Marine invasive species

Keith, Inti; Dawson, Terence P.; Collins, Ken J.; Campbell, Marnie L.

Published in:
Pacific Conservation Biology

DOI:
10.1071/PC15020

Publication date:
2016

Document Version
Peer reviewed version

Citation for published version (APA):
Keith, I., Dawson, T. P., Collins, K. J., & Campbell, M. L. (2016). Marine invasive species: Establishing pathways, their presence and potential threats in the Galapagos Marine Reserve. *Pacific Conservation Biology*, *22*(4), 377-385. https://doi.org/10.1071/PC15020

To be cited as:

Keith, I., Dawson, T.P., KJ Collins, K.J. and Campbell, M.L., 2016, Marine invasive species: establishing pathways, their presence and potential threats in the Galapagos Marine Reserve, *Pacific Conservation Biology*, 22 (4), 377-385, http://dx.doi.org/10.1071/PC15020.

Marine Invasive Species: Establishing pathways, their presence and potential threats in the Galapagos Marine Reserve

Inti Keith[A,B,E], Terence P. Dawson[A], Ken J. Collins[C] and Marnie L. Campbell[D]

A Centre for Environmental Change and Human Resilience, University of Dundee, Dundee, DD1 4HN, UK.
B Charles Darwin Foundation, Marine Science Department, Santa Cruz Island, Galapagos, Ecuador.
C Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton SO14 3ZH, UK.
D Environmental Research Institute, University of Waikato, Hamilton, New Zealand.
E Corresponding author. Email: inti.keith@fcdarwin.org.ec

Abstract

Worldwide, marine biological invasions of non-native species have increased significantly in recent years due to a rapid rise in global trade, transport and tourism. Invasions occur when non-native species are transported from one region to another and establish, often resulting in competition displacing native species and changing ecosystems. Historic literature searches were conducted along with dive surveys of the main ports and in sites around the archipelago in order to produce a baseline of which non-native species are present in the Galapagos Marine Reserve (GMR) at this time. Confounding processes of anthropogenic and natural activities are increasing the potential spread of marine invasive species in the Eastern Tropical Pacific and the GMR. We discuss the potential vectors facilitating marine invasions with the suggestion that marine traffic could be the most influential vector in the transport of marine non-natives to the GMR. The challenge for marine park authorities is to identify those species that are likely to cause negative impacts on native biodiversity and ecosystems before they establish in the Galapagos, and to develop pre-emptive strategies that would likely include prevention as well as risk-based management strategies to remove them or to mitigate their harmful effects.

Introduction

The Galapagos archipelago is located 1,000 km off the coast of Ecuador in the Eastern Tropical Pacific (ETP). The archipelago is a volcanic hotspot that consists of 13 large islands and over 100 smaller islands, islets, and rocks (Sachs & Ladd, 2010). This oceanic archipelago is home to two important Natural Heritage Sites, the Galapagos National Park (GNP) created in 1959 and the Galapagos Marine Reserve (GMR) created in 1998 with the Special Law for the Conservation and Sustainable Development of the

Galapagos Province (LOREG, 1998). The GMR extends to a distance of 40 nautical miles out from the coastal baseline that surrounds the archipelago, creating a protected area of about 138,000 km^2 (Danulat & Edgar, 2002).

The Galapagos Islands are renowned for their unique biological diversity, high levels of endemism, and the unique currents and oceanographic features that allow a variety of habitats to exist (Hickman, 2009). The archipelago is influenced by a number of major surface and submarine current systems and are characterized by a diverse wildlife compared to other islands, with representatives corresponding to the Indo-Pacific, Panama, and Peru regions of the Pacific (Banks, 2002, Hickman, 2009; Muromtsev 1963). Studies have shown, however, that marine ecosystems in the Galapagos are sensitive to climate change and not well adapted to extreme thermal impacts (Edgar *et al.* 2010).

The introduction of non-native species has been identified as the second most important reason for biodiversity loss worldwide after habitat destruction (IUCN, 2011, Jäger *et al*. 2007). The rate of biological invasions has increased during the last decades, mostly due to the accelerated spread of species due to growing global trade, transport, and tourism overcoming natural barriers to marine migration, such as currents, land masses, and temperature gradients that once limited the movement of species (Carlton, 1996; Seebens *et al*. 2013). Marine bioinvasions are currently recognised as a problem throughout the world's oceans, with humans having moved species beyond their native ranges for many years, whether deliberately or not, and some of these species have managed to establish and proliferate causing significant ecological, economic and health impacts (Campbell & Hewitt, 2013; Vitousek *et al.* 1997). Many marine organisms need assistance in order to move from one region to another, through anthropogenic or natural vectors (Hewitt & Hayes, 2002). Here we define a vector as the physical means, agent or mechanism, which facilitates the transfer of organisms or their propagules from one place to another (Carlton, 1996; Campbell & Hewitt, 2013; Hilliard, 2004; Hewitt & Hayes, 2002).

Several anthropogenic vector categories exist; a prime example is marine traffic, where shipping vessels can act as biological islands for species that live in harbours around the world (Wonham *et al.* 2001). For example, as ships transit or anchor in these areas, some species colonise their sub-surface areas and "hitch a ride". Maritime traffic includes ballast water and biofouling as well as numerous other mechanisms (e.g. anchor lockers). These vessels provide places for the settlement of species associated, provide protected spaces where both sessile and mobile fauna can settle, and enclosed spaces that hold water in which a wide range of organisms from plankton to fish can travel in (Wonham *et al.* 2001; Godwin, 2003). Biofouling of maritime traffic plays a key role in the spread of species due to the fact that many of these organisms can be moved between regions by commercial vessels and recreational vessels (Hulme, 2009; Kolar & Lodge, 2002). Other vectors exist that can disperse marine organisms throughout the world; some examples include current systems, climate variations, migrating species, and natural phenomena, such a major storm events. However, another vector that has been identified in recent years is marine debris. The possibility has been explored that marine species can adhere themselves to floating waste and can be transported thousands of miles to different bioregions (Chan, 2012).

The geographic isolation of the Galapagos Islands has limited natural immigration of new species historically enabling those few species that did arrive to evolve in the absence of competitors and predators. For this reason, oceanic islands are more prone to invasion by non-native species because of the paucity of natural competitors and predators that control populations in their native ecosystem. Islands often have ecological niches that have not been filled because of the distance from colonizing populations, increasing the probability of successful invasion (Loope *et al.* 1988).

The impacts of terrestrial invasive species have been studied extensively in the Galapagos Islands, with the consequence that there are now strict control and quarantine protocols to prevent the entry of terrestrial introduced species (Zapata, 2006). The Agencia de Regulación y Control de la Bioseguridad y Cuarentena para Galápagos (ABG) is the Galapagos Biosecurity Agency created in 2012. This agency is in charge of controlling, regulating, preventing and reducing the risk of the introduction, movement and dispersal of non-native organisms that might threaten human health, the terrestrial and marine ecosystems, the integrity of the islands and the conservation of biodiversity of the Galapagos Province (ABG, 2015). While research on terrestrial invasive species such as mammals, birds, plants and insects is well established, research conducted on marine invasive species and the impacts to the Galapagos Marine Reserve is sparse. The management of marine invasive species presents more challenges than terrestrial invasive species due to the high degree of natural connectivity between the islands within the GMR that exists and the logistics required to work in the marine environment.

The GMR is under threat from possible marine non-native species arrivals, given the connectivity that exists with the Eastern Tropical Pacific (ETP), the increase in tourism and associated marine traffic and the effect of extreme climatic events such as the El Niño Southern Oscillation (ENSO). This type of event brings unusually warm water across the central and east-central equatorial Pacific, giving opportunistic non-native species a window of opportunity to move into new ecosystems and outcompete native and endemic species.

The Charles Darwin Foundation (CDF) has been working with the ABG and the Galapagos National Park Directorate (GNPD), both part of the Ecuadorian Ministry of the Environment (MAE), the Ecuadorian Navy (DIRNEA) and the Navy's Oceanographic Institute (INOCAR) to establish a baseline of non-native marine species that are already established in the GMR, and to develop control measures and a management plan to prevent the arrival of new non-native marine species into the GMR. This paper illustrates the initial work that has been undertaken by the CDF and local government institutions since the start of the Darwin Initiative funded project *Marine Invasive Species Project: Prevention, Detection and Management* that began in 2012. The objectives of this paper are to present a baseline list of marine non-native species in the GMR, discuss the possible vectors by which these species could enter the GMR and how they could be managed.

Methods

A compilation of historical literature was gathered for non-native species reported in the Galapagos, with some of these records dating back to the Allan Hancock Pacific Expeditions conducted in the early 1930s (Taylor, 1945). In addition monitoring surveys were undertaken in the main ports of the archipelago, in selected sites around the GMR, and in protected bays and mangrove areas to assess the presence of non-native species in the GMR at the present time.

The species reported in the literature were then investigated further, looking at (a) their current native and introduced distribution, (b) their invasive capacity and whether the species has demonstrated invasive behaviour in other parts of the world, (c) if the ecological conditions are suitable in the GMR for the species to proliferate, and (d) if the species could have been transported by one of the dispersal vectors affecting the GMR. The global distributions of these species were determined using the Global Invasive Species Database (ISSG, 2015), the World Register of Introduced Marine Species (Pagad *et al.* 2015), World Register of Marine Species (WoRMS, 2015;) and Algaebase (Guiry & Guiry, 2015). Records of these species presence where also checked on the CDF marine database that holds records of all species reported in the GMR and their distribution (Bungartz *et al.* 2009).

Subtidal monitoring

There are around 380 sites that have been monitored as part of the GMR baseline and these are documented in the CDF marine database (Bungartz *et al.* 2009). In 2004 the GNPD led a process to signal all the coastal subzones in the GMR for management purposes, during this time the design of an annual subtidal monitoring program run by CDF was finalized. This program is based on the repetition of monitoring 64+ sites around the GMR, each site has three zones marked, tourism, fishing and protection. (Banks *et al.* 2014). The sites chosen for this study where based on the sites monitored in the past in the GMR in order to have a reference of the species recorded previously.

115 sites were surveyed using a proven standardised methodology developed by the CDF for long term evaluation of subtidal communities in the GMR; this methodology is also applied in other marine protected areas in the Eastern Tropical Pacific (ETP) (Banks *et al.* 2014). This methodology focuses primarily on recording the diversity, abundance and size of the species present in three major groups of macro fauna: fish, macro invertebrates and sessile organisms. Each sample consists of divers moving along a 50m transect parallel to the coast where visual censuses are conducted for the three taxonomic groups, this is done at a depth of 15m and 6m.

The fish monitoring consists of identifying the levels of species richness, measuring the population density, determining the size structure of each species and conducting a visual inspection for non-native species. An area of 500m^2 is monitored by a diver who swims along the transect considering an imaginary corridor of 5m wide x 5m high x 50m long, parallel to the transect.

The mobile macroinvertebrate monitoring focuses on simultaneously measuring the density and abundance of several species at a time, including commercial, non-commercial and non-native species. An area of 100 m^2 is monitored along the same 50m transect, the diver swims along in 5m segments considering a 1m strip at either side of the transect recording the number of invertebrates larger than 2cm.

Sessile organisms are an important component of marine communities. Due to their sedentary lifestyle, sessile organisms are good indicators of local conditions, long-term physical changes, biological changes and any effects that can be produced by natural phenomena or human caused disturbances. Their presence or absence is a good indicator of biological and abiotic processes prevailing, such as competition, interactions with predators or prey or large-scale effects such as current circulation patterns, recruitment events, temperature, or marine invasions. An area of 2.5 m^2 is monitored using a PVC quadrat of 0.5 x 0.5m (0.25m^2). Each quadrat has a grid of 5 x 5cm constructed with polypropylene twine with 81 intersection points to determine the abundance of each species. Quadrats are placed systematically every 5m along the same 50m transect. In each quadrat all species that fall in the 81 intersections must be counted and recorded, species that do not fall in the intersections recorded as present (Banks *et al.* 2014). Various samples were collected for later identification, or were sent to taxonomic experts to confirm identification or to conduct DNA studies.

Port monitoring

There are five populated islands in the archipelago, each with a main dock and several smaller docks: i) Puerto Baquerizo Moreno, on the Island of San Cristobal, ii) Puerto Ayora, on the Island of Santa Cruz, iii) Puerto Villamil, on the Island of Isabela, iv) Puerto Velasco Ibarra, on the Island of Floreana and v) Puerto de Seymour, on the Island of Baltra. There are several different components in the port monitoring methodology. Each port has a different layout and each has a different number of docks that require inspecting. Permission to inspect has to be obtained from the port authority as the ports are heavily visited with marine traffic, and health and safety protocols need to be followed. The monitoring of docks consists of conducting a visual inspection and recording the species present, taking scrapings from the dock walls or pylons for later identification in the laboratory, and recording a video transect for comparative analysis.

Two divers conducted the visual inspection, one records all fish and macroinvertebrates in the surrounding dock area and the other diver records the percentage cover of sessile organisms. The area surveyed is the total area around the dock starting at the shallowest depth possible to divers. The area covered varies on each dock, as the size of each dock is different. Sessile organisms are recorded using a PVC quadrat of 0.5 x 0.5m ($0.25m^2$) (Banks *et al.* 2014) and records are taken at three depths (e.g. 0.5m, -3m, and -7m). In addition, scrapings are collected at the same three depths as the sessile survey for later identification in the laboratory. The video transect records all areas surveyed by the divers including the areas where scrapings where taken. Photographs of potential non-native species that are present around the docks are also recorded to facilitate later species identification. During port monitoring, mooring buoys and/or navigation buoys are also inspected. The buoys consist of different parts, the marker buoy floating on the surface of the water, the chain and cement block on the sea floor. Visual inspections to all these areas are conducted, recording all species present. Scrapings of the base of the buoy are taken for later identification and a video recording of the marker buoy, the chain and the cement block is recorded. The area surrounding the cement block is also inspected for non-native species.

Protected bays and mangrove monitoring

The Galapagos Islands have many protected bays, with the majority located on the western islands of Isabela and Fernandina. A separate monitoring technique was developed for these areas, as these bays are small in size, shallow, have very low wave exposure, hence diving is not necessary. The monitoring of these bays was undertaken through directed searches for non-native species using snorkelling apparatus. A list of potential non-natives used for the identification of species during the directed searches, was compiled from literature collected on marine invasive species worldwide.. Photographs and samples of specimens were collected for later identification in the laboratory. The many bays of the archipelago support a number of mangrove habitats, where visual inspections of the intertidal zone of the mangroves were conducted in order to evaluate the presences of non-native species.

Results

The literature search produced seven potentially non-native species reported in the GMR. The first record found was for *Caulerpa racemosa* with this species registered in Galapagos by Farlow in 1899 on the Island of Isabela. It was registered again by Allan Hancock during the Pacific Expeditions in the 1930's (Eldredge & Smith, 2001; Farlow, 1902;

Molnar *et al.* 2008; Ruiz & Ziemmeck, 2011; Taylor, 1945). *Asparagopsis taxiformis* was first registered in the Galapagos by Dawson in 1963, (Chualáin *et al.* 2004; Dawson, 1963; Ruiz & Ziemmeck, 2011; Taylor, 1945). According to Hickman (1997), the blue crab *Cardisoma crassum* was an introduction to the Galapagos Islands although the evidence is uncertain. It was thought it was originally introduced when some live crabs escaped after being taken to a hotel in the town of Puerto Ayora on the Island of Santa Cruz. However in a publication on land crabs of Costa Rica, Bright (1966) reports the presence of the blue crab in the Galapagos Islands. On the other hand, Garth (1991) cites this species as absent and with undetermined invasiveness. *Bugula neritina* and *Pennaria disticha* were first registered during the Allan Hancock Pacific Expeditions, (Danulat & Edgar, 2002; Eldredge & Smith, 2001; Hickman, 2008; Ryland *et al.* 2001; Taylor, 1945; Molnar *et al.* 2008; Vieira *et al.* 2012). *Acanthaster planci* was first reported in the Galapagos by Hickman; it is only found at Darwin Island in the north of the Archipelago. (Cohen-Rengifo *et al.* 2009;). A small colony of *Schizoporella unicornis* was reported by Osborn (Taylor, 1945) on the Island of Santiago between 1932 and 1949 by the Allan Hancock Pacific Expeditions. In his report Osborn cites that this species had not been found previously in the eastern Pacific and further suggests that it could have been a recent introduction as it was found along with oysters from the Atlantic coast (Banta & Redden, 1990; Taylor, 1945).

In contrast, diving expeditions conducted since 2012 produced a list containing six out of the seven previously reported species in the literature and one new record for Galapagos (Table 1). *Schizoporella unicornis* is classed as introduced and naturalized by the Charles Darwin Foundation Checklist (Bungartz *et al.* 2009) but there has been no record of this species since Osborn reported it as present in the 1930's (Taylor, 1945), this species was not found during the yearly ecological monitoring surveys carried out by CDF since 2002 or by searches conducted in this research. For this reason, it has not been put on the list of non-natives present in the GMR at this time. A new record that this research produced was *Amathia verticillatum,* commonly known as the spaghetti bryozoans (McCann *et al.* 2015).

Table 1. Non-native species recorded in the GMR

Phylum	Family	Scientific name	Common name
Chlorophyta	Caulerpaceae	*Caulerpa racemosa*	Grape algae
Rhodophyta	Bonnemaisoniaceae	*Asparagopsis taxiformis*	Red sea plume
Arthropoda	Gecarcinidae	*Cardisoma crassum*	Blue crab
Bryozoa	Bugulidae	*Bugula neritina*	Brown bryozoan
Cnidaria	Pennariidae	*Pennaria disticha*	Christmas tree hydroid
Echinodermata	Acanthasteridae	*Acanthaster planci*	Crown of thorns
Bryozoa	Vesiculariidae	*Amathia verticillata*	Spaghetti bryozoan

The historic records of *Caulerpa racemosa* might influence people to think that this species is native due to the fact it has been present in the GMR for so long. CDRS has been been running marine monitoring programs since 1997 (Bustamante *et al.* 2000; Danulat & Edgar, 2002) and there are records of *C. racemosa* that date back to the 1970's. In this paper, it is suggested that *C. racemosa* is non-native due to the more recent findings of this species being found in sites where it had never been reported previously and the observation that this species distribution can proliferate or contract due to water temperature changes, suggesting previous ENSO events could have influenced this species' presence and distribution. Similarly, *Asparagopsis taxiformis* historical records list this species as present since the 1960's, but recent dive surveys have discovered new areas where this species was never recorded and has expanded rapidly; an example being the Mariela Islands off the island of Isabela.

Table 2. Non-native species found by means of different survey methodologies

Scientific name	Subtidal	Ports	Protected bays and mangroves
Caulerpa racemosa			×
Asparagopsis taxiformis	×	×	
Cardisoma crassum			×
Bugula neritina	×	×	
Pennaria disticha	×		
Acanthaster planci	×		
Amathia verticillata		×	×

Discussion and Conclusion

This research shows the presence of seven non-native species reported in the GMR at the current time. The historical literature and recent dive surveys support these findings but it is difficult to demonstrate whether anthropogenic vectors resulted in the introduction of these species or if they arrived naturally. An excellent example of an anthropogenic vector that could aid in the transport of non-native species from different regions to the GMR is marine traffic, however natural dispersal could also facilitate the transport of non-natives through oceanic currents. Other vectors include climate change and marine debris but these vectors raise the question of how to categorize non-native species transported by them as they are both natural processes that have been influenced by anthropogenic activity. The authors suggest that these species could have arrived to the islands through marine traffic, current systems and climate variations. Six out of the 7 non-native species from table 1 are also found in continental Ecuador and in other regions in the ETP. *Acanthaster planci* has not yet been recorded in continental Ecuador but has been recorded on the island of Cocos in Costa Rica, and in Panama.

The different methods used to search for non-native species has enabled the coverage of a wider range of habitats than if only one method had been utilized, likely resulting in more species now being identified (Table 2). The subtidal monitoring was essential because this method allowed us to search for species at different depths. The monitoring of the main ports in the region is of great importance and considered high priority, as these are the most likely areas where possible invaders can arrive due to the marine traffic from abroad and continental Ecuador. The protected bays provide excellent habitats for certain species to established, reproduce and compete with native species due to particular environmental conditions, such as water temperature, depth, visibility and low wave exposure, that favour certain categories of non-native species. With the information recorded we were able to map out the distribution of the seven species identified as non-native in the GMR currently (Figure 1).

The marine species in the GMR have evolved in relative isolation and have a large number of endemic species. The exposure of oceanic islands to marine non-natives has been often discussed in invasion biology reviews (e.g. Elton, 1958; Simberloff, 1995; Inglis *et al.* 2006). For a non-native species to establish in a new environment there must be suitable environmental conditions, lack of predators and the availability of resources for the species to proliferate, and these can be dynamic and highly variable in marine ecosystems. It has been suggested that island ecosystems often have accessible ecological niches that can be filled by opportunistic non-native species arriving from other regions and species that are associated with anthropogenic vectors are often more successful in filling these niches (Inglis *et al.* 2006; Wonham *et al.* 2000).

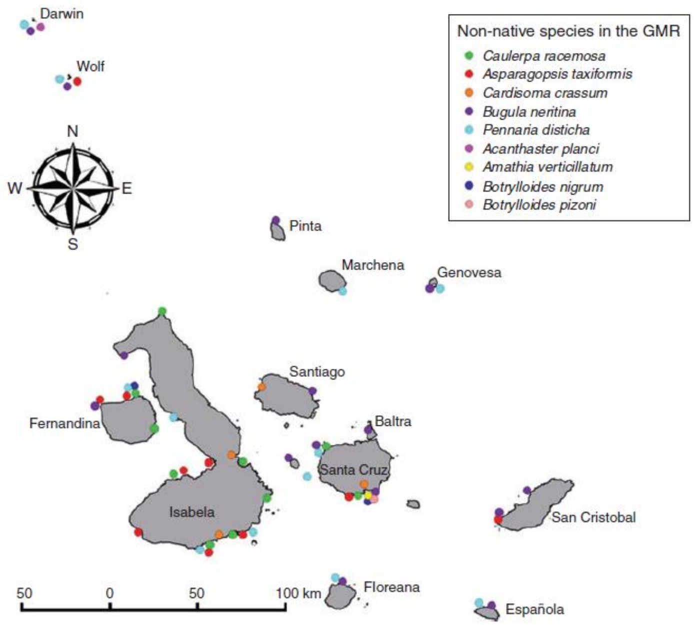

Fig. 1. Distribution of non-native species in the GMR.

Anthropogenic and natural vectors in the GMR

Marine traffic:

Since the accidental discovery of the Galapagos Islands in 1535 (McBride, 1918) and during the seventeenth and eighteenth centuries, the islands became a haven for pirates and whalers and the first introductions of domestic animals and invertebrates occurred. In the nineteenth century, whalers were attracted by the high productivity of the seas surrounding the islands and made this region their hunting grounds. Hence, it is thought that various marine species could have been introduced to the islands at this time with the amount of maritime traffic that existed. Following this, industrial-fishing boats entered the territorial waters during the 1940s and 1950s (Causton *et al.* 2008), and in 1942 during the Second World War, the United States of America constructed a Naval Base on the island of Baltra, which increased the number of vessels in the area.

As described, the history of the maritime traffic in the GMR is extensive, which makes it more difficult to know with certainty if some species existed naturally or if they where introduced in the past. An example is *Bugula neritina*, a brown bryozoan that has a worldwide distribution; it is thought that this species could have been transported on wooden hulls around the world (Eldredge & Smith 2001, Ryland *et al.* 2001, Molnar *et al.* 2008, Vieira *et al.* 2012). Currently the Galapagos Islands receives a large amount of marine traffic, and there are several categories of vessels; tourism, transport, cargo, fishing, private, scientific, patrol boats and oil tankers as well as the illegal fishing boats that enter the GMR (Campbell & Hewitt, 2007; Campbell *et al.* 2015). This movement of different vessels increases the threat of non-native species entering and spreading within the GMR.

Tourism is the principal economy of the Galapagos Islands (Piu & Muñoz, 2008), where 61% of the tourists who visit do so from boats. There are several different tourist itineraries that are administered by the Galapagos National Park. Cargo boats operate on a weekly basis and bring supplies to the main ports from the port of Guayaquil on mainland Ecuador. The number of boats traveling between the populated islands fluctuates significantly according to demand. During the first half of 2007, approximately 1,900 trips were made between the populated islands (Causton *et al.* 2008). However, a study conducted between February and November 2012, a period of only ten months, showed 8,685 departures and arrivals of inter-island vessels registered in the Isla Santa Cruz by the Navy of Ecuador (Parra *et al*. 2013). This shows an increase in marine traffic between the populated islands. Fishing boats, private, scientific and patrol boats are more difficult to record, since these do not have itineraries or fixed routes. Private yachts enter the GMR every year, with the majority of them arriving between the months of December and June. These yachts arrive from all over the world but the majority of the captains report Panama as their last port of call (Keith & Martinez 2014). According to records from the ABG in 2013, there where 273 private boats that entered the GMR (ABG, 2014).

Oceanic Currents:

Oceanic currents heavily influence trans-oceanic dispersal, these currents make it possible for species to be dispersed between widely separated areas, especially species capable of long distance larval transport (Hickman, 2009). The islands are no longer considered an isolated place due to the dynamic convergence of different oceanic regimes that provides incredible connectivity, which is partly responsible for the island's unique biodiversity (Hickman, 2009). It is widely recognised that four main currents influence the Galapagos archipelago (Banks, 2002) and these currents show a marked seasonality in their intensity and direction (Chavez & Brusca 1991) and provide connectivity between the Galapagos Islands groups. For most marine organisms with sessile, benthic or sedentary adult phases, movement is often limited to their larval phase and dispersal. However, these early life history stages are never entirely passive and represent a unique opportunity for individuals to be transported between geographically separated populations using the oceanic currents (Paris *et al*. 2013; Pineda *et al.* 2007).

Climate variability

The ocean is well known to play a dominant role in the climate system because it can initiate and amplify climate change on many different time scales. The best known examples are the inter annual variability of El Niño – Southern Oscillation (ENSO) events and the potential modification of the major patterns for oceanic heat transport as a result of increasing greenhouse gases (Semtner, 1995). The Galapagos Islands are regularly subjected to extreme climate variability through ENSO events. These strong climatic events cause increases in temperature, changes in current circulation and changes in precipitation. During 1982-1983 and 1997-1998, two strong El Niño events were marked with widespread damage caused to the marine ecosystem of the Galapagos Islands, largely due to trophic cascades and food shortages. During ENSO events, prolonged increases in sea temperature are induced as the warm surface waters of the western Pacific band migrate to the coast of South America (Banks, 2002). During such events when extreme conditions occur, the geographic range of some warm water species can expand, moving them to different regions. In the GMR the Green Sea urchin populations *Lytechinus semituberculatus* decreased during the last strong ENSO event, whereas, in contrast, the White Sea urchin *Tripneustes depressus* showed high rates of recruitment after the El Niño event (Brandt, 2002; Danulat & Edgar, 2002).

Natural processes enhanced by anthropogenic activity

Global warming:

The earth's climate has been changing throughout history though natural periodic cycles, but it is now thought that due to the amount of greenhouse gases in the atmosphere resulting from human activity, global warming is expected to have a significant impact on our future climate (IPCC , 2007) resulting in potential major impacts on species and ecosystems (Rahel, 2002; Hare & Whitfield, 2003). When a habitat has been changed, for example, through climate change, invasive species can take advantage of the disturbed environment to establish and spread more effectively than if the system was stable and could resist the invasion (Emerton & Howard, 2008). Biodiversity is being affected by climate change with changing temperature and rainfall patterns (Dawson *et al.* 2011). Whilst native species struggle to adapt to new conditions, many invasive species, being generalists, can more easily adapt, establish and spread (Emerton & Howard, 2008). There are cases recorded where long term changes in ocean temperatures have influenced the distribution of fish species resulting in a poleward expansion from their historical native range (Hare & Whitfield, 2003; Perry *et al.* 2005). How non-native marine species are reacting to these changes is yet to be fully examined or understood (Hewitt & Campbell, 2013). The change in global climate could affect the ecosystems in the GMR, allowing marine non-natives to take advantage and proliferate.

Marine debris:

Oceanic currents can also transport marine debris that can have species attached. Examples of these include lost fishing nets and abandoned fish aggregating devices. These can potentially harbour invasive species and can be carried by currents to different locations (Hilliard, 2004). The marine debris provides another example of a potential vector for introduced species (Vegter *et al.* 2014); a prime example of this was the Japanese tsunami in 2011. A year after the devastating earthquake and subsequent tsunami, a floating dock appeared on the coast of Oregon in the United States with several invasive species attached to it, some examples were: *Undaria pinnatifida* ("wakame") also known as Asian kelp, *Hemigraspus sanguineus,* commonly known as the Japanese shore crab, and *Asterias amurensis,* known as the Northern Pacific sea star (Chan, 2012). This demonstrates how invasive species can be transported across a large body of water by currents and winds attached to floating debris. Marine debris is human created waste that enters a natural environment where natural processes spread the debris.

Possible vectors for the present non-native species list of the GMR

Marine traffic is thought to be the most important anthropogenic vector for the transport of non-natives to the GMR. *Bugula neritina* and *Amathia verticillatum* are both well known fouling organisms that have been transported around the world for centuries. *A. verticillatum* continues to appear in new regions around the world, which resulted in the new record in the GMR (McCann *et al.* 2015). Due to the increase in traffic over the years and vessels arriving from around the world combined with the fact this species has been recorded on vessel hulls around the world (McCann *et al.* 2015), it is likely that this non-native arrival resulted from marine traffic. The non-native species *Caulerpa racemosa, Asparagopsis taxiformis and Pennaria disticha* could have been transported by marine traffic as well as through natural dispersal. Whereas *Acanthaster planci* could have arrived at Darwin through oceanic currents or it could have migrated due to sea temperature changes due to climate change or ENSO events. This is thought to be the case as it was reported after the 1997-1998 El Niño event (Hickman 1998). It has been suggested that the lack of genetic research conducted on *A. planci* has shown the lack of understanding of different populations in different regions around the world (Volger *et al.* 2008). This discovery could lead to new findings of this species distribution. The crab *Cardisoma* *crassum* could have arrived naturally through trans-oceanic dispersal or, as Hickman (1997) proposes, was unintentionally introduced to the Galapagos Islands when some individuals were brought from continental Ecuador as food.

Biological invasions have been reported on the coasts of Chile in recent years as well as on the coasts of Peru, with some introductions taking place due to aquaculture and some species undergoing rage expansion (Castilla et al. 2005). Surveys have also been conducted in Panama on both the Pacific and Atlantic side of the Panama Canal and species from Peru have been observed on Pacific Panama (Schlöder et al. 2013). These are just some examples of how the connectivity in the ETP and the southern hemisphere should be taken into account when looking at possible invasions occurring in the GMR.

Management of marine non-native species

The possible invasion of marine non-native species to the GMR, given the rapid expansion of marine traffic, the connectivity through oceanic currents and the climatic events that occur in the region is a reality that should not be ignored. The introduction of species and their subsequent proliferation in the archipelago have been identified for well over a decade as the principal threat to the conservation of Galapagos (CDF and WWF, 2002). The number of vessels arriving in the Galapagos from different parts of the world due to the connectivity has increased in recent years (ABG, 2014), escalating the possibility of an invasion. As more tourism and commerce grows in the islands the higher the risk of an invasion by marine non-native species. An efficient policy to support conservation and social sustainability must act on the connections between Galapagos, continental Ecuador, and the rest of the world, to reduce the flows of non-native species that enter (and leave) the archipelago (Grenier, 2010). The management of incoming vessels and adequate quarantine protocols need to be put in place. The ABG and the GNPD have commenced hull inspections to all boats entering the GMR, which is a starting point for the control of non-native species entering the GMR. However, more work has to be done to prevent species arriving. The inspection protocols have to be extended beyond the GMR, to the last port of call or beyond, all boats should arrive to the Galapagos with clean hulls and be re-inspected upon arrival.

It is uncertain how these species might respond to climate change or climate variability, which is why these species have been placed on a priority 'watch list'. The Charles Darwin Foundation, the Galapagos National Park Directorate (GNPD) and the Ecuadorian Biosecurity Agency (ABG), have established monitoring programs in order to keep an eye on these species spreading or causing further impacts to the GMR. Currently the species mentioned here have been observed in competition with native species for space, the most apparent example is the spread of Caulerpa racemosa in some of the protected bays around the archipelago. An increase in sea temperature could favour this species and allow it to expand further and proliferate.

There are several potential high-risk species that could damage the marine ecosystems of the Galapagos Islands. Some of these species have been identified by Campbell & Hewitt (2007) and more investigation is being undertaken currently. Species like the white coral *Carijoa riisei* has already been reported in continental Ecuador and in the island of Malpelo, Colombia (Sanchez *et al.* 2011), located 500 km west of continental Colombia and about 1200 km northwest from the island of Darwin. This species is a well known fouling organism (Eldredge & Smith, 2001) that could hitch a ride on boat hulls or currents could transport it. It is a priority to establish what the high-risk species are for the GMR in order to improve management protocols for marine invasive species. Prevention, early detection and rapid response protocols have to be put in place along with risk assessments and management strategies.

Acknowledgements

We thank Darwin Initiative UK, Galapagos Conservancy, The Galapagos National Park and The Galapagos Biosecurity Agency for their support in this research.