Biol Invasions (2023) 25:2849–2871
https://doi.org/10.1007/s10530-023-03077-5

ORIGINAL PAPER

A systems approach to biosecurity pays off: a case study investigating introduction pathways and interceptions of non-indigenous species at a biosecurity border

Barbara Kachigunda · Grey T. Coupland · Kerrie Mengersen · Devindri I. Perera · Johann van der Merwe · Simon McKirdy

Received: 28 June 2021 / Accepted: 26 April 2023 / Published online: 10 May 2023
© The Author(s) 2023

Abstract Introduction pathway studies generally describe the diverse routes by which non-indigenous species (NIS) can be introduced but rarely consider multiple introduction pathways occurring simultaneously. In this study, multiple pathways of NIS introduction were investigated during an industrial development on a remote island off the Australian coast. Fifteen introduction pathways were categorized in association with importing locality and the type of cargo they transported. The number and types of detection events for each introduction pathway were recorded during biosecurity inspections, cargo clearances, and surveillance conducted between 2009 and 2015. In total, more than 600,000 biosecurity inspections were completed, with 5,328 border detection events recorded constituting less than 1% of the biosecurity inspections. The border inspection events were classified as animals, plant material, soil, and organic matter, with 60% identified as dead or non-viable and 40% as alive. Of those detections, 2153 were classified as NIS, consisting of 659 identified species. Live NIS detected at the border constituted only 2% of the detections. Cargo vessel and inward-bound passenger numbers peaked during the major construction period and were associated with an increase in the number of live NIS detections. All introduction pathways have complexities, unique structural aspects, and niche areas that supported NIS in surviving the effects of treatment and evading detection during the mandatory compliance inspection. This study highlights that biosecurity incursions can be minimized if a systems approach is adopted to complement traditional and other biosecurity surveillance measures.

Keywords Systems approach · Transportation pathways · Vectors · Introduced pest management · Biosecurity · Surveillance · Freight vessels · Hitchhiker pest

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10530-023-03077-5.

B. Kachigunda (✉) · G. T. Coupland · J. van der Merwe · S. McKirdy
Harry Butler Institute, Murdoch University, Murdoch, WA 6150, Australia
e-mail: b.kachigunda@murdoch.edu.au

K. Mengersen
School of Mathematical Sciences, Queensland University of Technology, 2 George St, Brisbane, QLD 4001, Australia

D. I. Perera
Faculty of Computing and Technology, University of Kelaniya, Kelaniya, Sri Lanka

Introduction

Non-indigenous species (NIS) are a major threat to global biodiversity (Moser et al. 2018; Nghiem et al. 2013; Ojaveer et al. 2015; Schlaepfer 2018). Understanding the pathways responsible for NIS

introductions and using this knowledge to inform management decisions will reduce the likelihood of NIS entering a region or country (Convention on Biological Diversity 2014; Faulkner et al. 2016; Simberloff et al. 2013). Pathway studies often describe the diverse routes by which NIS can be introduced to a region but rarely consider multiple introduction pathways occurring simultaneously (Cope et al. 2017; Essl et al. 2015; Saul et al. 2017). The challenge, however, is to quantitatively assess the risk of pathways introducing and subsequently spreading NIS, especially pest species. A pathway-centered biosecurity management approach targets the "riskiest" pathways, where risk is a combination of the probability of an incursion/invasion and impact or consequences. Information about how and why NIS taxa are coming via specific pathways is analyzed, and targeted preventative strategies, such as early detection, import regulations, and pre-shipment protocols are implemented and tested over time (Faulkner et al. 2016; Lott and Rose 2016). If a systems approach to managing multiple pathways is adopted, then the assessment and management of risks posed by the diverse pest species can be managed more effectively resulting in proactive prevention of an incursion (Falk et al. 2011). For targeted pathways, colonization pressure should decrease over time as management protocols are adjusted accordingly (Pyšek et al. 2011; Simberloff 2009; Turner et al. 2020).

Historically, human-mediated arrivals of NIS have been very prominent due to trade and immigration patterns (Sikes et al. 2018). Accelerating rates of international trade, volume and diversity of goods and the efficiency of travel, and growth of international airline commerce have led to an increase in unintentional dispersal and an increase in the likelihood of NIS surviving transit (Hughes et al. 2019). Several studies have highlighted issues associated with human-mediated pathways and transportation of NIS (Hughes et al. 2019; McKirdy et al. 2019; Newman et al. 2018). Interception of NIS at ports of entry has become a complex and evolving task. Extensive research has been conducted on invasive alien species (IASs) on human-inhabited islands (Rojas-Sandoval et al. 2017; Russell et al. 2017; Toral-Granda et al. 2017; Turbelin et al. 2017; Wasowicz 2014) where high numbers of NIS introductions have been attributed to stowaways, contaminants, and intentional release as part of horticulture and agriculture activities (Hughes and Convey 2010; Hughes et al. 2019; Wasowicz 2014). Further, human-associated pathways including cargo, vehicles, fresh food, ships, clothing, and personal equipment are highly effective in the translocation of NIS despite the implementation of sanitary practices such as footbaths, checking of clothes for seeds, use of sniffer dogs, and X-raying of baggage at entry points (Meissner et al. 2009). Statistical profiling for the intervention of biosecurity risk material can be a useful tool for improving the efficiency of detecting personnel and individuals at high risk of non-compliance, as well as strong educational awareness (Lane et al. 2017; Meissner et al. 2009). It should be emphasized that inspection alone is not 100% effective in preventing incursions and some studies have shown that inspections alone have relatively low interception efficiency (Caley et al. 2015; Meissner et al. 2009; Suhr et al. 2019).

The identification and categorization of pathways follow the Convention on Biological Diversity (CBD) classification as interpreted by the IUCN (2017) where pathways by which NIS arrive can be subdivided into the following categories: importation of a commodity; the arrival of a transport vector; or spread from a neighbouring region. Introduction pathway for this study refers to the physical means by which NIS may potentially be introduced to a new environment, such as within machinery, luggage, or on wet sides of a vessel (Convention on Biological Diversity (CBD) 2014).

The systems approach

The Quarantine Management System (QMS) in place on Barrow Island (BWI), a remote island off the western coast of Australia, is a fully integrated biosecurity system across the biosecurity continuum. The biosecurity continuum involves the implementation of pre-border, border, and post-border activities to minimize the likelihood of pests and diseases arriving and establishing on BWI (Whattam et al. 2014). The focus was predominantly on pre-border activities where quarantine measures were embedded within the procurement, contracting, and logistics processes (Scott et al. 2017). A systems approach was implemented where at least two or more quarantine measures were implemented to reduce the risk of NIS being present on cargo, vessels, aircraft, and people

during preparation for shipment, in storage, during loading, and in transit and to minimize detection at BWI border.

During the risk assessment phase, a diverse set of 15 cargo/personnel/vessel introduction pathways (e.g., domestic vessels, personnel and luggage, and food and perishables) was identified for the construction phase of a liquified natural gas (LNG) project on BWI (Chevron Australia 2017). The construction of the LNG plant presented significant opportunities for the introduction of NIS. As such, detecting potential quarantine risk material arriving via the various introduction pathways became a priority in biosecurity management of the island (Chevron Australia 2017), and was a requirement under both federal and state government legal frameworks (Act 2003; Act 1999) for the 40 years expected lifespan of the project (ACIL Allen 2015).

This study aims to characterize introduction pathways transporting goods and personnel to Barrow Island over a specific period (i.e., during the construction and operation of an industrial project) to determine which introduction pathways have the highest likelihood of introducing terrestrial NIS to the island. Results of the study are used to develop recommendations to improve how future biosecurity efforts for Barrow Island and in a broader context, terrestrial biosecurity surveillance, can be developed through consideration of problematic introduction pathways.

Material and methods

Study site

Barrow Island (BWI) is the second-largest continental island off the Western Australia coastline, located 60 km off north-western Australia (Department of Environment and Conservation 2007). The island was declared a "Class A" Nature reserve in 1910 (Moro and Lagdon 2013). The potential for the introduction of NIS to remote, sparsely inhabited islands is often limited due to the nature of their seclusion and isolation. However, islands are particularly vulnerable to invasion because of the likelihood of high endemism and reduced beta diversity of islands (Suhr et al. 2019). The remoteness of BWI refers to its natural history, its ecological affinities with the mainland, and its resilience to environmental extremes. Currently, 2,800 terrestrial and subterranean species have been documented on the island, some of which are listed as vulnerable or threatened, 13 mammal species (including two species of bats), and 24 endemic invertebrate species (Moro and Lagdon 2013). These mammal species have persisted due to their isolation from the mainland, lack of predation by introduced predators such as cats, foxes, and rats, and their resilience to evolving within an arid and sub-tropical climate (Kier et al. 2009). Wildlife on the island is adapted to extreme fluctuations in climate and in particular, rainfall, ranging between 30 and 300 mm and mean maximum temperatures ranging between 20–34 °C (Moro and Lagdon 2013).

Three phases existed during the LNG project development (September 2009 to December 2015), each with different biosecurity risks:

1. Early construction phase-October 2009 to December 2011, which consisted mostly of site preparations and earthworks.
2. Major construction phase-January 2012 to December 2014, which consisted mainly of major construction activities relating to the building of the three LNG processing plants and all the supporting infrastructure such as gas turbine generators, slug catchers, Boil Off Gas (BOG) flare, Mixed Refrigerant/Multiple Propane (MR/PR) compressors, etc.
3. Transitional phase-January 2015 to December 2015, which mainly consisted of preparations for start-up, commissioning tests, and eventual start-up and initial operations.

For this study, the border is defined as the entry point of cargo, vessels, or people to Barrow Island. The specific entry points were Perth Airport, Western Australian Petroleum Pty. Ltd. Landing Site (WAPET Landing Site), and Material Offloading Facilities (MOF), and Pioneers Material Offloading Facility (PMOF), (Chevron Australia 2017) see (Fig. 1). At the border, data were classified as events and non-events (where the biosecurity risk material (BRM) was live/ viable or dead/non-viable respectively), and also as intercepts (detected prior to final clearance) or incidents (detected after final clearance).

Pre-border inspections were done at designated points internationally in Asia (i.e., Indonesia, Malaysia, Singapore, South Korea, Thailand, and China),

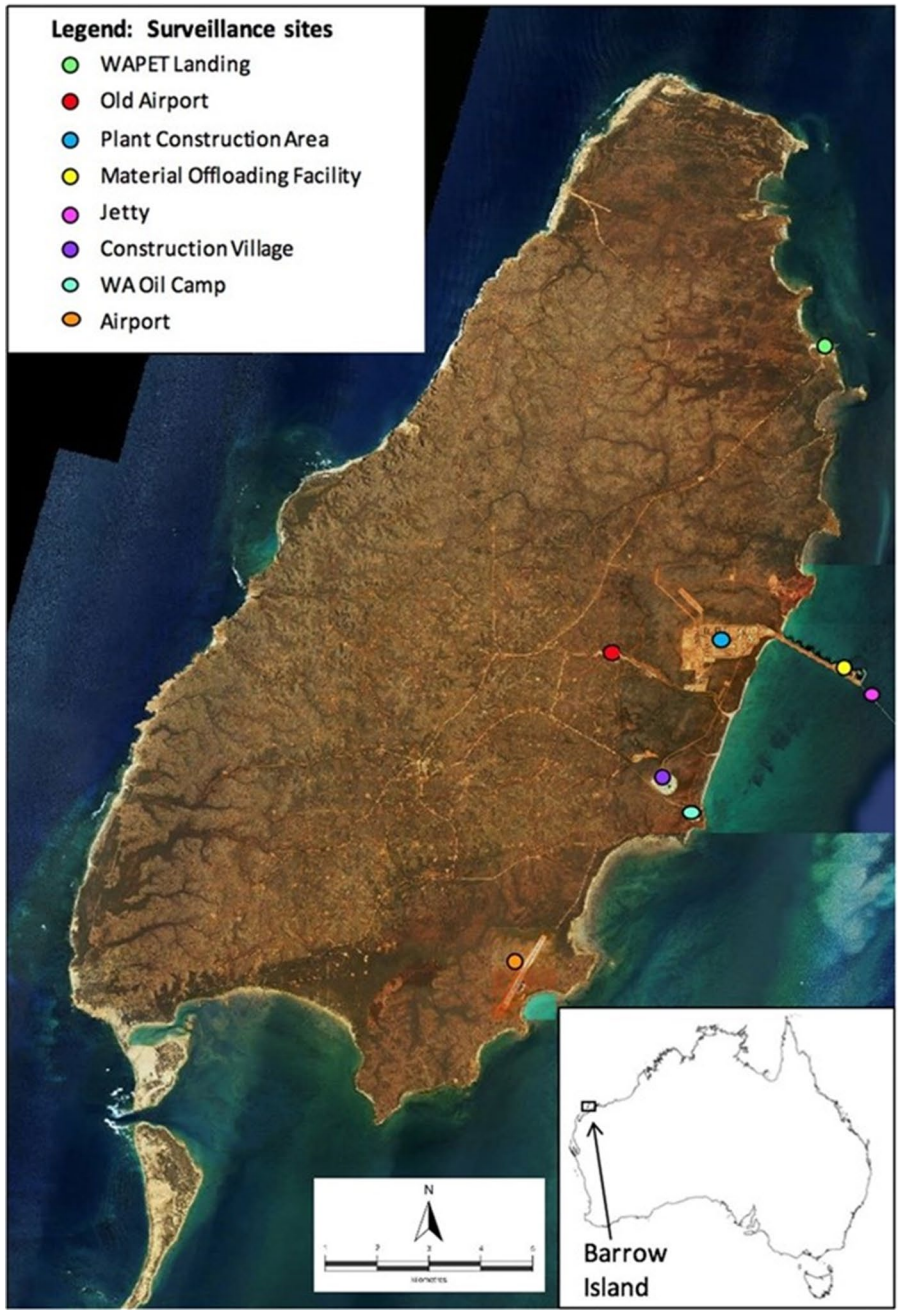


Fig. 1 Specific biosecurity borders on Barrow Island, Australia (air and seaports)

Europe (England and Italy), the United States of America, as well as locally within Australia (i.e., New South Wales, Queensland, and Western Australia). Pre-border inspection sites within Western Australia included Fremantle Port, Karratha, Dampier, Onslow, Perth Airport, Broome, Welshpool Depot, and Henderson. Pre-border biosecurity inspections were implemented by external approved agencies and independent contractors. Border and border detections were primarily through cargo and facility inspections, while post-border detections were also a result of scientific surveillance programs and through the participation of an educated and well-informed workforce as citizen scientists. Post-border inspection occurred after final cargo clearance and included points where the consignments were offloaded for use

on BWI, such as the Gorgon LNG Plant, the Construction Village, the Production Village, and Western Australia (WA) Oil Camp (Fig. 1).

Domestic vessels (landing craft, tugs, barges, and cargo carriers) transported cargo from local areas in Western Australia, such as Broome, Dampier, Exmouth, Fremantle, and Henderson. There was a preference for containerized cargo as they were International Organisation for Standardization (ISO) compliant, easy for warehousing, and weather and rodent-proof. Flat rack containers were used to transport large structural materials and heavy loads, such as pipes and machinery. Modules were large, prefabricated LNG plant components constructed in international construction yards and shipped to BWI. The wide range of cargo required to construct the LNG plant at times necessitated unique shipping conditions, as some of the equipment could not be fitted into standard containers. In such circumstances, the cargo was wrapped or crated when practicable. A variety of equipment was sourced internationally from China, Indonesia, Malaysia, Singapore, South Korea, Thailand, and Italy, and the cargo was imported directly to the island to minimize biosecurity risks through stops en route. The southeast Asian ports of Singapore, Malaysia, and Thailand and the east Asia port of Qingdao (China) have emerged as dominant hubs for international shipping, and now represent a considerable biosecurity risk (Lee et al. 2008; Wang and Wang 2011). Consequently, knowledge of species potentially transported from these donor regions was important in formulating pre-border biosecurity management strategies.

The various introduction pathways were defined by the type of cargo they transported, with associated biosecurity protocols varying with the introduction pathway (Table 1). Event data were recorded on (i) introduction pathway; (ii) physical location where specimens were collected; (iii) date of the event; (iv) the origin of the commodity; (v) specimen taxa (order

Table 1 Comprehensive description of the introduction pathways to Barrow Island, Australia (Chevron Australia, 2017)

Introduction pathway	Abbreviation	Description
Personnel and Luggage	PL	All cabin crew and passengers that travel to BWI and their luggage
Offshore Personnel Transfer	OPT	Transfers of personnel from non-compliant or uncontrolled offshore facilities and neighbouring island to BWI
Containerized goods	CoG	Items that were cleaned, treated, inspected and packed into containers for transportation
Crated goods	CG	Items that were inspected and packed into crates for transportation
Modules	MOD	Large, prefabricated LNG plant components constructed in international construction yards and shipped to BWI
Food and Perishables	FP	All food and materials associated with camp requirements sent to BWI
Sand and Aggregate	SA	Comprises road base, trench fill, sand, and aggregate
Special and Sensitive Goods	SSG	These items cannot be washed, cleaned, or chemically treated, and due to their nature, composition or intended use, requires special handling and inspection
Plant and Mobile Equipment	PME	Includes tracked and wheeled vehicles, earthmoving machinery, welders, compressors, work platforms, cranes, contractor tools and trailers on which equipment may be transported to BWI
Airfreight/Aircraft	AIRFC	Includes both passengers and all freight transported by aircraft
Domestic Vessel Wetside	DVW	All vessels arriving at BWI and its neighbouring waters from Western Australia ports
Domestic Vessel Topside	DVT	
International Shipment Wetside	ISW	All vessels arriving at BWI and its waters from international ports
International Shipment Topside	IST	
Flat rack	FR	Portable, open-topped, open-sided units that fit into existing twist lock on cargo vessel decks or on top of standardized container; suitable for complex to handle and heavy loads where cargo needs loading from the above or from the sides, such as pipes and machinery

(i) Topside—part of the hull between the waterline and the deck

(ii) Wetside—part of the hull below the waterline

or lowest taxonomic resolution), and (vi) any additional information specific to each detection incident. Detection events were divided into five categories: (i) vertebrates; (ii) invertebrates; (iii) seeds; (iv) undefined plant material, and iv) soil/organic matter.

Hierarchy of inspection controls for the Quarantine Management System at Barrow Island

The QMS in place on BWI is a fully integrated biosecurity system where quarantine measures were embedded within the procurement, contracting, and logistics processes (Scott et al. 2017). The system focused on prevention (risk assessment of the pathways), detection (inspections pre-border, at border, and post-border), and finally eradication, control, and mitigation (Chevron Australia 2017).

Early engagement ensuring operational control

Trained and company-accredited biosecurity inspectors conducted all pre-border, border, and post-border inspections. Pre-border inspections were carried out prior to cargo being loaded on vessels for transport to BWI, border inspections (on arrival), and post-border and final inspections (outside the development site).

Wherever possible, biosecurity designs were implemented during the fabrication and manufacturing processes and well in advance of the actual procedural inspection such as:

- incorporating design solutions into modules and pre-assembled units and pipe racks that eliminated niche areas by blocking or boxing out concealed areas.
- purpose-built food processing facilities and the mainland and 'no ingress, no egress' dining facilities on Barrow Island.
- purpose-built containers that facilitated inspections, treatments, and sealed out cross-contamination of cargo after containerization.
- purpose-built passenger check-in, inspection, screening, and departure lounge for aircraft from Perth to Barrow Island.
- quarantine storage, treatment, and cleaning facilities.
- shrink-wrapping of non-containerized/ crated cargo to minimize cross-contamination during transit and storage (International Petroleum Industry Environmental Conservation Association, 2012).
- unique to Barrow Island, pre-border and border inspections were done on 100% of the cargo, all cargo was cleaned, treated, and inspected twice before shipment by project accredited inspectors (Scott et al. 2017).

For each pathway, guidelines for inspections are given in Appendix A; Measures to Prevent Introductions of NIS and Marine Pests (Chevron Australia 2017). The full inspection procedure involved up to three tiers (red, blue, and green stages respectively) at separate handover points, supported by a document and multi-stage tagging system (Material Management Ticket (MMT) to ensure biosecurity compliance. All cargo, vessels (including aircraft), people, and their luggage were free of discernible evidence of biosecurity risk material (BRM). BRM was defined as plants, plant material, seeds, invertebrates, and vertebrates, as well as the agreed marine pests selected from the Australian Priority List of Marine Pests (Australian Bureau of Agricultural Resources and Economics 2018; Wells et al. 2009).

The inspected cargo that was compliant pre-border was tagged red by the contractor or vendor. The red tag was the vendor/contractor's declaration that the material/equipment was free from discernible evidence of biosecurity risk material (BRM) and that the packaging met the contractual biosecurity requirements. Before leaving vendor premises or staging areas in the supply chain (e.g., a project supply base or a contractor's quarantine-approved premises), the cargo was tagged blue by the project-accredited inspectors as confirmation that the item met the biosecurity compliance and was ready to be transported to the island. This often-required internal inspections and disassembly of complex equipment. The blue tag indicated that the cargo was free from BRM, that the documentation was correct and that all appropriate biosecurity treatments had been applied, and that the cargo was authorized to proceed in the supply chain. The blue tag was valid for seven days, otherwise aspects of the process had to be repeated. Finally, when verification that external and internal surfaces of the consignments had been completed, or confirmation that the integrity of the cargo had been maintained since the blue tag inspection, the consignment was green tagged indicating it was ready for

transportation to BWI. This green tagging was valid for only 48 h within which time the cargo had to be transported to BWI. Upon arrival at BWI, further inspections verified that no biosecurity risk material was picked up during transit and that nothing had been missed during the initial screening. Final cargo clearance was done where the consignments were offloaded. Subsequently, the cargo was transported to various locations for use on BWI.

Anything non-compliant was remediated within a Quarantine Approved Premises either by recleaning or by fumigation with either methyl bromide or ethyl formate if no flight risk existed and the BRM could be successfully contained. In very exceptional cases, the cargo was refused access to the island and was returned to the mainland or remediated at sea at a safe location offshore.

Diagnostics, classification, and responses

Detected BRM were recorded as events whether dead/non-viable or alive/viable. BRM were stored for later taxonomic identification or confirmation by trained subject matter experts. It should be noted that the terrestrial inspection effort was focused on any species present on cargo, aircraft, people, and vessel topsides whereas, the marine inspection effort was focused only on vessel wetsides. The inspection standard was for all cargo, vessels, aircraft, and people to be free for discernible evidence of plants, plant material, propagules, seeds, invertebrates, vertebrates, and marine pests (collectively referred to as BRM). The vessel wetsides inspection protocol followed an agreed potential marine pest list for reasons related to the unique biodiversity realities of the Barrow Island marine ecosystem (Hayes et al. 2005; Marine Pest Sectoral Committee (MPSC) 2018).

For the terrestrial introduction pathways, all detection events were recorded and classified according to their impact on terrestrial biodiversity on BWI. Interceptions were classified as either indigenous, non-indigenous (NIS), non-indigenous established, or uncertain (awaiting taxonomic classification) (Jarrad et al. 2011; Majer et al. 2013; Murray et al. 2015). Exemplar species were identified as being representative of the vertebrate, invertebrate, and plant species likely to enter and establish on Barrow Island with potentially catastrophic consequences. These included but were not limited to *Rattus rattus* (black rats), *Hemidactylus frenatus* (Asian House Gecko), *Cenchrus ciliaris* (buffel grass), and *Pheidole megacephala* (big-headed ant).

High-risk species were identified from a suite of species with known invasive characteristics in similar environments, the difficulty of detecting the species, and the difficulty in eradicating such species should they establish on Barrow Island (Chevron Australia, 2017; Stoklosa 2005). Species were also identified based on their known invasiveness elsewhere in the world, for example, the highly invasive species *H. frenatus*. Between 1999 and 2010, a study on incursions and interceptions of exotic vertebrates in Australia identified the Asian House gecko as a species with extreme establishment risk based on historical introductions and climate models using risk assessment models (Bomford 2008; Henderson and Bomford 2011).

Features for identification of high-risk species included climate matching with the country of origin, prior invasion success, propagule pressure, physiological tolerance, dispersal mode, and life history (Keller et al. 2007; Mathakutha et al. 2019; Seebens et al. 2017). It should be highlighted that for Barrow Island, all NIS were unacceptable, and detection of any NIS was mandatory as this was a ministerial requirement under the Barrow Island Act of 2009 (Chevron Australia 2017; Environmental Protection Authority 2009).

Invasiveness in plants is generally not a good predictor of impact according to van Klinken et al. (2013). However, Jelbert et al. (2019) showed that recovery from demographic disturbance and reproductive capacity (fecundity and seedling survival) are useful traits to predict invasiveness across the plant kingdom. For example, the invasive grass *Cenchrus ciliaris*, an existing NIS on the island, was unintentionally introduced during a restoration program.

As part of preparedness to respond to a possible introduction of NIS or marine pests, all detections were compared against a Species Action Plan List (SAPs) that was developed in consultation with the Chevron Quarantine Expert Panel (QEP). This was part of the ministerial commitment to developing SAPs for all existing NIS, those that might be introduced in future, known, or considered high-risk species including marine pests (Environmental Protection Authority 2016). The QEP consisted of experts from the government, scientific organizations, and

independent technical consultants tasked to provide technical advice concerning quarantine management on the Gorgon Gas Project to both Chevron Australia and the Australian Government.

The SAPs were categorized as follows:

1. NIS exemplar species representing broad taxa (requiring similar management responses),
2. NIS present before construction commenced and that are not covered by the exemplar SAPs,
3. NIS established attributable to the Gorgon Gas Project,
4. NIS considered being high-risk species unless covered by an exemplar SAP, located at mainland and overseas locations where cargo destined for Barrow Island originate from (Chevron Australia, 2017) (Appendix 1),
5. Marine pests identified as high risk for the waters surrounding Barrow Island.

Statistical methodology

Data were analyzed quantitatively as events where BRM was detected and the number of units per event detected. A quarantine detection event was where a suspected NIS or Marine Species was observed and reported, while a non-event was an identification that a specimen was not a NIS or marine pest species, a specimen which was non-viable or dead, hence posed no risk to the biodiversity of BWI, or was deemed not to be related to the project (e.g., a natural introduction or establishment attempt). A detection event was either a specimen of an organism or multiple specimens of the same organism. The detections events were classified as dead or alive, viable or non-viable; and indigenous or non-indigenous. Sometimes a combination of both dead and alive organisms was recorded (Scott et al. 2017). For practical reasons, in extreme cases some of the counts, such as seeds and ants, were estimated by factors of 10 (scaled to 100 or 1000 s) as per Scott et al. (2017).

Detections also included trace evidence indicating the presence (at any point in time) of organisms, including cobwebs, scat, and fur/feathers. It was important to determine the frequency of finding BRM regardless of the quantity because such frequency of detection provided valuable information that may indicate a gap in the quarantine measures or seasonality of certain events that may refocus efforts. The counts then determined the abundance of the units detected.

Quarantine events were classified as either an incident or an intercept, and were defined as follows:

- An intercept was the detection, containment, and removal of suspected NIS prior to Final Quarantine Clearance while marine pests included those detected on the wetsides while the vessel was within the limited access zone (a zone of 2.5 km offshore) or controlled access zone (a zone 500 m the project marine infrastructure) (Chevron Australia 2017).
- An incident occurred when there was a detection of NIS or marine pest on BWI after Final Quarantine Clearance or the proliferation of a NIS population on BWI or marine pests in the waters surrounding BWI as a consequence of project activities.

Quarantine incidents were classified as Level 1, 2, or 3 depending on the severity of risk the detection posed to the biodiversity of BWI. Incident Level 1 was low risk e.g., prohibited foods, *Ommatoiulus moreleti*, and parachute seeds. Incident Level 2 was either when uncertainty existed as to the risk posed due to their ability to survive on BWI or suitability of habitats or the risk was high but the ability to detect and eradicate was readily achievable due to factors such as visibility, fecundity, or slow dispersal e.g., *Christinus marmoratus*, *Solenopsis invicta* or *Setaria verticillata.* Incident Level 3 was when there was high risk, detection and eradication were likely to be difficult. Species classified under Incident level 3 included the *R. rattus*, *C. ciliaris, H. frenatus*, and the *Perna viridis*. Marine pests were those detected on the wetsides of vessels.

Analyses of introduction pathways to the island occurred in four parts:

1. The overall characterization of detection event,
2. All indigenous and NIS detected,
3. Live and dead NIS detected,
4. Viable and non-viable.

Firstly, logistics data comprising freight tonnage (total, domestic and international), inward-bound air passengers, and inspection hours were summarized.

Spearman's rank correlation analysis using (cor.test in R) was used to assess the correlation between species diversity and the number of detections across the years. Introduction pathways were assessed based on Shannon-Weiner's diversity index as a measure of species richness, diversity, and evenness in Primer 7 (Anderson et al. 2008). An introduction pathway with greater species diversity was considered to have a higher likelihood of introducing NIS because there was a larger probability of NIS being amongst the species (Lockwood et al. 2009). A Bray-Curtis similarity index was calculated to assess similarities between introduction pathways, dependent on species abundance between any two introduction pathways. Similarity profiles (SIMPROF) were constructed, and non-metric Multidimensional Scaling (MDS) was used to group the various introduction pathways according to the contaminants they transported. The cophenetic correlation coefficient was used to determine the goodness of fit of clustering in the MDS. A value greater than 0.8 signified that the dendrogram clustering profile reported did not alter the original clustering groups (Romesburg 2004). MDS stress values closer to zero indicated that the groupings were a good fit statistically. Shade plots were used to display the changes in the relative abundance of species by introduction pathways using presence/absence and fourth-root transformations.

Results

Variation in freight among project phases

Between October 2009 and December 2015, 3,864,842 tonnes of freight (excluding approximately 10 million tonnes of rock) were transported to the island, consisting of 1,835,569 tonnes of international freight and 2,029,273 tonnes of domestic freight (Fig. 2). The atypical tonnage of freight recorded during the transition period for both domestic and international freight was attributed to specific activities occurring during that time.

Specific peaks in detections corresponded to peak freight during major construction phase in April 2012, January 2013, April 2013, and November 2014 (Fig. 3). Domestic and international freight tonnage to Barrow Island did not exhibit a consistent pattern, with several spikes; spikes are indicative of new construction activity, different cargo profiles, new contractors on site, etc. (pers comm van der Merwe 2020). High tonnage of freight was recorded between October 2011 and December 2012, with spikes during the construction phase in May 2013, April 2014, and February 2015, corresponding to the peak construction phase (Fig. 3).

In contrast, air-passenger movement to BWI continued to increase steadily until May 2015, then declined sharply as fewer personnel were required for the transition phase and subsequent operational phase (Fig. 4).

Species richness was positively correlated with the number of detections ($r = 0.883$, $p < 0.0001$). Variation in the number of detections corresponded to changing patterns in freight tonnage (domestic and international) and with the number of air passengers arriving on the island.

Introduction pathways with the highest detections rates were Domestic Vessel Topside (27.6%), Flat Rack (19.4%), International Shipment Topside (19.2%) and Containerized Goods (11.4%), accounting for 77.7% of all the border detection events between 2009 and 2015. Vessels underwent multiple biosecurity inspections throughout their voyages to ensure that their cargo was free of BRM. Despite this concerted effort, these four pathways had the highest number of detections indicating in-transit contamination, primarily from hitchhiker pests.

Variation in activities associated with the three construction phases was reflected in border detection events. In the early construction phase, most border detections were associated with the following introduction pathways: Containerized Goods, Flat Racks, Plant and Mobile Equipment, International Shipment Topside, and Domestic Vessel Topside. This was related to the nature of equipment that was required on site. Priority was given to the acquisition of new equipment; however, the use of used equipment was unavoidable that increased the risk of BRM, notwithstanding the disassembly of complex equipment during preparation, treatment, and inspection.

Following the commencement of the major construction phase, all introduction pathways recorded significantly higher counts of both pre-border and border detections, except for Domestic Vessel Wetside, International Shipment Wetside, Sand and Aggregate, and Special and Sensitive Goods. This was related to a dramatic increase in freight

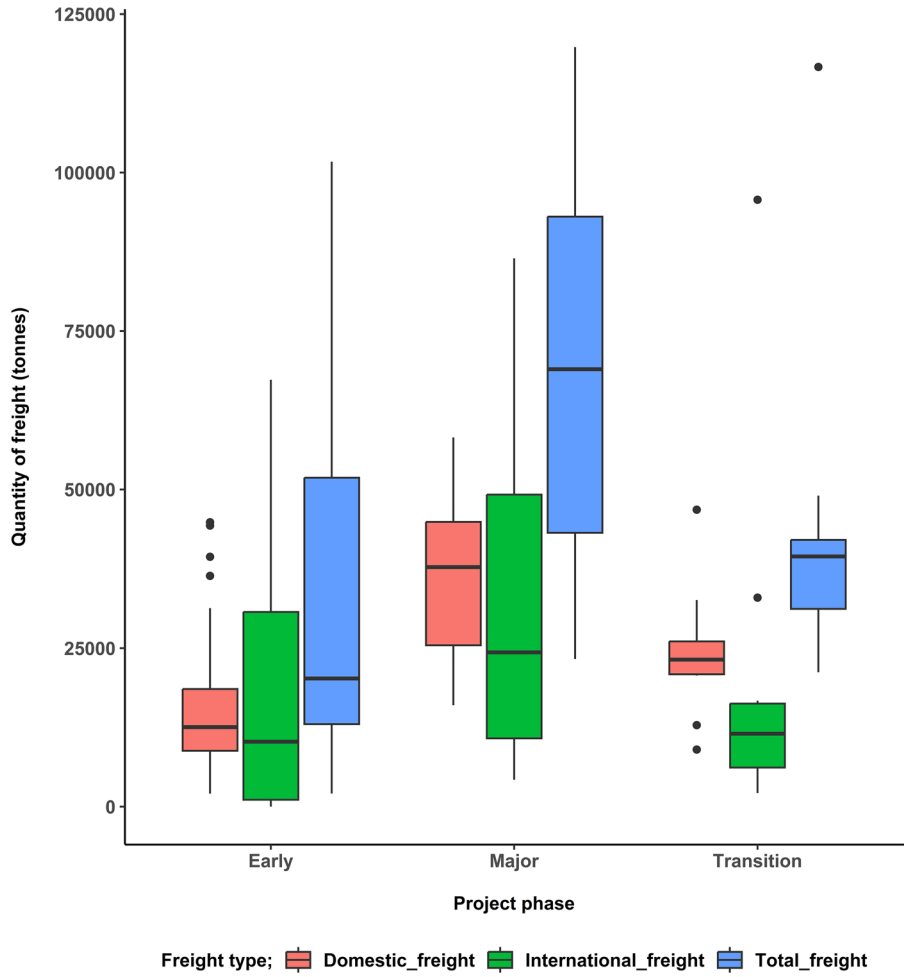


Fig. 2 Distribution of freight (tonnes) to Barrow Island, Australia from 2009 to 2015 by project phase

volumes and people moving onto the island. More construction activity meant more beds, more food, and more supporting functions, i.e., administration, emergency management, health, and safety, which contributed to higher detection counts.

Detections declined significantly during the transition phase for other introduction pathways except with Containerized Goods, Plant and Mobile Equipment, Food, and Perishables, and Personnel and Luggage. During this phase, the focus was more on the early start-up and operations functions that required significantly fewer people on site. Other activities related to removing redundant and surplus equipment and material off the island posed a much smaller risk profile from a biosecurity perspective.

Variation in the species diversity and abundance of detections

The detection events totaled 5,328 and were classified as incidents, intercepts, indeterminate, or non-events. Live NIS detected prior to final clearance (intercepts) and after final clearance (incidents) constituted 27% and 2% of the detection events respectively. Indeterminate events made up 14% of the detection events and were specimens that could not be classified taxonomically because of the life stage (e.g., juvenile or nymph stage) or taxonomic keys were not available e.g., moths. Finally, non-events (57% of the detection events) were dead indigenous, non-indigenous or NIS already known to occur on Barrow Island before the commencement of the project due to historic

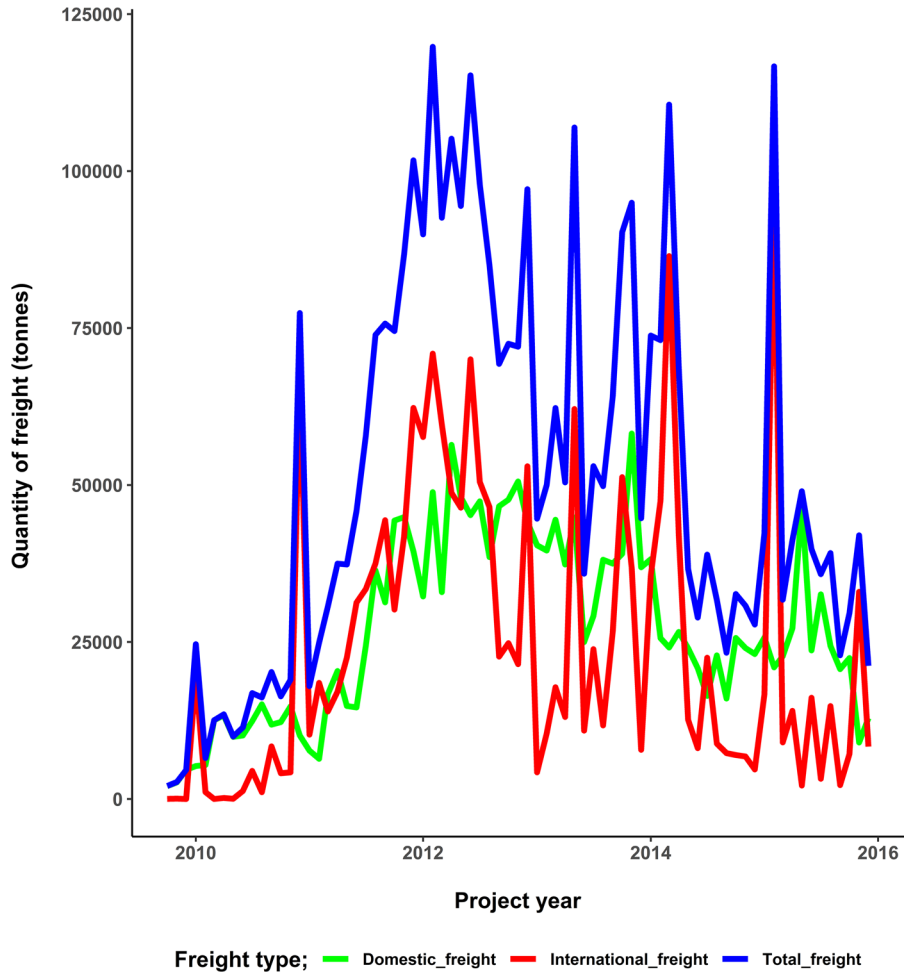


Fig. 3 Quantity (tonnes) and type of freight transported to Barrow Island, Australia between October 2009 and December 2015

activities unrelated to the Gorgon Project (Fig. 5). Of critical significance were incidents (114) that accounted for 2% of the total detection events. These incidents consisted of 69 invertebrates, 26 seed, 12 plant propagule, and seven vertebrates, making up 61%, 23%, 11% and 5% of the incidents, respectively.

In terms of biosecurity risk material classification, the detection events recorded were 65% animals (vertebrates-143 and invertebrates-3,323), and 35% were plant material (470) and seed (1,392). Of the 3,323 invertebrate species detected, 3,259 (98%) were arthropods and 64 (2%) were molluscs. Of the 659 NIS detected, 605 NIS were arthropods and 54 were molluscs. Insects were the dominant arthropod class detected consisting of 2,842 (85.5%) detections with 513 (18.1%) NIS, while the remainder were spiders, centipedes, millipedes, crabs, and springtails. The 513 NIS insects consisted of 35 incidents, 141 intercepts, 307 non-events, and 30 indeterminate species. The insect orders Coleoptera, Lepidoptera, Hymenoptera, Hemiptera, and Diptera constituted 84.2% (2,393) of the arthropod detection events with 412 NIS detected. The dominant insect order was the Coleoptera with 937 detection events, Lepidoptera and Hymenoptera constituting 479 and 414 detections, followed by Hemiptera with 324 and Diptera with 239 events. The dominant NIS incidents were the *Blattella germanica* (11) and the *Drymaplaneta semivitta* (8) out of a total of 41 insect incidents. No high-risk invertebrate species were detected i.e., *Pheidole megacephala* or *Monomorium destructor.* Additional information on the distribution of the orders in Class Insecta are given in SI 1: Distribution of detections and abundance of orders in Class Insecta at biosecurity border inspection for Barrow Island, Australia from 2009 to 2015

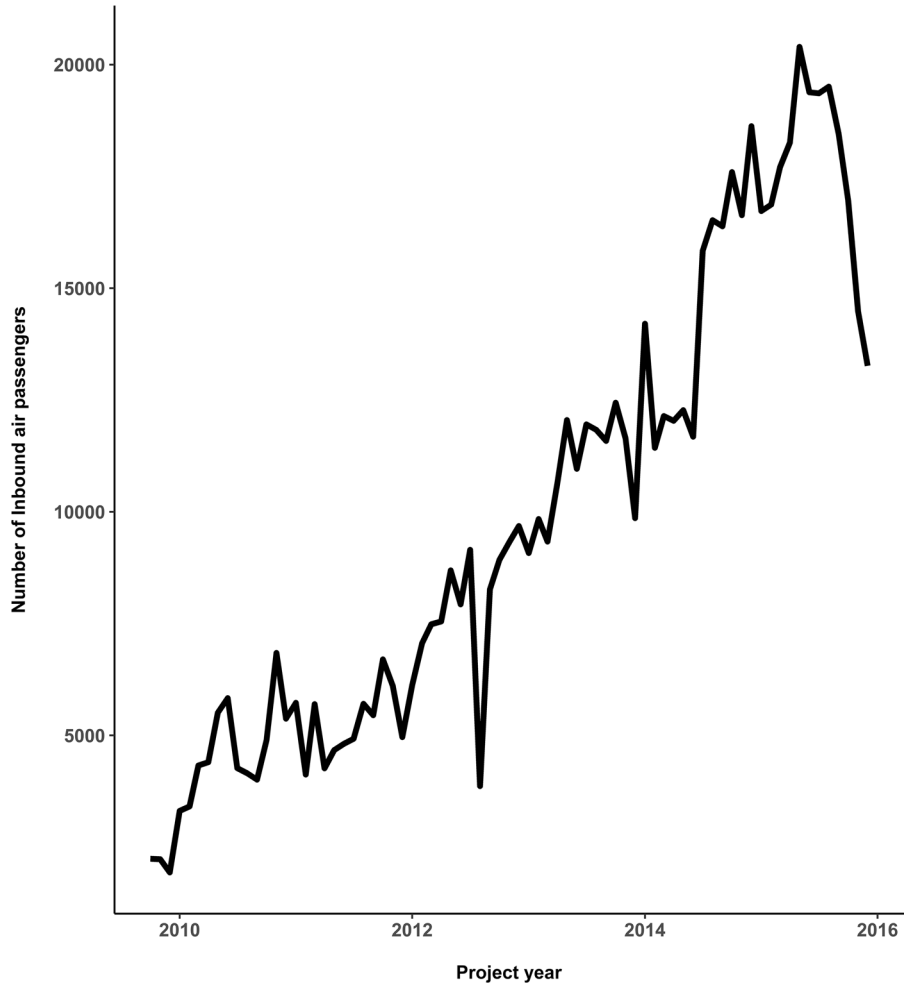


Fig. 4 Passenger movement to Barrow Island, Australia between October 2009 and December 2015

ranked according to the detection counts (ALA: http://www.ala.org.au) (Table 2).

The live specimens of *Ommatoiulus moreleti*, which is a pest species in Perth where many supply bases, storage yards, contractor premises, and most workers came from, were found in Airfreight/Aircraft, Containerized Goods, Personnel and Luggage, and Food and Perishables pathways (Fig. 6). *Ommatoiulus moreleti* is unlikely to survive on Barrow Island due to the dry climatic conditions. Of the top ten NIS species, all were detected in the Food and Perishables pathway,, except *Coleocoptus senio* and *Oryzaephilus surinamensis*. These exceptions were found only on Containerized Goods and Airfreight/Aircraft pathways, respectively. *O. surinamensis* is a stored product pest recorded from products such as e.g., rice, flour, cereals, nuts, and beans, and in this instance, it was found in oats cereal (from luggage) in Airfreight and Aircraft.

Distinct groupings of introduction pathways were identified using non-metric multidimensional scaling (MDS) analysis based on commonality of species associations using presence/absence transformation (Table 3).

Groupings A and B had 14.6% and 14.3% similarity using the Bray Curtis similarity, whilst C and D had individual introduction pathways, namely Modules and International Shipment Topside. Two-dimensional stress for nMDS was 0.06 indicating a good separation of the pathways into the four groups.

Further, using analysis of similarity (ANOSIM), the sample statistic R was 0.8, with a 0.08% level of significance. Pairwise analyses showed that only groups B and D were significantly different

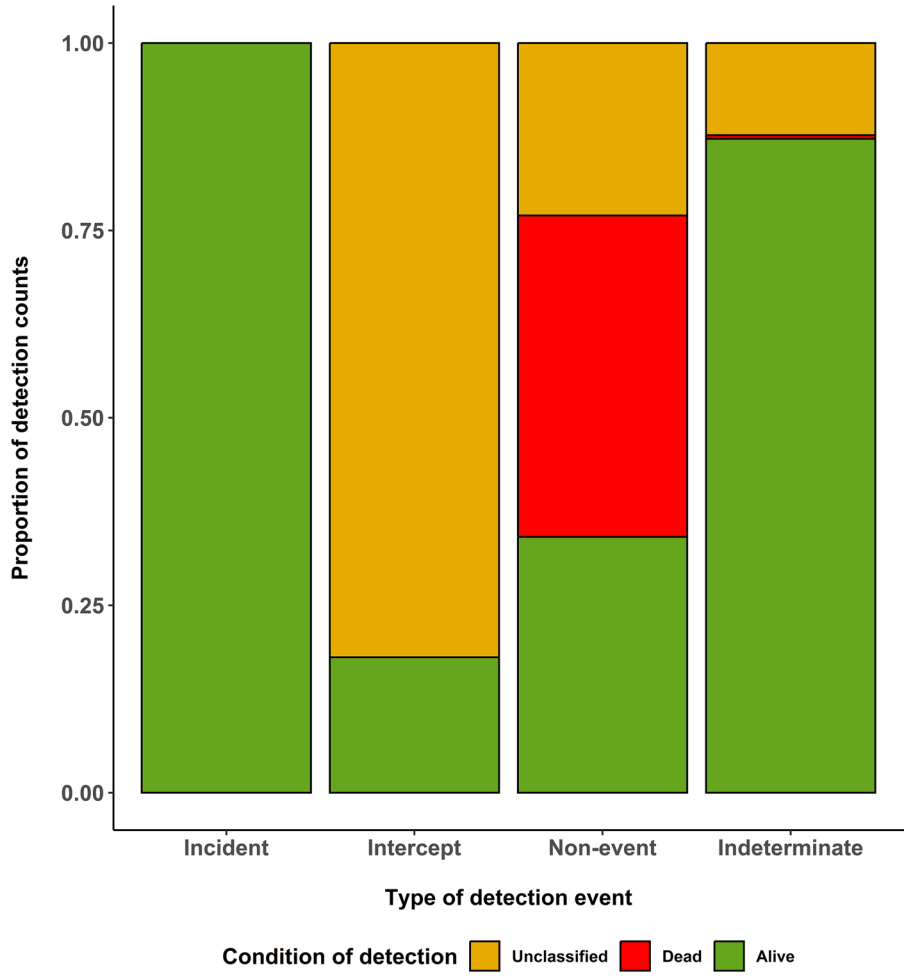


Fig. 5 Classification of detection events for Barrow Island, Australia from 2009 to 2015 by viability (dead/alive)

Table 2 Live non-indigenous insect species classified as Incidents for Barrow Island, Australia from 2009 to 2015

Order	Species	Common name
Blattodea	*Blattella germanica*	German Cockroach
	Drymaplaneta semivitta	Gisborne cockroach
Coleoptera	*Anthrenus verbasci*	Variegated carpet beetle
	Coleocoptus senio	Longicorn Beetle
	Coptocercus rubripes	Round-headed Wood Borer
	Listroderes difficilis	Vegetable weevil
	Meloidae Palaestra sp. *A*	Blister beetle
	Oryzaephilus surinamensis	Saw-toothed grain beetle
	Phrynocaria astrolabiana	Ladybird
Dermaptera	*Carcinophora occidentalis*	Earwig
	Forficula auricularia	European earwig
Hemiptera	*Cimex lectularius*	Bed Bug
	Plautia affinis	Shield bug
Hymenoptera	*Ochetellus glaber*	Black house ant
Lepidoptera	*Epiphyas postvittana*	Light brown apple moth

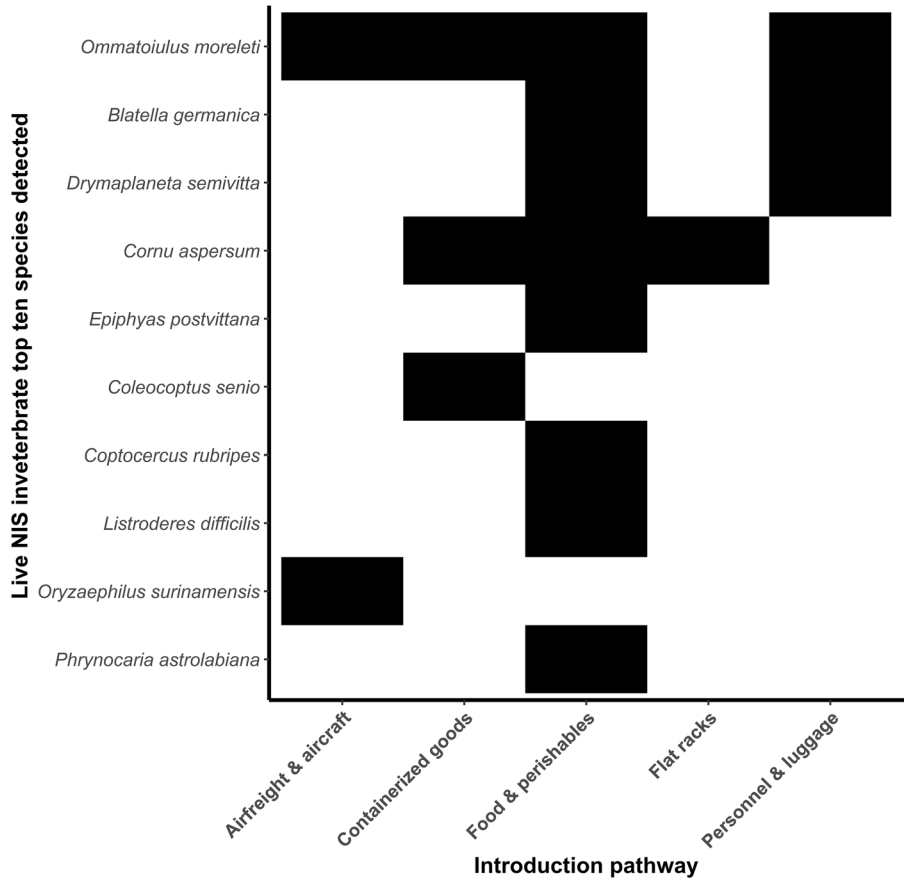


Fig. 6 Distribution of ten most frequently detected invertebrate species by introduction pathway for Barrow Island, Australia from 2009 to 2015 (shaded black for presence and white for absence)

Table 3 Diversity and distribution of non-indigenous invertebrate species detection events by introduction pathway for Barrow Island, Australia from 2009 to 2015 using non-metric multidimensional scaling (nMDS).

Introduction pathway	Number of detection events	Number of Species	Species richness	Species evenness	Shannon-Weiner Index	nMDS similarity grouping
	N	S	D	J'	H'($\log_e$)	
Direct Vessel Topside	171	102	21.93	0.8054	3.725	A
Food and Perishables	125	60	12.81	0.6279	2.571	A
Personnel and Luggage	105	40	8.469	0.6083	2.244	A
Containerized Goods	53	38	8.034	0.8749	3.182	A
Flat racks	57	37	7.817	0.7938	2.866	A
Plant and Mobile Equipment	15	13	2.606	0.6072	1.557	A
Offshore Personnel Transfer	1	1	0	–	0	B
Airfreight and aircraft	14	13	2.606	0.6695	1.717	B
Modules	17	12	2.389	0.893	2.219	C
International Shipment Topsides	101	73	15.63	0.745	3.196	D
Sand and Aggregate	0	–	–	–	–	–
Special and Sensitive Goods	0	–	–	–	–	–
Crated Goods	0	–	–	–	–	–

N.B. Calculations for D-Margalev's species richness index; J'-Pielou's species evenness index; H'-Shannon-Weiner diversity index were conducting using methodology from Clarke and Gorley (2015)

($p = 0.036$). There was only one detection event of invertebrates on Offshore Personnel Transfer (OPT).

Three introductory pathways were free of NIS invertebrate detections, namely Sand and Aggregate, Special and Sensitive Goods, and Crated Goods because of the nature of the goods they transported and the biosecurity protocols that were applied. For example, in the Sand and Aggregate pathway, the sand was deep-mined and stored in containers, while for Crated Goods the wood was chemically immunized according to the Australian timber preservation standards (AS1604) and Special and Sensitive Goods (that are manufactured or assembled under clinical or hygienic conditions) were thoroughly inspected before being placed in containers.

There were 1,862 detection events for plants, seeds accounted for 74.8%, while 25.2% were plant material including leaves, twigs, and stems. The most commonly detected seeds were Orders Poales (64.8%), specifically the parachute seeds *Typha* sp., *Cortaderia* sp. followed by Asterales (22.8%), mainly *Sonchus oleraceus*. These three species, in the context of Barrow Island, can be classified as benign weeds that are known pioneer or disturbed specialist species. There were 1,122 NIS seed detection events, and only 0.5% (6) were *C. ciliaris* detections on Containerized Goods (CoG) and Flat racks (FR). Most seeds that contaminated vessel topside and the cargo on the deck were parachute seeds that settled on vessels and on cargo during transit from the mainland to the island, or from international staging areas and fabrication facilities en route to Barrow Island (J. van der Merwe, personal communication 2020). *Typha* sp. is a cosmopolitan iconic plant occurring in high densities in the Perth wetlands. The species is associated with permanent water that is not found naturally occurring on Barrow Island (other than one small seep/spring on the far side/west coast). The species and genus are found worldwide except in the Antarctica (Bansal et al. 2019; Zhou et al. 2018). *Typha* sp. seeds can attach to machinery, humans, and their luggage, and can be transported long-distance dispersal on cargo, via storms, floods, winds, and birds (http://www.ala.org.au). *Cortaderia* sp. and *S. oleraceus* are weeds that thrive in low fertile soils and can exhaust surface soil water preventing the establishment of native plants. They are pioneer plants on disturbed lands such as road verges. Of interest were nine detections of three *Avena* species that are commonly transported via people and their luggage and plant and mobile equipment, two of the identified pathways we discuss.

Most live detections (76.7%) were from four introduction pathways, Food and Perishables (22.3%), Personnel and Luggage (22%), International Shipment Topside (17.6%), and Domestic Vessel Topside (14.8%). No live vertebrates were detected on Personnel and Luggage, while no live plant material was detected on International Shipment Topside.

There were 79 NIS vertebrate detections of which seven were quarantine incidents namely three *Litoria rubella*, three *Christinus marmoratus*, and a single *Amphibolurus longirostris*. Note that another unassigned incident, the *H. frenatus* was recorded at the WAPET landing. No *R. rattus* were found, but on four occasions single scat samples were found on Containerized Goods, Direct Vessels Topsides, Food and Perishables, and International Shipments Topsides.

Live NIS detection events were highest in 2013 when a step-change in construction activity occurred. This step-change included a change in freight profile as international cargo increased and the spike in workers, many working on Barrow Island under the strict quarantine regime for the first time, and the resulting increase in hospitality, catering, and housekeeping activities for the more than 8,500 workers on-site at peak. This resulted in increased live NIS detections for the following pathways: Food and Perishables (27 detections) and Personnel and Luggage (31 detections), while limited live NIS detections were found in 2010 and 2015. Live NIS detections on Food and Perishables (FP) and Personnel and Luggage (PL) pathways were seen throughout the project life (Fig. 7). The atypical distribution of the total detection events was for the pathways International Shipment Topside and Sand and Aggregate, which had relatively low numbers of detections events (1,034 and 8 respectively) but in contrast had high numbers of organisms/units detected (5,333 and 952 respectively).

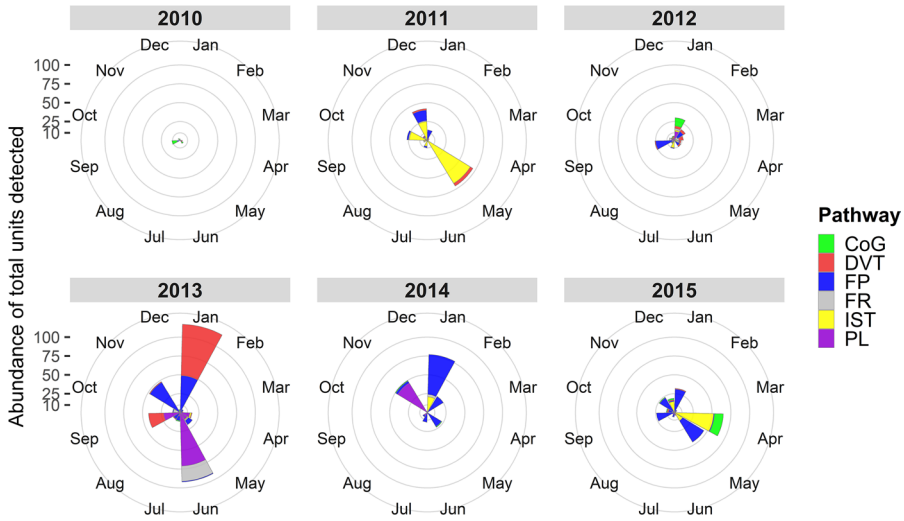


Fig. 7 Temporal variation (years and months) in the total detections of live non-indigenous species for Barrow Island, Australia for each introduction pathway from 2010 to 2015. N.B In the legend the introduction pathways are: CoG-Containerized Goods; DVT-Domestic Vessel Topside; FP-Food and Perishables; FR-Flat Racks; IST-International Shipment Topside; PL-Personnel and Luggage

Discussion

The arrival and survival of NIS (i.e., live NIS) at biosecurity borders globally are of great concern and the subject of extensive biosecurity effort. Pathway studies generally describe the diverse routes by which NIS can be introduced but rarely consider multiple introduction pathways occurring simultaneously. In this study, border detection events were investigated during a major industrial development on a remote island for 15 introduction pathways. These pathways were identified as high risk initially through unique qualitative risk assessments conducted before the project commenced. It was recognized that in-transit contamination was inevitable through hitchhiker pests that sometimes have dormant life stages, allowing them to survive extended periods in transit. (Hayes et al. 2005; Stoklosa 2004). Each introduction pathway had a unique suite of characteristics that resulted in an association with specific NIS. This required specific barriers that were tested and adopted as measures to reduce the associated risks of introduction via these pathways. As such, each pathway required different approaches for effective biosecurity management.

Cargo, vessel, aircraft, and personnel inspections resulted in 600,000 biosecurity inspections, with less than 0.1% NIS detections. Detection of 3.5% NIS established on the island before the Gorgon LNG Project provides an indicator of the exposure pressure historically experienced on Barrow Island when a comprehensive biosecurity management system was not in place (M. Thomas, personal communication, 2020). Post-border surveillance showed that no NIS species had been introduced and become established on Barrow Island post inception of the industrial project (Scott et al. 2017). The limited number of NIS species that were detected on Barrow Island have been eradicated, e.g., *H. frenatus*, sporadic germination of *Typha* sp. in drains on the construction site, *Sonchus* sp. on mainly cleared and disturbed areas, tomato mainly in the confines of the accommodation camp (amongst the clusters of buildings), or those NIS that are under a long-term quarantine control response such as *C. ciliaris* and *A. javanica*. There is on-going high biosecurity vigilance for NIS species that have a high ecological impact, are rapidly invasive, and are known to have been present (e.g., the successfully eradicated *A. javanica*) or are present on Barrow Island, such as *C. ciliaris* (only as historic seedbanks) and the *H. frenatus* that was introduced through the WAPET Landing.

This research reaffirmed that vessel topsides (Direct Vessel Topsides and International Vessels Topsides), external surfaces of Flat Rack, and Containerized Goods have the propensity to transport a diverse assemblage of NIS and had the highest counts of live NIS at the border (Miralles et al. 2021). It also highlighted the challenge of managing in-transit contamination events. As such, these pathways presented significant challenges to the biosecurity strategy that had an objective of zero introduction of NIS to the island. Many detections were of the *Typha* sp. (seeds), which are

easily dispersed by wind and consequently readily contaminate exposed surfaces during transit (Scott et al. 2017). Vessel topsides were cleared of BRM before loading and after loading, hence most of the contamination happened during transit. Topsides of vessels had a high propensity for becoming infected as they have large, exposed surfaces, allowing organisms to attach/ hide more readily, and as such have an increased chance of hitchhikers being transported with the vessel. Coleoptera and Lepidoptera were the most frequently detected insect orders on vessel topsides. In both cases, these were flying insects that were attracted to the lights on the vessels and were mostly species endemic to BWI. It should be noted that the vessels were fitted with low sodium vapour lights, and this attracted even fewer insects. Further, Lepidoptera species have the propensity to hide in dark gaps and crevices, are attracted to ship lights, and their pupae and eggs affix easily to steel surfaces and hence can be transported in containers and machinery undetected (Jenkins et al. 2014; Meurisse et al. 2018). In this study, there were 24 detection events of insect eggs, mainly from orders Araneae, Lepidoptera, and Coleoptera, 13 detection events were insect pupae from Hemiptera, Diptera, and Hymenoptera.

Vessel speed, journey duration and ports of call, location of cargo loading, and origin of cargo can all influence the capacity of vessels to transport non-indigenous species (Hulme 2009; Inspector-General of Biosecurity 2018). The cargo loading process itself can attract organisms according to the timing of loading (i.e., night versus daytime) and the speed/ duration with which loading occurs (Caton et al. 2006). However, in this study night-time loading was prohibited because there was a high risk of insects being attracted to the lights. To minimize attracting insects into the staging and loading areas on the mainland supply bases, non-attracting low sodium vapour lights were used within these areas, and insect attracting lights were installed on the periphery of these areas to attract flying insects away from the loading and staging areas. Inside supply base warehouses low sodium vapour lights sought to achieve the same outcome.

Duration and conditions during transit affect the survival of species detected at biosecurity borders, e.g., the effect of residual chemicals reduces the likelihood of survival, which influences the probability of establishment and recruitment in the receiving environment (Essl et al. 2015; Pyšek et al. 2011). Most live species detected on vessels on arrival at BWI were species known to occur on Barrow Island. Due to shipping schedules, arriving vessels would lie at anchor overnight awaiting discharge the next morning with minimum operational lighting required maritime safety regulations. This attracted insects, notably moths, that could survive the residual insecticide applied at the time of loading to cargo containers, flat racks, and out-of-gauge equipment due to limited time exposed before inspection during discharge and final clearance. The likelihood of NIS survival was thus further reduced by this application of residual insecticide to vessel topsides.

By their very nature, different introduction pathways vary in the availability and accessibility of suitable niches, availability of food sources during transit and suitable environmental conditions. Consequently, these factors influence the type of organisms that are likely to be transported. This is further enhanced by the biological and ecological characteristics of the organism, or the product/item being transported. (Sheikh et al. 2017). As an example, in the Food and Perishable Pathway, fresh food was challenging in terms of the elimination of NIS due to the nature of the food (e.g. green leafy vegetables had small insects such as leave miners, micro wasps, fruit had scale insects, while brassicas had micro insects in flowering heads, etc.) that evaded the best efforts of washing, peeling, topping, tailing, seeding and then pre-sealing in packaging before shipment. Similarly, flat racks and containers have niche areas such as twist locks, underside niches, wooden gluts, and plywood floorboards that harbour fugitive species attempting to evade detection.

Consequently, introduction pathways require (if not demand) a refinement of biosecurity protocols much more than a greater inspection effort to minimize the likelihood of their transporting unwanted biosecurity risk material. This was evident in the specification within the QMS that required a hierarchy of controls emphasizing design solution, procurement, and contracting requirements, training, and education of the entire workforce. Further biosecurity measures including preparation, cleaning and treatment specifications of goods, unique inspection protocol (including disassembly of equipment, stage tagging, custody, and control protocol, clearance, and rejection process) support post-border by strong surveillance

and monitoring commitments which included a preparedness to respond capability.

As part of this industrial project on BWI, biosecurity measures included a design solution that eliminated known niche areas on equipment and the modularized units associated with the gas processing facility. These included and were not limited to weeping holes that prevented pooling of water, boxing out of areas difficult to inspect and treat, grated walkways, container designs that eliminate difficult underside inspection and supported the ease of washing, automated container wash-bay designs, and many more. Given the inherent difficulty of managing food free from any BRM, catering facilities were developed on the mainland and on the island that supported the processing of fresh and pre-packaged food (frozen food by nature did not pose a biosecurity risk). In addition to the discussed preparation and inspection of fresh food, packaged food, such as flour and cereal, were transported in their packaged state and thus had the potential to contain stored pests before shipment. To prevent such BRM from escaping onto BWI, fit-for-purpose kitchen and dining facilities were designed on the island that included 'no ingress, no egress' specifications including but not limited to air curtains, temperature-controlled areas, specially designed loading docks, and a closed waste management system.

Specific pathways related to workers (Offshore Personnel Transfers, Personnel Luggage, and Aircraft/ Airfreight), present serious challenges in terms of biosecurity compliance and monitoring. Workers were expected to undergo inductions, project-specific quarantine training related to various roles and jobs, comply with specific biosecurity protocols (including a declaration card on voluntary compliance), and any oversight was corrected at final inspection after check-in where footwear, bags, equipment were rejected. Enforcing worker compliance was challenging, however improved biosecurity relied on appropriate and ongoing education, training, and most importantly, compliance. Frequently visited islands, like the Galápagos Island, are likely to experience an increase in the introduction of invasive species due to increasing human activity (Balchin et al. 2019; Toral-Granda et al. 2017). In contrast, BWI is likely to have a reduced workforce as it goes into the operational phase of the project. To assist biosecurity managers in overcoming these inherent human-related risks, statistical profiling for the intervention of biosecurity risk material can be a useful tool for improving the efficiency of detecting personnel at high risk of non-compliance and thus focus thorough inspection on the targeted cohort (Lane et al. 2017). Transient workers presented a higher biosecurity risk than permanent workers who were more attuned and familiar with strict biosecurity protocols. Biosecurity managers need to be mindful of the problems posed by visitor/ worker non-compliance and associated with future human movement globally.

Not surprisingly, the number of detections and species diversity increased relative to the movement of freight and personnel to BWI, with a peak in construction activity between 2012 and 2014. More importantly, the volume of traffic was positively related to the abundance of different classes of live NIS detected, with detections of NIS insects and seeds increasing with vessel traffic. Strict adherence to vessel biosecurity measures is therefore necessary (Booth and Wells 2012; Clarke et al. 2017; Zabin et al. 2018).

When biosecurity managers are assessing data, it is important to acknowledge propagule pressure, which incorporates the increased intensity of arrival events (i.e., frequency of detections) and the propagule size (abundance of organisms detected) (Simberloff 2009). Propagule characterization is important for invasive species with Allee effects (i.e., species whose survival probability increases with the density of the population) and low propagule pressure (Courtois et al. 2018). This is an important differentiating factor as the higher the frequency of detection, the greater the likelihood of an incursion event. In terms of biosecurity management, close attention should be paid to introduction pathways that demonstrate the potential for both types of detection patterns.

Our study identified that the most abundant detections were invertebrates, followed by seeds, with a smaller proportion of plant material and vertebrates. Similar patterns were observed during a study of the Australian Federal Department of Agriculture and Water Resources (DAWR) vessel inspection data from January 2010 to December 2015 (Clarke et al. 2017) further highlighted that the nature of vessel inspection procedures was heavily biased towards terrestrial and non-aquatic species. Apart from visual inspection, a variety of techniques can be implemented to detect insects, and these include baited

traps and lures, acoustic and laser vibrometry (Poland and Rassati 2019; Suckling 2015).

Although all detection events are important in understanding biosecurity risks or gaps in biosecurity requirements, live NIS species presented the real biosecurity risk to BWI and were analyzed in greater detail. On BWI, the focus was on incidents that were classified as levels 1–3, with increasing severity of the risk to biodiversity on BWI. There was one unassigned Level 3 incident (the original pathway of introduction could not be determined but was accepted as project attributable) involving an Asian House Gecko at the WAPET Landing in April 2015, which was successfully eradicated. Single detections of *C. marmoratus* were recorded on Food and Perishables, Containerized Goods and Flat Racks pathways. There was uncertainty about the risk posed by the marbled gecko due to its ability to survive in the arid and hot BWI environment. Risk assessments at the beginning of the project identified Food and Perishables, Personnel and Luggage together with the Sand and Aggregate Pathway as the priority pathways and posing the highest high risk. Though the Sand and Aggregate Pathway was initially assessed as a priority pathway, the implementation of strict mining requirements (deeper than 2 m) and processing and storage requirements (including containerization of all sand and aggregate into half-height containers) and large enclosed bunded storage on BWI resulted in a very low risk of NIS introduction. This demonstrated that with good biosecurity management, and adequate design specifications and procedural requirements a zero-detection outcome is possible even for high-risk pathways.

Some detection events were trace elements (e.g., cobwebs, scats, fur, skin, remains of fish, and faeces of seabirds that rested or ate the meal on deck) indicating a presence at some point in time of an organism. Ramsey et al. (2018) demonstrated the difficulty of collating scat observation to the presence of live foxes in Tasmania since the scat only demonstrated that a live organism had been present, but its current location was indeterminate. Trace evidence was, however, useful as indicators of where the organism is likely to be found to direct future surveillance efforts. It should be noted that when vessels left for BWI, they were free of discernible biosecurity risk material as they underwent two verification checks immediately prior to leaving.

Taxonomic classification to species levels was not done for many of the specimens because either taxonomic tables were not available, the specimens presented were in poor condition, only parts of the specimen were available, or were unidentifiable life stages (juveniles). However, a para-taxonomic framework provided continuity in identification between specimen and specimen classification is an ongoing project for Barrow Island. Efforts are underway to establish a complete molecular database for all invertebrates that will eliminate any uncertainty regarding the indigenous status of a detection. Also note that in all instances, incidents were positively identified, and indeterminate status was applied to intercepts and non-events (as defined earlier).

Conclusion

Transportation of live NIS is of greatest biosecurity concern because they are a viable incursion source should they establish in suitable habitats. Consequently, determining where live NIS are most likely to be detected is key to effective biosecurity. Quantitatively evaluating NIS detections in various introduction pathways is an important process in assisting biosecurity managers in focusing on biosecurity surveillance and reducing the likelihood of incursions. In our study, each introduction pathway differed in the abundance and frequency of NIS detections. There are multiple reasons for these differences, including the type of commodity being transported, the potential of the commodity to attract organisms, surveillance effort, ease of treatment introduction pathway type, and surveillance success by target species. Greater biosecurity effort needs to be focused on exposed surfaces and human-related pathways since these introduction pathways are susceptible to live NIS and thus pose a definable biosecurity problem. Our study emphasized that the introduction pathways with the highest likelihood of detection varied with the port of origin and the cargo being transported.

It is important to highlight that biosecurity border inspection data are rarely made available other than to designated organizations and departments due to the sensitivity of the information, confidentiality and privacy concerns, and the potential for misinterpretation and misuse of information, as

evidenced in trade disputes (Fraser et al. 2019). The accessibility of these data was an exception and should be encouraged more broadly to increase the knowledge base in biosecurity research. Further, the collaboration between academia, industry, and government in research allows a comprehensive approach to research issues feeding directly into policy and innovation, while economically benefitting society at large. Opportunities like these should be encouraged in mainstream research.

The way forward is to ensure that introduction pathways are adequately risk-assessed and modifications to biosecurity management procedures are sufficient and suitably flexible to adapt to changing biosecurity factors associated with the movement of personnel and cargo (including what happens on vessels and aircraft even after verification and validation of their compliance). The systems approach in combining biosecurity assessment of multiple pathways and pests simultaneously across the biosecurity continuum demonstrated the effectiveness of this strategy in biosecurity surveillance and monitoring resulting in reduced NIS detections at border and post-border. Adaptive use of data in decision-making allows timely interventions, pinpoints where resources can be effectively applied, and minimizes the likelihood of incursions.

Whenever resource development occurs or there is an expansion into undisturbed areas, it is imperative that a comprehensive biosecurity programme is implemented to minimize loss or significant impact on biodiversity. In places of high conservation value, such as Barrow Island, the goal should be to prevent the introduction of new non-indigenous species as standard practice as it is not possible to accurately predict which NIS will be the next pest in a new environment.

Acknowledgements The authors acknowledge the support provided by Jenna van Niekerk from Chevron Australia Pty Ltd in providing the data for this research. KM acknowledges support from the Australian Research Council (ARC) Centreof Excellence in Mathematical and Statistical Frontiers (ACEMS) and the ARCLaureate Fellowship Program under the project 'Bayesian Learning for DecisionMaking in the Big Data Era' (FL150100150).

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This research was conducted under an Australian Postgraduate Award through Murdoch University.

Data availability On request with permission from Chevron Australia Pty Ltd.

Code availability Available from corresponding author.

Declarations

Conflict of interest Dr. Barbara Kachigunda, Dr. Grey Coupland, Prof.Kerrie Mengersen, Dr. Devindri. I. Perera, Dr. Johann van der Merwe, and Prof.Simon McKirdy declare no potential conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Act BI (2003) Barrow Island Act, N0 061 of 2003, Parliament of Western Australia. https://www.legislation.wa.gov.au/legislation/statutes.nsf/law_a6988.html

Act E (1999) Environment Protection and Biodiversity Conservation Act. Commonwealth of Australia

Allen ACIL (2015) C. A snapshot of Chevron's realised and forecast economic benefits in Australia. https://australia.chevron.com/-/media/australia/publications/documents/acil-allen-report-snapshot.pdf

Anderson M, Gorley RN, Clarke RK (2008) Permanova + for primer: guide to Software and statistical methods. Primer-E Limited

Australian Bureau of Agricultural Resources and Economics (2018) Marine Pest Sectoral Committee (MPSC), Australian Priority Marine Pest List: processes and outcomes. https://www.marinepests.gov.au/

Balchin J, Duncan D, Key G, Stevens N (2019) Biosecurity on St Helena Island–a socially inclusive model for protecting small island nations from invasive species. Island Invasives 62:468

Bansal S, Lishawa SC, Newman S, Tangen BA, Wilcox D, Albert D, Anteau MJ, Chimney MJ, Cressey RL, DeKeyser E (2019) Typha (Cattail) invasion in north american wetlands: Biology, regional problems, impacts, ecosystem services, and management. Wetlands 39(4):645–684

Bomford M (2008) Risk assessment models for establishment of exotic vertebrates in Australia and New Zealand. Invasive Animals Cooperative Research Centre Canberra

Booth G, Wells F (2012) Setting a new benchmark in managing biofouling on vessels operating in a sensitive marine environment. In: International Conference on health, safety and environment in oil and gas exploration and production

Caley P, Ingram R, De Barro P (2015) Entry of exotic insects into Australia: does border interception count match incursion risk? Biol Invasions 17(4):1087–1094

Caton BP, Dobbs TT, Brodel CF (2006) Arrivals of hitchhiking insect pests on international cargo aircraft at Miami International Airport. Biol Invasions 8(4):765–785

Chevron Australia (2017) Gorgon Gas Development and Jansz Feed Gas Pipeline; Terrestrial and Marine Quarantine Management System

Clarke K, Gorley R (2015) Getting started with PRIMER v7. PRIMER-E: Plymouth. Plymouth Marine Laboratory

Clarke S, Hollings T, Liu N, Hood G, Robinson A (2017) Biosecurity risk factors presented by international vessels: a statistical analysis. Biol Invasions 19(10):2837–2850

Convention on Biological Diversity (2014) Pathways of introduction of invasive species, their prioritization and management. https://www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-09-add1-en.pdf

Cope RC, Ross JV, Wittmann TA, Watts MJ, Cassey P (2017) Predicting the risk of biological invasions using environmental similarity and transport network connectedness. Risk Anal 5:796

Courtois P, Figueres C, Mulier C, Weill J (2018) A cost–benefit approach for prioritizing invasive species. Ecol Econ 146:607–620

Department of Environment and Conservation (2007) Management Plan for the Montebello/Barrow Islands Marine Conservation Reserves 2007–2017 management plan no 55. Department of Environment and Conservation. https://trove.nla.gov.au/version/38933726

Environmental Protection Authority (2016) Report 1499 - Gorgon Gas Development - Additional Construction Laydown and Operations Support Area (1499). https://www.epa.wa.gov.au/sites/default/files/EPA_Report/Rep%201499%20Gorgon%20API%20060114.pdf

Environmental Protection Authority (2009) Gorgon Gas Development revised and expanded proposal: Barrow Island Nature Reserve (Chevron Australia Pty Ltd.) Report and Recommendations of the Environmental Protection Authority. Bulletin, Issue

Essl F, Bacher S, Blackburn TM, Booy O, Brundu G, Brunel S, Cardoso A-C, Eschen R, Gallardo B, Galil B (2015) Crossing frontiers in tackling pathways of biological invasions. Bioscience 65(8):769–782

Falk I, Wallace R, Ndoen ML, Surata SPK, Royce P, Mudita IW, Martiningsih NGAGE, Litaay T, Mampouw HL, Jayantini I (2011) A strategy for managing Biosecurity Across Borders. In: Managing biosecurity across borders. Springer, pp 215–236

Faulkner KT, Robertson MP, Rouget M, Wilson JR (2016) Understanding and managing the introduction pathways of alien taxa: South Africa as a case study. Biol Invasions 18(1):73–87

Fraser R, Cook DC, Haddock-Fraser J (2019) Wto and environment-related International Trade Disputes, the: Biosecurity and Ecosystem Services Risks. World Scientific

Hayes K, Sliwa C, Migus S, McEnnulty F, Dunstan P (2005) National priority pests: Part II Ranking of Australian marine pests. In: An independent report undertaken for the Department of Environment and Heritage by CSIRO Marine Research

Henderson W, Bomford M (2011) Detecting and preventing new incursions of exotic animals in Australia. Invasive Animals Cooperative Research Centre Canberra, ACT, Australia

Hughes KA, Convey P (2010) The protection of Antarctic terrestrial ecosystems from inter-and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. Glob Environ Change 20(1):96–112

Hughes KA, Convey P, Pertierra LR, Vega GC, Aragón P, Olalla-Tárraga M (2019) Á. Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: a preliminary risk assessment. J Environ Manag 232:73–89

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol 46(1):10–18

Inspector-General of Biosecurity (2018) Hitchhiker pest and contaminant biosecurity risk management in Australia. igb.gov.au/Pages/default.aspx

International Petroleum Industry Environmental Conservation Association (2012) Quarantine management for the Barrow Island gas processing plant and oilfield. IPIECA. Gorgon gas processing plant and oilfield operated by Chevron on Barrow Island, Australia. https://www.ipieca.org/resources/case-study/quarantine-management-for-the-barrow-island-gas-processing-plant-and-oilfield/

Jarrad FC, Barrett S, Murray J, Parkes J, Stoklosa R, Mengersen K, Whittle P (2011) Improved design method for biosecurity surveillance and early detection of non-indigenous rats. New Zealand J Ecol 35(2):8964

Jelbert K, Buss D, McDonald J, Townley S, Franco M, Stott I, Jones O, Salguero-Gómez R, Buckley Y, Knight T (2019) Demographic amplification is a predictor of invasiveness among plants. Nat Commun 10(1):1–6

Jenkins DA, Mizell III, Van Bloem RF, Whitmire S, Wiscovitch S, Zaleski L, C., Goenaga R (2014) An analysis of arthropod interceptions by APHIS-PPQ and customs and border protection in Puerto Rico. Am Entomol 60(1):44–57

Keller RP, Lodge DM, Finnoff DC (2007) Risk assessment for invasive species produces net bioeconomic benefits. Proc Natl Acad Sci 104(1):203–207

Kier G, Kreft H, Lee TM, Jetz W, Ibisch PL, Nowicki C, Mutke J, Barthlott W (2009) A global assessment of endemism and species richness across island and mainland regions. Proc Natl Acad Sci 106(23):9322–9327

Lane SE, Gao R, Chisholm M, Robinson AP (2017) Statistical profiling to predict the biosecurity risk presented by non-compliant international passengers. *arXiv preprint arXiv:1702.04044*

Lee S-W, Song D-W, Ducruet C (2008) A tale of Asia's world ports: the spatial evolution in global hub port cities. Geoforum 39(1):372–385

Lockwood JL, Cassey P, Blackburn TM (2009) The more you introduce the more you get: the role of colonization

pressure and propagule pressure in invasion ecology. Divers Distrib 15(5):904–910
Lott M, Rose K (2016) Emerging threats to biosecurity in Australasia: the need for an integrated management strategy. Pac Conserv Biology 22(2):182–188
Majer J, Gunawardene N, Taylor C, Harvey M (2013) The terrestrial invertebrate fauna of Barrow Island, Western Australia. Western Australian Museum
Marine Pest Sectoral Committe (MPSC) (2018) Australian Priority Marine Pest List:process and outcomes. http://www.marinepests.gov.au/what-we-do/emergency/rapid-response-manuals
Mathakutha R, Steyn C, le Roux PC, Blom IJ, Chown SL, Daru BH, Ripley BS, Louw A, Greve M (2019) Invasive species differ in key functional traits from native and non-invasive alien plant species. J Veg Sci 30(5):994–1006
McKirdy SJ, O'Connor S, Thomas ML, Horton KL, Williams A, Hardie D, Coupland GT, van der Merwe J (2019) Biosecurity risks posed by a large sea-going passenger vessel: challenges of terrestrial arthropod species detection and eradication. Sci Rep 9(1):1–14
Meissner H, Lemay A, Bertone C, Schwartzburg K, Ferguson L, Newton L (2009) Evaluation of pathways for exotic plant pest movement into and within the greater caribbean region. USDA, USA
Meurisse N, Rassati D, Hurley BP, Brockerhoff EG, Haack RA (2018) Common pathways by which non-native forest insects move internationally and domestically. J Pest Sci 5:1–15
Miralles L, Ibabe A, González M, García-Vázquez E, Borrell YJ (2021) If you know the enemy and know Yourself": addressing the Problem of Biological Invasions in Ports through a New NIS Invasion threat score, routine monitoring, and preventive action plans. Front Mar Sci 8:242
Moro D, Lagdon R (2013) History and environment of Barrow Island. Suppl Western Aust Museum 83:001–008
Moser D, Lenzner B, Weigelt P, Dawson W, Kreft H, Pergl J, Pyšek P, van Kleunen M, Winter M, Capinha C (2018) Remoteness promotes biological invasions on islands worldwide. Proc Natl Acad Sci 115(37):9270–9275
Murray J, Whittle P, Jarrad F, Barrett S, Stoklosa R, Mengersen K (eds) (2015) Design of a surveillance system for non-indigenous species on Barrow Island: plants case
Newman J, Poirot C, Roper-Gee R, Leihy RI, Chown SL (2018) A decade of invertebrate colonization pressure on Scott Base in the Ross Sea region. Biol Invasions 20(9):2623–2633
Nghiem LT, Soliman T, Yeo DC, Tan HT, Evans TA, Mumford JD, Keller RP, Baker RH, Corlett RT, Carrasco LR (2013) Economic and environmental impacts of harmful non-indigenous species in Southeast Asia. PLoS ONE 8(8):e71255
Ojaveer H, Galil BS, Campbell ML, Carlton JT, Canning-Clode J, Cook EJ, Davidson AD, Hewitt CL, Jelmert A, Marchini A (2015) Classification of non-indigenous species based on their impacts: considerations for application in marine management. PLoS Biol 13(4):e1002130
Poland TM, Rassati D (2019) Improved biosecurity surveillance of non-native forest insects: a review of current methods. J Pest Sci 92(1):37–49
Pyšek P, Jarošík V, Pergl J (2011) Alien plants introduced by different pathways differ in invasion success: unintentional introductions as a threat to natural areas. PloS ONE 6(9):e05896
Ramsey DS, Barclay C, Campbell CD, Dewar E, MacDonald AJ, Modave E, Quasim S, Sarre SD (2018) Detecting rare carnivores using scats: implications for monitoring a fox incursion into Tasmania. Ecol Evol 8(1):732–743
Rojas-Sandoval J, Tremblay RL, Acevedo-Rodríguez P, Díaz-Soltero H (2017) Invasive plant species in the West Indies: geographical, ecological, and floristic insights. Ecol Evol 7(13):4522–4533
Romesburg C (2004) Cluster analysis for researchers. Lifelong Learning Publications, London
Russell JC, Meyer J-Y, Holmes ND, Pagad S (2017) Invasive alien species on islands: impacts, distribution, interactions and management. Environ Conserv 44(4):359–370
Saul WC, Roy HE, Booy O, Carnevali L, Chen HJ, Genovesi P, Harrower CA, Hulme PE, Pagad S, Pergl J (2017) Assessing patterns in introduction pathways of alien species by linking major invasion data bases. J Appl Ecol 54(2):657–669
Schlaepfer MA (2018) Do non-native species contribute to biodiversity? PLoS Biol 16(4):e2005568
Scott JK, McKirdy SJ, van der Merwe J, Green R, Burbidge AA, Pickles G, Hardie DC, Morris K, Kendrick PG, Thomas ML (2017) Zero-tolerance biosecurity protects high-conservation-value island nature reserve. Sci Rep 7(1):772
Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M (2017) No saturation in the accumulation of alien species worldwide. Nat Commun 8:14435
Sheikh AA, Rehman N, Kumar R (2017) Diverse adaptations in insects: a review. J Entomol Zool Stud 5(2):343–350
Sikes BA, Bufford JL, Hulme PE, Cooper JA, Johnston PR, Duncan RP (2018) Import volumes and biosecurity interventions shape the arrival rate of fungal pathogens. PLoS Biol 16(5):e2006025
Simberloff D (2009) The role of propagule pressure in biological invasions. Annu Rev Ecol Evol Syst 40:81–102
Simberloff D, Martin J-L, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M (2013) Impacts of biological invasions: what's what and the way forward. Trends Ecol Evol 28(1):58–66
Stoklosa RT (2004) Application of engineering risk management to protect the conservation values of Barrow Island from invasion by non-indigenous species. In: Engineers Australia 2004 RISK Conference, Melbourne, Victoria, Australia
Stoklosa R (2005) How-to guide for conducting risk-based assessments of quarantine threats to Barrow Island. Technical Appendix D2. 31
Suckling DM (2015) Can we replace toxicants, achieve biosecurity, and generate market position with semiochemicals? Front Ecol Evol 3:17
Suhr EL, O'Dowd DJ, Suarez AV, Cassey P, Wittmann TA, Ross JV, Cope RC (2019) Ant interceptions reveal roles of transport and commodity in identifying biosecurity risk pathways into Australia. NeoBiota 53:1

The Atlas of Living Australia (2008). www.ala.org.au. Accessed 20 Aug 2022

Toral-Granda MV, Causton CE, Jäger H, Trueman M, Izurieta JC, Araujo E, Cruz M, Zander KK, Izurieta A, Garnett ST (2017) Alien species pathways to the Galapagos Islands, Ecuador. PLoS ONE 12(9):e0184379

Turbelin AJ, Malamud BD, Francis RA (2017) Mapping the global state of invasive alien species: patterns of invasion and policy responses. Glob Ecol Biogeogr 26(1):78–92

Turner R, Plank MJ, Brockerhoff E, Pawson S, Liebhold A, James A (2020) Considering unseen arrivals in predictions of establishment risk based on border biosecurity interceptions. Ecol Appl 2:896

van Klinken RD, Panetta FD, Coutts SR (2013) Are high-impact species predictable? an analysis of naturalised grasses in northern Australia. PloS ONE 8(7):e05895

Wang C, Wang J (2011) Spatial pattern of the global shipping network and its hub-and-spoke system. Res Transp Econ 32(1):54–63

Wasowicz P (2014) Identifying and ascribing the relative significance of introduction pathways for non-native plants into Iceland. Environ Socio-economic Stud 2(4):28–37

Wells FE, McDonald JI, Huisman JM (2009) Introduced marine species in western Australia. Department of Fisheries

Whattam M, Clover G, Firko M, Kalaris T (2014) The biosecurity continuum and trade: border operations. The handbook of plant biosecurity. Springer, Dordrecht, pp 149–188

Zabin C, Davidson I, Holzer K, Smith G, Ashton G, Tamburri M, Ruiz G (2018) How will vessels be inspected to meet emerging biofouling regulations for the prevention of marine invasions? Manage Biol Invasions 9(3):195–208

Zhou B, Tu T, Kong F, Wen J, Xu X (2018) Revised phylogeny and historical biogeography of the cosmopolitan aquatic plant genus Typha (Typhaceae). Sci Rep 8(1):1–7

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.