate	2
Average pH	1	Autumn Nitrate	2
Maximum Salinity	1	Winter pH	1
Minimum Nitrate	1	Winter Salinity	1
		Spring Salinity	1
		Summer Salinity	1

Wildlife Service, 2006), though these are biased towards terrestrial systems and provide little guidance on practical measures to prevent or manage MIS in the Antarctic region.

Of greatest concern are those species which are predicted to survive in the environmental conditions for several continuous time periods. This shows consistent environmental suitability for those species and that they are less likely to represent modelling errors or species which are borderline matches, though it does not suggest that all life stages could successfully survive in the area. Using two different models with three different aggregations of environmental variables allowed us to investigate how sensitive predictions were to the choice of model and variables. Only one of the five species showed agreement between the annual model and seasonal model: *A. amurensis*. This mismatch between the annual and seasonal models may infer that the high seasonality of primary productivity in the Antarctic region, rather than specific extremes of the environmental variables, is the barrier to successful introduction of species.

Our results indicate that a common assumption that sea surface temperature is a key barrier to MIS may be flawed. It is important to point out, however, that environmental suitability does not necessarily confer that a species will become established in these locations, as there are other important factors, like propagule pressure and the availability of a mechanism for anthropogenic transfer, that are required for a species to reach a new region. However, it does highlight that greater effort should be focused on preventing these species from entering the region.

For all regions, the predatory Northern Pacific sea star, *A. amurensis*, has been shown to be environmentally suited using both annual and seasonal models for all time periods and both RCPs (with the exception of the seasonal model applied to Casey presently or in 2030). *A. amurensis* is currently subject to a National Control Plan due to its "...having significant and potential future impacts on Australia's marine environment, social uses of the marine environment and the economy" (Aqueal Pty Ltd, 2008b, p. 11). This species displays considerable phenotypic plasticity and can alter spawning times to coincide with local conditions (Buttermore et al., 1994; Byrne et al., 1997; Ling et al., 2012). This species has an introduced range that includes Canada and Alaska, indicating its ability to tolerate cold conditions and the presence of sea ice (Byrne et al., 2016). It is not a species that is commonly associated with hull fouling; however, there is evidence of hull settlement of juvenile *A. amurensis* in the Derwent River, Tasmania, Australia, along with an adult of the

species being found in the sea chest of a vessel (Hewitt et al., 1999, 2004). More detailed information regarding this species is found in the Data S5.

*Undaria pinnatifida* is another species which was predicted to be environmentally suited to the subantarctic islands now and at 2030 by an annual model (with 3 aggregated variables) and now and at 2030 and 2050 by a seasonal model (with 4 aggregated variables). The present day introduced range encompasses Australia, New Zealand, Europe, Argentina and California (James et al., 2015). In Australia, it is also subject to a National Control Plan (Aquenal Pty Ltd, 2008a). *U. pinnatifida* is a poor competitor that struggles to establish in stable environments but thrives in disturbed environments (James & Shears, 2016; Valentine & Johnson, 2003). Physical disturbance is predicted to increase in Antarctic and subantarctic benthic ecosystems via more frequent iceberg scouring (Barnes & Souster, 2011; Peck et al., 2005), less sea ice opening up new areas to iceberg scour and increased winds leading to larger waves in coastal areas (Stark et al., 2019). As disturbance via iceberg scour can occur throughout the year and recovery from a scour event can take many years, there is potential for this species to find areas of suitable habitat if they are transported to the region from known source locations in Australia and New Zealand (Aquenal Pty Ltd, 2008a; Stark et al., 2019). In addition, other forms of anthropogenic disturbance around Antarctic stations, such as pollution (Stark et al., 2014), may enhance the chances of other species establishing in these areas if local species are intolerant of such disturbances (Piola & Johnston, 2008). This species attaches to suspended objects and vessel hulls at, or just below, the waterline and is more commonly encountered on vessels which are moored for extended periods of time (Hewitt et al., 1999)—such as by Australia's previous icebreaker ship *Aurora Australis* in Hobart for overwintering. This species was also recently predicted to be a high risk of invading the Antarctic Peninsula region in an expert analysis of the invasive species threat to the Peninsula region (Hughes et al., 2020). More detailed information regarding this species is found in the Data S6.

*Geukensia demissa* is another species which was predicted to be environmentally suited to the three continental stations by the annual model. The occurrence records of this species on the Ocean Biogeographic Information System indicate that this species is found in the United States, northern Spain and on the Antarctic Peninsula (King George Island). There is no information in the literature regarding the Antarctic finding of this species. The OBIS record makes reference to a published study (Tatián et al., 2008) as a bibliographic reference; however, this paper mentions *G. demissa* as a comparative species for measuring carbon flux in suspension feeders. Therefore, this species entry was either: a) incorrectly identified as *G. demissa*, or b) the first record of this MIS in the greater Antarctic region. The prediction of this species as being environmentally suited to Antarctica should be treated with scepticism until confirmation of the taxonomy of the specimen from the Antarctic Peninsula region.

Environmental suitability is not the only factor determining if a species can become established in a new environment. Even though adults may be able to survive in an environment, this does

not necessarily infer that successful establishment will occur, as was recently highlighted in the case of the non-persistent population of *Mytilus cf. platensis* in the South Shetland Islands (Cárdenas et al., 2020). Recent work found that there is a risk of *A. amurensis* becoming a threat to the Australian subantarctic before the end of the century; however, it did not find the same for the Antarctic (Maria Byrne et al., 2016). The study experimentally found thermal limits for different life stages from the Tasmanian population of *A. amurensis* and that these limits are narrower for larval development than for adult survival. Nevertheless, this species displays high phenotypic plasticity, and populations from other regions of the world may have the capacity to successfully reproduce at colder temperatures than the Tasmanian population (Buttermore et al., 1994; Byrne et al., 1997; Ling et al., 2012). While it is highly likely that any introductions of this species to the Australian Antarctic and subantarctic locations will be sourced from Tasmania, ships from many other regions also visit Australia's Antarctic stations and subantarctic islands, including from Russia, China, France, Japan, New Zealand, Chile, as well as tourist ships visiting multiple ports.

There are examples of other invasive species, such as *Carcinus maenas* (European green crab) and *Rhinella marina* (cane toad), which have the ability to quickly acclimate to cold conditions well below those experienced in its native range, indicating that predictions of species distributions are likely to be underestimated in highly plastic species (McCann et al., 2014; Tepolt & Somero, 2014) or in species with broader thermal tolerances (Janion-Scheepers et al., 2018). This means that the species we predicted as being suited to the environment only in one time period may be able to persist into the future, despite current modelling predicting otherwise. While some of our predicted species may represent error in the modelling, those species that are presently found in the higher latitudes (such as *C. japonica* and *H. musciformis*) could be better suited to the environment than we have predicted here, and some species that we predicted as not being able to survive may in fact pose a risk. We also do not understand the potential synergistic interactions that environmental variables could have that may enhance survival outside of the experimentally identified thermal tolerance limits. See Data S4 for additional information on the predicted species.

Propagule pressure is also an important component of invasive species establishment (Lockwood et al., 2009). Unlike most global ports, East Antarctica and Australia's subantarctic receive relatively little shipping traffic. For example, the Australian Antarctic stations and Heard Island received less than 15 ship visits for the 2016–2017 season (McCarthy et al., 2019). Current shipping traffic is limited mostly to the warmer half of the year, with the shipping season running from October to March. At higher latitudes fast ice inhibits shipping traffic throughout the colder months. The passage of ships through sea ice in the warmer months acts as a natural hull cleaner, scouring fouling organisms from the hull of ships. However, the subantarctic islands are not surrounded by any sea ice, so if the first port of call after overwintering in a northern port, commonly Hobart

(but not always) is a subantarctic island; then, there is no removal of hull fouling organisms before reaching these areas. One way to mitigate this is to schedule the first shipping voyage of the season following overwintering to include a period of traversal through sea ice before arriving at the subantarctic islands, though many vessels currently avoid sea ice where possible for safety reasons (Hughes & Ashton, 2017; Ware et al., 2014). Although traversal through sea ice has the capacity to scour the hull of fouling organisms, this does not include protected or enclosed niche areas, such as sea-chests, moon pools, wet wells, instrument cavities and propeller shafts (Lee & Chown, 2007). Traversal through sea ice also damages antifouling that has been applied to the ship, making them more susceptible to fouling (Lee & Chown, 2009). Further research on fouling community composition in hull and protected niche areas is required to better understand the propagule load carried by research and resupply vessels (though, see Lee & Chown, 2007) as these niches may pose a substantial risk to marine invasions in the Antarctic that is currently overlooked.

One key limit of our study is that it is based on an incomplete record of global species presence. Some of the hull fouling marine invasive species identified may inhabit regions at higher latitudes, but they may simply not have been found yet, or have not been uploaded to the OBIS database. This means that even though species that we may have expected to see, such as *Mytilus galloprovincialis* (Lee & Chown, 2007), that were not predicted to survive the environmental conditions of the Australian Antarctic and subantarctic by the end of the century in our study, could actually be an example of type II errors in the underlying dataset. The format of the dataset required for analysis, however, could be adapted to allow input of experimental data, and incorporating the results of thermal experiments and occurrence data from additional databases and primary literature sources could enhance the overall predictions.

Our study introduces a novel method of identifying and predicting when and where marine invasive species could occur using multiple environmental variables. The methods used in our study can be readily adapted to other regions of the Antarctic and subantarctic to identify species which may be environmentally suited now and in the future, particularly as new climate models become available. There is also a need to explore the potential for endemic Antarctic and subantarctic marine species to be carried by anthropogenic means to other regions of the Southern Ocean, and how species could be carried naturally throughout the region (Hughes et al., 2019). Overall, the chance of an introduction occurring, now through to the end of the century, to the Australian Antarctic stations and subantarctic islands is currently deemed to be a very low risk. There is low propagule pressure; however, increased interest in the Antarctic region, such as an increase in shipping activity, will increase this pressure (McCarthy et al., 2019). The highly cold-stenothermic endemic species in Antarctic and subantarctic ecosystems are under increasing stress as a result of climate change and are ill-prepared to cope with the additional stress of novel species (Ingels et al., 2012). Focus must now shift to improving quarantine procedures and investigating novel monitoring tools, such as eDNA, to prevent the introduction

and establishment of MIS in the near-pristine marine ecosystems of the Antarctic and subantarctic regions.

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## PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/ddi.13246>.

## DATA AVAILABILITY STATEMENT

R code used for this study is found in the Supplementary Material for this paper. The data used for this study are available at <https://doi.org/10.5061/dryad.3ffbg79hf>.

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**BIOSKETCH**

Oakes Holland is a PhD candidate at the Institute for Future Environments at Queensland University of Technology. In her research, Oakes' goal is to use emerging tools and technologies to better predict invasive species threats to the greater Antarctic region.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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