Whales and Vessels: Economic Valuation of Whale Watching and Marine Spatial Planning Surrounding Dominica

Sidney Gerst, Laura Ingulsrud, Shellby Johnson, Callie Steffen

Faculty Advisor: Dr. James Frew

Client: Dominica Sperm Whale Project

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Sidney Gerst

Laura Ingulsrud

Shellby Johnson

Callie Steffen

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. James Frew, Faculty Advisor

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List of Abbreviations

AIS	Automatic Identification System
ATBA	Area to be Avoided
CLIA	Cruise Lines International Association
DSWP	Dominica Sperm Whale Project
FAD	Fish Aggregating Device
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
IMO	International Maritime Organization
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
MaxEnt	Maximum Entropy Modeling
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OPP	Ocean Primary Productivity
SDM	Species Distribution Model
TSS	Traffic Separation Scheme
USD	U.S. Dollar
WSC	World Shipping Council

Abstract

The Commonwealth of Dominica is a Small Island Developing State in the Caribbean that receives approximately 33% of its gross domestic product (GDP) from travel and tourism. Within the broader scope of its tourism industry, there is a draw for ecotourism related to whale watching and swim-with-whale tours. Most whale-related tourism is centered around an eastern Caribbean community of sperm whales whose habitat includes the waters off the west coast of Dominica. Dominica's economy is heavily dependent on vessel traffic for the import and export of goods, as well as tourism. Vessel traffic is increasing, as well as the overall growth of tourism in Dominica. Dominica does not currently use shipping lanes to regulate vessel traffic through its coastal waters. As a result, the local sperm whale community faces ship strike threats from decentralized vessel traffic. Here, we demonstrate how economically important the sperm whales are to Dominica, and outline potential vessel traffic recommendations to reduce ship strike mortality in the eastern Caribbean sperm whale community. Our findings suggest the whale tourism industry in Dominica generates approximately $3 million U.S. dollars (USD) in annual net profit, based on available data. We recommend the Dominican government implement offshore and inshore shipping lanes that avoid the area of high sperm whale habitat suitability, as well as a vessel speed reduction zone encompassing this highly suitable habitat.

Executive Summary

The goal of this project is to help both the eastern Caribbean sperm whale community and the ecotourism economy of Dominica thrive by providing a strategy to ensure greater protection to the sperm whales that support Dominica's economy. Our project's client, Dr. Shane Gero of the Dominica Sperm Whale Project (DSWP), has studied this community of sperm whales for 15 years. His research has shown the community to be behaviorally distinct and isolated, highlighting the need for its protection. To contribute to this continuing effort, our project: 1) evaluates the monetary value of sperm whale tourism in Dominica; and 2) develops a marine spatial plan that regulates vessel traffic and reduces vessel speed within sperm whale habitat in the coastal waters off Dominica's west coast.

Background

The eastern Caribbean sperm whale community is under threat; at current reproduction and mortality rates, the Dominican sperm whale community could reach a dangerously small size by 2030 (Gero & Whitehead, 2016). Sperm whale populations globally are already fragile; even with optimal conditions, the potential rate of increase of a population is small. In the case of eastern Caribbean sperm whales, current mortality is too high to support a sustainable population (Whitehead & Gero, 2015).

This decline may be partially due to collision with ships, or "ship strikes" (Gero & Whitehead, 2016). Reducing the mortality risk of eastern Caribbean sperm whales requires an economic valuation of the whales to incentivize their protection and improved marine spatial planning for vessel traffic areas to reduce whale-vessel interactions. These objectives will also support Dominica's tourism, fisheries, and maritime sectors. The tourism sector benefits from the continued presence of the whales to sustain whale-related tourism activities. The fisheries sector benefits from the implementation of vessel traffic areas that avoid the ongoing loss of fish aggregating devices (FADs). The maritime sector benefits from the improvement of vessel traffic organization in Dominica's waters.

The Commonwealth of Dominica is a Small Island Developing State in the Caribbean that received approximately 33% of its gross domestic product (GDP) from travel and tourism in 2018 (World Travel & Tourism Council, 2019). Within the broader scope of its tourism industry, there is a draw for ecotourism related to whale watching and swim-with-whale tours. Most whale-related tourism is centered around the eastern Caribbean community of sperm whales whose habitat includes the west coast of Dominica. Globally, sperm whales are listed as vulnerable by the International Union for Conservation of Nature (IUCN). This

community of eastern Caribbean sperm whales is behaviorally distinct and is geographically isolated. These characteristics make it unlikely for the community to rebound if it is extirpated, and highlights the need for its protection (Gero & Whitehead, 2016).

Collisions with vessels, or "ship strikes," are a known source of significant mortality for sperm whales and other large whales (Rockwood, Calambokidis, & Jahncke, 2017). Dominica's economy is heavily dependent on vessel traffic for the import and export of goods, and the majority of tourists to Dominica arrive via cruise ships (Conn & Silber, 2013). Globally, cruise ship traffic is increasing and so is the overall growth of tourism in the Caribbean (Moscovici, 2017). In addition, primary international shipping routes go through the Caribbean Sea, and it is anticipated that the density of shipping activities will increase (Miller, 2015). The International Maritime Organization (IMO) has not established traffic separation schemes (TSS), or "shipping lanes," regulating vessel traffic in and out of Dominica. As a result, the local sperm whale community faces increased threats from unregulated and increasing vessel traffic, which increases the probability of ship strike risk. The eastern Caribbean sperm whale community is an important contribution to Dominica's economy, and without improved regulation of vessel traffic, the threats to its survival could undermine the stability of the country's ecotourism sector.

Results

The economic valuation quantifies the annual net profit of the sperm whale tourism industry, and specifies how much of that profit is directly contributing to Dominica's economy. Our findings reveal that the sperm whale tourism industry in Dominica generates approximately $3 million U.S. dollars (USD) in annual net profit, which includes whale watching, swim-with-whale, and cruise ship sources. Approximately $1.1 million USD of that annual profit benefits Dominica's economy.

The marine spatial plan suggests vessel routing options that reduce the risk of lethal ship strikes and includes a map of proposed vessel traffic areas. The vessel traffic recommendations include offshore and inshore shipping lanes and a vessel speed reduction zone where vessels would be required to travel at speeds of 10 knots or less. A time cost analysis for vessels traveling through the vessel speed reduction zone revealed that merchant vessels have the largest time cost, followed by cruise ships, and high speed ferries have the smallest time cost.

An SQLite database and R code are also provided, so that future analyses can continue to update and assess whale and vessel interactions off the west coast of Dominica.

Recommendations

We recommend further research to update the economic valuation spreadsheet with more complete data to improve the estimation accuracy of Dominica sperm whale tourism's monetary contribution.

We recommend the Dominican government implement offshore and inshore shipping lanes that avoid the area of high sperm whale habitat suitability, as well as a vessel speed reduction zone encompassing this highly suitable habitat.

Project Objectives

1. Evaluate the monetary value of sperm whale tourism in Dominica.
2. Develop a marine spatial plan for the coastal waters west of Dominica that regulates vessel traffic and reduces vessel speed within sperm whale habitat.

Significance

The client, Dr. Shane Gero, is the founder and principal investigator of the Dominica Sperm Whale Project (DSWP). The DSWP research program has tracked the size and movement of a community of eastern Caribbean sperm whales in Dominica's coastal waters for over 15 years. Coincident with the overall growth of tourism in Dominica, whale-centered tourism has increased to take advantage of unique viewing opportunities of these sperm whales. However, a recent decline in Dominica's sperm whale community is threatening the longevity of the community and therefore the stability of the related whale tourism sector of this Small Island Developing State.

Dominica's economy relies heavily on tourism and travel, which accounted for approximately 33% of the country's total gross domestic product (GDP) in 2018 (World Travel & Tourism Council, 2019). Whale-related tourism makes up an unquantified, but likely substantial, contribution to this number and attests to Dominica's nickname, the "Whale Watching Capital of the Caribbean."

One known source of significant mortality for sperm whales elsewhere in the world, which may be a factor in the observed decline in the community of sperm whales in the eastern Caribbean, is collision with vessels, or "ship strikes" (Rockwood, Calambokidis, & Jahncke, 2017). High speed ferries, which are increasing their trips between islands in the Lesser Antilles archipelago, have proven to be a significant source of sperm whale mortality off the Canary Islands, a similar deep-water archipelago (Fais et al., 2016). Dominica's economy is heavily dependent on vessel traffic for the import and export of goods as well as on tourism. Merchant vessels, cruise ships, and high speed ferries comprise a majority of the vessel traffic in these waters, and are important to the island's economy. Primary international shipping routes go through the Caribbean Sea, and it is anticipated that the density of shipping activities will increase (Miller, 2015). The International Maritime Organization (IMO) has not established traffic separation schemes (TSS), or "shipping lanes," regulating vessel traffic in and out of Dominica. As a result, the local sperm whale community faces increased threats from unregulated and increasing vessel traffic, which increases the probability of ship strike risk. Recent work by the DSWP has shown that current reproduction and mortality rates make the eastern Caribbean sperm whale community vulnerable to reaching a dangerously low population size by 2030. The Caribbean's sperm whale community is also geographically isolated which makes it unlikely for the community to rebound if they are extirpated (Gero & Whitehead, 2016).

This project aims to analyze and propose marine spatial planning measures to protect Dominica's local sperm whale community. By evaluating the monetary contribution of sperm whale tourism, we intend to show that protection of these whales is necessary to support the ecotourism sector of Dominica's economy. The results of this project will support Dominica's Fisheries Division and Climate Resilient Execution Agency's goal to build a national marine spatial plan and ocean policy for a new blue economy.

Background

Physical Characteristics of Dominica's Coastal Waters

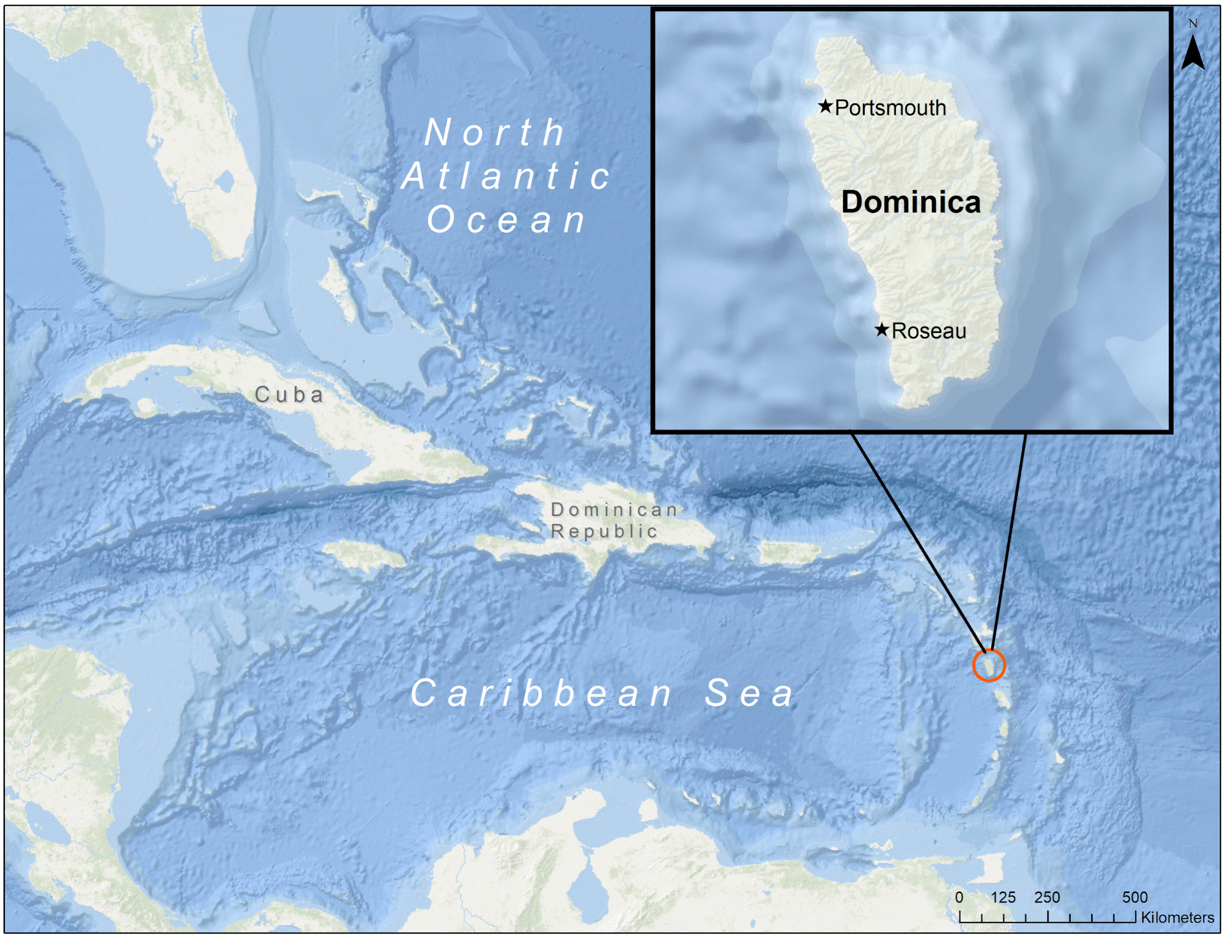

Figure 1. Locator Map of Dominica. Dominica is located in the Lesser Antilles archipelago in the eastern Caribbean, north of Martinique and south of Guadeloupe. Dominica has two ports, Portsmouth and Roseau.

Bathymetry

Dominica's coastline is 153km long and its coastal waters include a 715km^2 continental shelf, with approximately 150km^2 of shelf shallower than 50m (Steiner, 2003). Due to the characteristics of the shelf, water depths off the west coast of the island can reach depths of 500m or greater quickly, according to bathymetric data from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NOAA, 2020). Consequently, sperm whales can be found closer to the island, as they prefer ocean depths of 1,000m or greater (Whitehead, 2009).

Primary Productivity

The Space Information Laboratory at the University of Puerto Rico at Mayagüez has used satellite imagery to advance the understanding of phytoplankton in the Caribbean. The Caribbean Sea receives freshwater intrusions from the Orinoco River in the fall and from the Amazon River during spring to summer, as well as coastal upwelling from the trade winds off Venezuela. The satellite data suggest that these hydrological events are important to phytoplankton fertilization in the eastern Caribbean Sea, which contributes to primary productivity levels. The Caribbean Sea has been classified as oligotrophic (low in nutrients); however, analyses of satellite data indicate that the region may be better classified as mesotrophic (moderate nutrient levels). Ocean Primary Productivity (OPP) images suggest that OPP rates are high in the summer and fall, and low in the spring and winter, indicating that seasonal events instigate variability of OPP in the Caribbean Sea (Gilbes & Armstrong, 2004).

Sperm Whale Natural History

The sperm whale (*Physeter macrocephalus*) is listed by the International Union for Conservation of Nature (IUCN) as a vulnerable species of toothed whale (*Odontoceti*) found in all oceans of the world ranging from the Arctic and Antarctic to the equator. It has one of the largest distributions of any marine mammal (Taylor et al., 2008). From 1800 to 1987, the species' population drastically declined due to commercial whaling. Spermaceti, a waxy substance found in the whale's head, was sought after for oil lamps, candles, and lubricants. The worldwide stock of sperm whales is not precisely known, but estimated at between 300,000 to 450,000 individuals (NOAA, 2019). Females form social units, averaging 6.76 whales per social unit in the eastern Caribbean sperm whale community, which has a smaller range than sperm whales found in other regions (Gero et al., 2014). Females are always found with other females, and most tend to stay within their social unit for their entire life with close female relatives (Whitehead, 2009). At approximately nine years old, females are considered sexually mature, and reproduce every five to seven years with a 14-16 month pregnancy. Calves will nurse for several years, and also begin eating solid food before they turn one year old. Males will leave the family in their early teens, but only begin to actively breed in their late twenties. Males are often found with other males of approximately the same size and age. As they get older and larger, males often migrate toward the poles and their groups decrease in size; oftentimes the largest males are solitary. When males are sexually mature, they return to tropical waters to mate (NOAA, 2019).

Within the social units, females communally care for their young. Young sperm whale calves do not regularly dive to foraging depths for as long as their mothers, so they usually remain at or near the surface. Members of groups with calves seem to intentionally stagger their dives to “babysit” the young (Whitehead, 2003). Sperm whales eat approximately 3.5% of their weight daily, with prey consisting of primarily squid. Their deep dives average around 600m for 45 minutes, and can reach up to 3,000m for 60 minutes. When returning to the surface from a deep dive, sperm whales recover and breathe for approximately nine minutes (NOAA, 2019). Female and young sperm whales spend approximately 75% of their time foraging. However, from time to time, during periods of several hours, they gather at or near the surface to rest or interact with each other (Whitehead, 2003).

Female sperm whale home ranges or “grounds” can span approximately 2000km across, but ranges in the Caribbean appear much smaller, spanning a distance of approximately 460km within the Lesser Antilles (Gero et al., 2007). Sperm whale grounds are usually areas of high primary and secondary productivity (Whitehead, 2003; Whitehead, 2009). When there is plenty of prey available, the whales stay in relatively small ranges 10-20km across. Female sperm whales are most often found in water deeper than 1000m and at latitudes less than 40°, which corresponds roughly to sea surface temperatures greater than 15°C. Although sometimes seen close to oceanic islands rising from deep ocean floors (as is the case in Dominica), most female sperm whales stay far from land (Whitehead, 2009). Sperm whale distribution is concentrated in deep waters over high-relief bathymetry, which reflects high prey density in these areas (Roberts et al., 2016).

Eastern Caribbean Sperm Whales

Sperm whales found in the eastern Caribbean are behaviorally distinct and appear isolated from communities in neighbouring waters of the North Atlantic. A total of 521 individual sperm whales have been identified in the eastern Caribbean via photo-identification, primarily off of Guadeloupe and Dominica. In Dominica, a group of sperm whales is defined as all individuals coordinating behavior and movement that are seen within the same day. Groups do not imply that there is a social connection between individuals. Sperm whale social structures are defined by units, where social relationships have been observed as long-term and stable companionship throughout multiple years. There have been 25 social units formally identified in Dominica’s waters, with 9 other social units currently pending definition. There is usually only one unit of about seven sperm whales off the island of Dominica at any given time. The females and calves within the broader community of eastern Caribbean sperm whales are found year-round in the eastern Caribbean sea (Gero et al., 2014).

Threats to Eastern Caribbean Sperm Whales

Sperm whales face multiple threats from climate change, vessel strikes, entanglement, noise pollution, and contaminants (NOAA, 2019). Sperm whales are not well adapted to recover from population depletion, as the species has a maximum rate of increase of approximately 1% per year (Taylor et al., 2008). Starting around 2008, the eastern Caribbean sperm whale community was observed to be declining. Of the 16 social units for which there are reliable estimates of the total number of individuals between 2005 and 2015, 12 units have experienced decreases in the number of adults. Two units saw an increase, two units had no change in numbers, and almost one in three calves did not survive their first year. Since the eastern Caribbean sperm whale community is small and behaviorally distinct, if these whales are extirpated they may not be replaced by sperm whales found in neighbouring waters of the North Atlantic (Gero & Whitehead, 2016).

Ship Strikes

Vessel collisions with whales, or "ship strikes," have been identified as a significant source of human-caused mortality for whale populations around the world. Ship strikes are relatively rare with low probability of detection, but any resulting mortalities present a threat for long-lived, low fecundity whale populations (Rockwood, Calambokidis, & Jahncke, 2017). A study in the Canary Islands — a deep-water archipelago similar to the Lesser Antilles — found that the current level of ship strikes is too high to sustain long-term population viability of the local sperm whales (Fais et al., 2016). Although few ship strikes to sperm whales have been documented and/or reported, this could be attributed to negative buoyancy after a strike occurs, or the fact that their stocky body shape reduces the likelihood that they will get caught on vessel bows after a collision (Clarke, 1978). Recovery rates of sperm whales hit by vessels depend on lung inflation upon mortality; whaling records indicate that most float at death (Rockwood, Calambokidis, & Jahncke, 2017). Sperm whales are susceptible to ship strikes during surface intervals between deep foraging dives, and while resting. Calves may be more susceptible than adults, as they stay at the surface while the adults dive to forage (Papastavrou et al., 1989). In order to avoid a collision, ship crews need to detect and maneuver to avoid the whale. Alternatively, the whale has to detect the vessel, identify it as a threat, and escape, which may or may not be successful given the vessel speed and route. Vessel speed in particular has been identified as the primary factor driving the outcome of ship strikes, with faster vessels having a higher probability of both striking and killing whales (Gannier & Marty, 2015). For all whale species threatened by vessel traffic, lethal ship strikes are most often caused by ships greater than 80m in length, and traveling faster than 14 knots (Laist et al., 2001).

Dominica History and Economy

Dominica was a French colony during the mid-1600s and was occupied by both France and Britain during the mid-1700s. It was not until 1805 that France yielded its ownership and Dominica became part of the British Empire (Burnett & Uysal, 1991; Payne, 2008). Under British rule, there were periodic cycles of economic struggle and prosperity. After independence was gained in 1978, Dominica's economy continued to experience similar cycles (Burnett & Uysal, 1991; Hubbell, 2008; The Commonwealth, 2019b). Much of this is due to Dominica's natural environment (landscape and exposure to hurricanes) and its dependence on preferential trade relationships with foreign nations, mainly the European Union. Several studies comment on Dominica's push toward ecotourism as an attempt to diversify its originally agricultural-based economy. These studies acknowledge how fisheries have also played a role in the economy (Burnett & Uysal, 1991; Sebastian, 2002; Hubbell, 2008; Payne, 2008; Slinger-Friedman, 2009; Ramdeen et al., 2014; Sidman et al., 2014).

Development of Tourism and Ecotourism

Dominica can be distinguished from its Caribbean neighbors due to its unique topography. The island does not have the white sand beaches that typically attract tourists to Caribbean islands. There are also no intercontinental flights to Dominica, which can make it difficult to reach (Payne, 2008; Slinger-Friedman, 2009). Instead, the country is known for its mountainous ecosystem, lush tropical forests, rocky shores, and black sand beaches (Hubbell, 2008; Slinger-Friedman, 2009). As of 2009, Dominica attracted only 1% of tourists that visited the Caribbean region. As a result, Dominica's natural landscape has remained more pristine than neighboring Caribbean nations, providing a particular ecotourism niche which now contributes to the nation's economy and the well-being of the Dominican people (Slinger-Friedman, 2009).

Within the last four decades, the government of Dominica began to market its unique landscape as an alternative to traditional Caribbean tourism, and started to view the island's natural environment as an asset to tourist development. A national tourism policy, first drafted in 2005, was implemented around this alternative tourism strategy, and the "Nature Island of the Caribbean" began to see steady increases in tourist visits. Increases in visitor numbers were some of the highest in the region between 1989 and 2003. In 2003 alone, estimates of tourism revenue reached up to $43 million U.S. dollars (USD; Slinger-Friedman, 2009; Commonwealth of Dominica Ministry of Tourism and Legal Affairs, 2013). Tourism can be linked to the economic growth seen between 2004 and 2005 (The

Commonwealth, 2019a). At the time, the bulk of this revenue came from stayover tourists, but cruise ship tourists also contributed, and as of 2006, outweighed the number of stayover tourists (Slinger-Friedman, 2009). However, Dominica's Ministry of Tourism reported that cruise ship calls decreased by 6.5% in 2015 (Jacob, 2016).

The benefits of this rise in tourism and ecotourism have been examined through survey questionnaires and interviews with Dominican citizens that work in the tourism industry. Some of those surveyed include people working in hotels, restaurants, tour companies, dive shops, farming, craft shops, and even fishermen. The rise of the tourism industry created employment opportunities (10.3% increase from 1974-2005) and surveys reported a rise in income of those working in the industry (Slinger-Friedman, 2009).

In 2007, the economy was impacted when Hurricane Dean caused widespread damage and was further impacted in 2009 from the global recession. The economy stalled until 2014, when modest annual growth of 1% was observed (The Commonwealth, 2019a). In 2017, Dominica experienced economic losses in tourism and housing after being hit by Hurricane Maria (World Bank, 2017).

Fisheries and Fish Aggregating Devices

The marine fisheries sector in Dominica, while not a driver of the GDP, is a key component of the country's livelihood and food security. Dominicans that live near the coast rely on catches for subsistence and artisanal purposes, but nearshore reef fisheries have become severely depleted (Sebastian, 2002; Ramdeen et al., 2014). In particular, species such as snapper, grouper, and parrotfish were overfished by the mid-1980s (Ramdeen et al., 2014). Due to limited and depleted resources in nearshore waters, Dominica's primary fishery targets pelagic species, aided by the use of anchored fish aggregating devices (FADs; Ramdeen et al., 2014; Sidman et al., 2014). FADs are used by small boats, typically crewed alone or in pairs, using almost exclusively hand lines to reel in pelagic fish, which can reach hundreds of pounds. The FADs are anchored with 3000m-long lines, and drift according to prevailing currents.

FADs were introduced to Dominica in 1987 and are built to float on or right beneath the surface of the ocean and attract various pelagic species (Sebastian, 2002; Ramdeen et al., 2014; Sidman et al., 2014). These devices concentrate fish in a known location, which increases the efficiency of fishing. Initially, Dominica's FADs were constructed from bamboo, assembled into a raft that could be up to 30 feet long and 15 feet wide. Modern FADs are constructed with purse seine net below the surface and plastic containers and buoys to mark them (Sebastian, 2002). Since the introduction of FADs, pelagic catch has increased by 60-70% (Sidman et al., 2014).

Generally, FADs are deployed privately by individuals or small groups, including community-based fisheries cooperatives, and the number of FADs and their locations are not shared with others in the fishery. The government has deployed public FADs to provide more opportunities for FAD fishing; however, these are not favored due to crowding issues and low maintenance of the rafts in comparison to private FADs (Sidman et al., 2014).

Cruise Ship and Whale-Related Tourism Industry

Cruise Ship Tourism Industry

The cruise ship industry is a growing part of Dominica's economy. Most tourists visit the island via cruise ship, due to limited access by air. Over 70% of tourists visiting Dominica arrived via cruise ship between 1985 and 2004 (Bresson et al., 2011). Over 29 different cruise companies call at Dominica seasonally between October and April each year (A Virtual Dominica, 2019).

Sustainability in the cruise ship industry is important to Dominica and its residents. Cruise Lines International Association (CLIA) is an alliance between cruise ship operators who strive to meet sustainable actions, such as avoiding marine biological hotspots. A majority of the cruise companies who arrive in Dominica belong to CLIA (CLIA, 2019).

Whale Watching Tourism Industry

Whaling in Dominica was prominent before the 1986 moratorium on commercial whaling (Gero & Whitehead, 2016). Dominica, as well as neighboring islands St. Lucia, Grenada, Antigua, and Barbuda, received money for fisheries projects from Japan in exchange for their vote against anti-whaling issues at International Whaling Commission (IWC) annual meetings. Since the moratorium, Dominica has veered away from major whaling, but they are still allowed to hunt smaller cetaceans such as dolphins for cultural purposes. Overall, the country is promoting ecotourism through whale watching (Herrera & Hoagland, 2006).

Whale watching is a substantial part of Dominica's economy, though the exact economic contribution has not been quantified. The number of reported whale watchers in Dominica increased from 14 individuals to 14,500 individuals from 1991-2008. The direct expenditure in Dominica in 2008 was $585,000 USD for whale watching tickets and the indirect expenditure (i.e., contributions to the local economy attributed to the person participating in the whale watch activity) was $1.2 million USD (O'Connor et al., 2009). As the industry has grown and changed since 2008, these numbers require updating.

In 2008, there were four main whale watching operators who received clientele primarily from cruise ships visiting the island, as well as via hotel bookings. There were 20 employees in the whale watching industry, and the average ticket price of a tour was approximately $40 USD per person per trip (O'Connor et al., 2009). As of 2019, the prices are around $70 USD per person per trip, and the industry has grown substantially. For a much higher fee, tourists can purchase a spot on swim-with-whale tours, which is undertaken through swim-with-whale operators acquiring research permits from the Dominica Fisheries Division (A Virtual Dominica, 2019).

Swim-With-Whale Tourism Industry

Swim-with-whale tourism in Dominica began after 2010. International tour guides partner with local whale watching operators and work together to find clients who want to swim with sperm whales. The international swim-with-whale tour operators charter vessels from local operators for weeks at a time, and provide in-water experiences that allow tourists to spend time with the whales in their natural habitat. A research permit is required from the Dominica Fisheries Division of the Ministry of Agriculture and Fisheries. This enables the industry as an exemption to Dominica's Fisheries Act, the legal framework which governs and protects marine resources. The research permits cost $3,000 USD each. Each permit covers up to 10 days of water time. Permits only limit dates and not behaviour of the boats or swimmers while undertaking the tours, although operators are beginning to establish local guidelines for these activities. There is no real limit to the number of people the permit covers, but international tour guides prefer to have around 6-8 guests at a time. Permits are issued either directly to international guides, or to local operators running the tours. The typical swim-with-whale tour consists of the international tour guide or a local guide getting in the water with two tourists at a time, several times a day whenever whales are at the surface, to swim with the sperm whales (S. Gero, personal communication, February 3, 2020).

Ship Strikes, Shipping, and International Agreements

Multiple organizations are relevant to the issue of preventing ship strikes off the west coast of Dominica. Management measures to reduce ship strikes may require implementation of international vessel routing schemes such as shipping lanes and slow speed zones for vessels. Any changes off the coast of Dominica must be approved by the IMO to ensure they are reflected on navigation charts (IMO, 2020).

International Union for Conservation of Nature

The sperm whale is listed as "vulnerable" by the IUCN, and collisions with ships are cited as a threat. The IUCN acknowledges there has been a lack of recovery and even a decline in some regional subpopulations of sperm whales, and encourages assessments of the status of these subpopulations (Taylor et al., 2008).

International Whaling Commission

The IWC is the main international institution responsible for the conservation and stewardship of large cetaceans. Dominica has been a member country of the IWC since 1992 (IWC, 2019). The IWC has developed a report, "Strategic Plan to Mitigate the Impacts of Ship Strikes on Cetacean Populations," with the goal of developing approaches and solutions by 2020 to reduce ship strikes. The IWC advises that the most effective way to mitigate ship strikes is to reduce the spatial overlap of whales and vessels; if this is not possible, vessels should slow down and keep a lookout (IWC et al., 2017). The IWC is working with other international organizations such as the IMO to reduce collision risk.

International Maritime Organization

The IMO is the global standard-setting authority for the safety, security, and environmental performance of international shipping (IMO, 2019). IMO has adopted routing measures that can be used to protect cetaceans from shipping, and has issued a guidance document for minimizing the risk of ship strikes with cetaceans (IMO, 2009; IMO, 2017). IMO-adopted routing measures to protect large whales have been implemented in 10 specific geographic areas, and the international shipping industry has shown voluntary compliance with altering their vessels' courses to protect whales. Shipping lanes in five regions have been successfully shifted to reduce the spatial overlap of high density whale habitat and shipping traffic (Vanderlaan & Taggart, 2009).

As a Member State of IMO, Dominica would be required to submit a formal proposal justifying the need for an IMO measure such as implementing shipping lanes or areas to be avoided (ATBAs) to reduce ship strikes with the eastern Caribbean sperm whale community (Geijer & Jones, 2014). Dominica would need to submit the proposed routeing measures to IMO's Sub-Committee on Navigation, Communication, and Search and Rescue, which would then evaluate the proposal and make a recommendation regarding its adoption. The recommendation would then be passed to the Maritime Safety Committee for adoption (IMO, 2020). Once an IMO measure is approved, the delineated zone of shipping policy applies to all IMO Member State vessels. Compliance with IMO measures to reduce ship strikes is generally high; this can be leveraged to enable behavioral change in vessel traffic and ease the need for top-down legislation and enforcement by an individual IMO Member State (Geijer & Jones, 2014).

World Shipping Council

The World Shipping Council (WSC) is involved in the issue of protecting endangered North Atlantic right whale populations, which face mortality risk from ship strikes along the U.S. east coast. While the WSC does not agree with the current 10 knot seasonal speed limit regulation imposed by the U.S. National Marine Fisheries Service (NMFS) to protect these endangered whales, it supports other IMO measures such as the establishment of ATBAs and shipping lanes to reduce ship strikes (WSC, 2019).

Case Studies

Whale Tourism

The following case studies examine whale-centered tourism industries elsewhere in the world.

Whale Tourism Case Study: Tonga

Tonga is similar to Dominica in that it is also a Small Island Developing State that benefits from ecotourism and whale watching. It is one of the few island nations in the South Pacific that hosts humpback whales year round. In 2002, an economic analysis of Tonga's whale watching industry was completed. The main difference between the two island nations of Tonga and Dominica is that the majority (80%) of visitors to Tonga arrive via aircraft. This allows the tourists to spend more time directly on the island, which results in more money spent on-island, rather than returning to a cruise ship directly after an excursion. The total direct expenditure from whale watching fares of just over 9,000 whale watching visitors was $115,000 USD in 2002. Total overall tourism expenditure contributed $700,000 USD in 2002 to Tonga's economy (Orams, 2002).

Although an explicit analysis on swim-with-whale tours has not been completed in Dominica, there have been other studies that express the relationship between whales and humans in the water together, specifically in Tonga. The Tongan swim-with-whale industry focuses on swimming with mother-calf groups, because these are more likely to be resting in shallow waters close to shore. In general, swim-with-whale programs have been shown to increase individual whale travel speed, reorientation rates, surface activity, time spent travelling, and avoidance responses, which reduces time spent feeding. To achieve a sustainable use of swim-with-whale tourism, studies suggest management should be focused on swimmer behavior. There was a significant difference between loud, splashing swim approaches and quiet approaches (Kessler et al., 2013).

Whale Tourism Case Study: Channel Islands National Marine Sanctuary

The Channel Islands attract both consumptive and non-consumptive forms of revenue to the coast of California through ecotourism. Consumptive refers to activities like fishing and consumptive diving where resources are taken and used directly, while non-consumptive activities include kayaking, island sightseeing, whale watching, non-consumptive diving, and sailing. Whale watching is a popular activity, as the Santa Barbara Channel is one of the best places to see blue whales, and provides vital habitat to other cetacean species such as humpback, fin, and gray whales (Gonyo et al., 2017). A 2005 socioeconomic impact analysis of the Channel Islands region using 1999 data as the baseline for analyses reported that whale watching accounted for 26% of all non-consumptive recreation activity (Leeworthy, Wiley, & Stone, 2005). This equates to 25,984 person-days from whale watching alone and an estimated revenue of $1.5 million USD to local operators, supporting 119 jobs. This estimate can amount to as much as $4.3 million USD in revenue to the local economy when total passenger spending is accounted for (Channel Islands National Marine Sanctuary, 2019).

Reducing Ship Strikes

The following case studies examine efforts in other areas of the world to reduce ship strike threats to large whales.

Reducing Ship Strikes Case Study: North American East Coast

With a population of less than 400 individuals, the North Atlantic right whale is one of the most endangered whales in the world. In the 1990s, management actions taken included voluntary measures, outreach, and research. Despite these efforts, each year ship strikes continued to result in right whale deaths. In 1999, these voluntary measures were deemed insufficient at preventing ship strikes and the recovery of North Atlantic right whales. In 2001, NMFS formed a working group to address the ship strike issue. A strategy was created that consisted of five elements: 1) continued research; 2) education and outreach; 3) using the Endangered Species Act to consult on federal actions; 4) an agreement with Canada to protect the whales; and 5) operational actions of commercial and recreation vessels (Abramson et al., 2011).

There are three regulations for commercial vessels within the Stellwagen Bank National Marine Sanctuary. The first regulation shifted the shipping lanes to move commercial vessels to an area of historically low right whale density. This regulation is predicted to reduce ship strikes by 58%. The shift in shipping lanes was negotiated between the U.S. Coast Guard, NMFS, and the IMO. The second regulation requires Liquefied Natural Gas carriers to slow down to 10 knots or less in response to real time detections of right whale acoustics in the shipping lanes. The third regulation, administered by NOAA, requires commercial ships to slow down to 10 knots or less within Seasonal Management Areas off the U.S. east coast. Two of these Seasonal Management Areas intersect with the Stellwagen Bank National Marine Sanctuary boundaries during the right whale feeding season (Abramson et al., 2011).

Off the coast of the U.S. and Canada, two voluntary ATBAs have been implemented to protect North Atlantic right whales. High compliance was found with an established ATBA adopted by the IMO on the Scotian Shelf to reduce vessel strike mortality in North Atlantic right whales (Vanderlaan & Taggart, 2009). Utilizing these IMO routing measures is an effective way to conserve whale populations without excessively impacting shipping interests (Silber et al., 2012).

The mitigation of ship strikes along the North American east coast using the methods above has significantly benefited North Atlantic right whales, leading to increases in the population over the last decade (Rockwood, Calambokidis, & Jahncke, 2017).

Reducing Ship Strikes Case Study: North American West Coast

A study estimating mortality of blue, humpback, and fin whales from modeling of ship strikes on the U.S. west coast recommends combining shipping lane modifications and re-locations, ship speed reductions, and creation of ATBAs by vessels in ecologically important locations. Specifically, the authors recommend four strategies: 1) further efforts to relocate shipping lanes away from high density areas of whales; 2) extension of lanes further offshore so that high-traffic routes between ports are shifted away from coastal concentrations of whales; 3) creation of ATBAs in cooperation with the IMO; and 4) implementation of a graduated slow-steaming requirement within the U.S. Exclusive Economic Zone where ships travel at increasingly reduced speed as they travel closer to shore. The fourth recommendation has the greatest potential to mitigate the widespread threat of ship strikes, and has the added benefit of decreasing pollution, carbon emissions, and fuel costs, which could partially offset the price to the shipping industry of longer transit times (Rockwood, Calambokidis, & Jahncke, 2017).

A recent study analyzing ship strike risk for fin whales in the California Current System found that the California coast's shipping lanes contained 14% of traffic volume and contributed 13% of all ship strike risk within North America's west coast shipping lanes in 2013. While vessel speed reductions within shipping lanes may be an effective remediation for ship strikes, these speed reductions only address a small fraction of overall ship strike risk within the California Current System. Modifications to shipping lane placement, which may locally reduce fin whale strikes, would also only partially alleviate a portion of the ship strike risk. Additional speed restrictions outside of shipping lanes, where vessels travel between the lanes and ports, would more effectively reduce the overall risk of ship strikes. The study concluded that speed reductions should be considered an effective measure for reducing mortality due to ship strikes, as well as improving fuel efficiency and reducing anthropogenic noise and emissions. The authors also stressed the need for considering mitigation measures beyond their study area, and consider spatial management schemes such as the expansion of shipping lanes and ATBAs (Keen et al., 2019).

Reducing Ship Strikes Case Study: Mediterranean

In 2006, a re-configuration of shipping lanes in the Strait of Gibraltar was proposed to the IMO. Recognizing that this modification would intensify vessel traffic through key sperm whale aggregation areas, the Spanish Maritime Authority proposed to establish a security area where vessels were advised to limit maximum speed to 13 knots and to navigate with particular caution. After review, the IMO published the 13 knot speed recommendations, added it to International Nautical Charts, and disseminated a Notice to Mariners. This speed reduction measure became the first vessel speed recommendation instituted in a shipping lane for the purposes of whale conservation (Silber et al., 2012).

A recent study looked at reducing collision risks between large vessels and the eastern Mediterranean sperm whale subpopulation along the Hellenic Trench. This study focused on routing measures as the sole mitigation as IMO frequently implements these measures, whereas vessel speed restrictions are rarely implemented and generally have low compliance. The study estimated the proposed routing measures would reduce the overall vessel collision risk for sperm whales in the study area by approximately 70% (Frantzis et al., 2019).

Another study focused on migratory whale conservation in the Mediterranean proposed that a regional network of shipping activity restrictions through the IMO is the most effective method to reduce ship strikes. By using a combination of IMO-endorsed shipping regulations, seasonal high-use habitats and migratory corridors could be protected. This study suggested using the IMO Particularly Sensitive Sea Area management tool along with Associated Protection Measures that regulate international shipping activities to protect key areas where unique marine environment and whale critical habitats occur together. The study proposed using these IMO measures to impose vessel speed reduction during the seasonal presence of whales (Geijer & Jones, 2014).

Methods

Economic Valuation

The goal of this economic valuation is to determine the annual net profit generated from sperm whale tourism in Dominica, and specifically how much of that value directly contributes to the Dominican economy. In order to estimate annual net profit, we aimed to find a range of net profit values for the primary businesses that comprise the whale tourism sector: whale watching tour operators, swim-with-whale tour operators, tour booking companies (e.g., hotels and dive shops), and cruise lines that offer whale watching excursions to their passengers while in Dominica. The total combined annual net profit from all groups would provide an estimate for the net profit of the entire sector.

Three estimates of annual net profit were found: 1) using a combination of both survey responses and online research, which we refer to as ”available data”; 2) using only survey response data; and 3) using data sourced only from online research.

Annual net profit was calculated based on available data from survey responses and online research. Available data includes information gathered from both survey responses and online research. For values calculated using available data, some responses may be duplicated as the survey was carried out anonymously, and data sourced from online research could be repeated in the survey responses. Due to lower than expected survey responses and lack of complete online data, the results from the available data were combined and extrapolated to produce an estimate of annual net profit. See Appendix A2 for a detailed spreadsheet that includes calculations for survey responses and online research should more complete data become available in the future.

Calculations

The following equations were created based on economic information collected from available data, from both the survey and online research. Equations were also created to calculate extrapolated values to account for missing data for all operators.

Available Data: Whale Watching and Swim-With-Whale

To calculate total annual net profit for whale watching and swim-with-whale tour operators, the following equation was adapted from a study evaluating the socio-economic value of shark-diving tourism in Palau (Vianna et al., 2012):

Equation 1: $$NPW = (WET * W) - E$$

- *NPW* = Annual net profit from sperm whale tourism
- *WET* = Average whale tourist expenditure per trip
- *W* = Number of whale tourists per year
- *E* = Average expenses for whale tour operator

Cruise Line Profit

To calculate the annual net profit related to the surplus cruise lines make by charging their passengers a higher ticket price than the whale watching tour operators charge, the following equation was adapted from the previous equation:

Equation 2: $$NPWC = PC * WW * TPD$$

- *NPWC* = Annual net profit for cruise lines from sperm whale tourism
- *PC* = Average proportion of whale watchers from cruise ships
- *WW* = Number of whale watchers per year extrapolated for 5 whale watching tour operators
- *TPD* = Average ticket price difference

The proportion of whale watchers from cruise ships (*PC*) is the average percentage of clientele that whale watching survey respondents indicate are from cruise ships. The ticket price difference (*TPD*) is the difference of the prices charged by whale watching tour operators and the prices cruise lines charge their passengers to go on whale watching tours. The number of whale watchers per year (*WW*) is the vessel capacity multiplied by the average number of trips per year for all 5 whale watching operators in Dominica. These calculations are only for whale watching operators, as participants in swim-with-whale tours typically fly into Dominica rather than arrive on a cruise ship.

Extrapolated: Whale Watching and Swim-With-Whale

In order to estimate total annual net profit for operators that either did not provide survey responses or we could not find online data for, extrapolated values were calculated using the following equation for whale watching and swim-with-whale tourism:

Equation 3: $$Extrapolated\ NPW = \frac{T}{n}\sum_{i=1}^{n} NPWi$$

- *T* = Total number of operators
- *n* = Number of operators that responded to the survey

Whale Watching Tour Operators

We obtained available data for 3 out of the 5 whale watching tour operators (*T* = 5, *n* = 3). The extrapolated annual net profit was calculated by multiplying the mean annual net profit of the 3 operators we had data for by the total number of whale watching operators (5 operators).

Swim-With-Whale Tour Operators

We obtained available data for 6 out of the 10 swim-with-whale tour operators (*T* = 10, *n* = 6). The extrapolated annual net profit was calculated by multiplying the mean annual net profit of the 6 operators we had data for by the total number of swim-with-whale tour operators (10 operators).

Range of Values for Total Annual Net Profit: Whale Watching and Swim-With-Whale

To account for uncertainty in both the available data values and the extrapolated values, low, high, and mean net profit estimates were calculated.

For the available data, low annual net profit values were calculated by multiplying an operator's low price charged per ticket, low vessel capacity, and number of trips per year. Low capacity was the reported number of whale watching tourists needed to make a trip worthwhile financially.

Estimates for high annual net profit were calculated using an operator's high price charged per ticket and high boat capacity, multiplied by the number of trips per year.

Mean estimates for net profit were calculated by finding the mean of the low and high ticket price and vessel capacity, multiplying those mean values by the number of trips per year.

Economic Benefits to Dominica

Since all 5 whale watching tour operators are local to Dominica, we assume that all net profit from whale watching operators is going back into Dominica's economy. For cruise ships, we assume the entire annual net profit does not contribute to Dominica's economy, as this value captures the surplus created by cruise lines charging their passengers a higher ticket price than what the whale watching operators charge. However, all 10 of the swim-with-whale tour operators are run by companies operating outside of Dominica. Therefore, we can estimate how much of the swim-with-whale tour operators' net profit is going back to Dominica's economy by incorporating the costs to swim-with-whale tour operators and guests that contribute to Dominica's economy.

International swim-with-whale operators are charged a research permit fee, which covers 10 days, and operators pay to charter local dive boats for their tours. To calculate a portion of the benefits to Dominica, we multiplied the total number of trips per year for all operators by the average local charter boat cost. Typical swim-with-whale trips are five days.

We then added this value to the permit cost to get an average estimate of costs incurred by swim-with-whale operators. These costs are assumed to be direct benefits to the Dominican economy, as research permits are issued by the government and charter boats are operated by locals. This estimate was calculated for both survey data and online research separately.

Equation 4:
$$BD = (TT * CB) + P$$

- BD = Economic benefit to Dominica from swim-with-whale tours
- TT = Total number of trips (assuming each trip is 5 days)
- CB = Average charter boat costs
- P = Research permit costs

The following are additional examples of costs incurred by swim-with-whale operators and guests that we did not have available data for:

- Hotel bookings
- Food and beverage
- Additional purchases

Survey

We created a survey to better understand the economic aspects of whale-related tourism in Dominica. It targeted four business categories: 1) cruise ship tour coordinators; 2) tour booking agencies; 3) whale watching tour operators; and 4) swim-with-whale tour operators. Questions were based on general information about the company's operation and specific economic information about their business in Dominica (see Appendix A1). We administered the survey via email in October 2019 to a list of contacts provided by the client, Dr. Shane Gero. A total of 62 recipients were contacted to complete the survey. We sent out periodic reminder emails with the survey attached, and called the individual cruise lines and international swim-with-whale tour operators as a final reminder. Follow up correspondence continued until January 2020.

Research

We collected publicly available information online for whale watching tour operators, swim-with-whale tour operators, and cruise lines to supplement survey responses and provide a starting point to collect comprehensive data on companies involved in sperm whale tourism in Dominica.

Economic Model Spreadsheet

To document our calculations and collected data as well as support future work exploring the economic contribution of sperm whales in Dominica, we designed a spreadsheet for our economic valuation model to serve as a computational tool for our client and the Dominican government. We created the spreadsheet following the "Microsoft Excel Data Curation Primer" to ensure the spreadsheet was accessible and easy to use (Janée et al., 2019). We adapted an example given by the Data Curation Network for a computation or modeling spreadsheet to create our economic model spreadsheet (Bemrah Aouachria et al., 2016). The spreadsheet includes instructions for how to use it, as well as different sheets to calculate the annual net profit for whale watching tour operators, swim-with-whale tour operators, and cruise line companies (see Appendix A2).

Marine Spatial Plan

Data Preparation

Whale Presence Data

DSWP documented opportunistic sightings of sperm whale clusters with photographs taken from their research vessel. The camera used to take photos of the whales did not have Global Positioning System (GPS) capabilities, but each photo was associated with a time. GPS locations of the research vessel were provided by DSWP. Therefore, even though whale cluster photos did not contain GPS locations, the time associated with the GPS location of the research vessel could be paired with the corresponding time of a cluster sighting photograph. This allowed for a reconstruction of sperm whale presence location, based on where the research vessel was at the time of a cluster sighting. The resulting data include sperm whale presence points off the west coast of Dominica from 2005-2018, excluding 2006 and 2013 (see Appendices B2 and C1).

AIS Data

Automatic identification system (AIS) data were collected from stations on Dominica and surrounding islands from 2012-2019, excluding 2016 due to Hurricane Maria (see Appendix

B3). AIS vessel data for all years had to be combined into one cohesive dataset before any vessel track analyses were conducted, as each year of AIS data were stored in a separate file. Data also needed to contain attributes related to both descriptive information (e.g., vessel type, vessel identification, etc.), and position information (e.g., speed, GPS locations, etc.). The more recent AIS data from 2017-2019 were complete with both descriptive and position information. However, AIS data for 2012-2015 did not originally contain descriptive information, so these attributes had to be sourced from an external database. We used R to combine all years of AIS data, which were then imported into an SQLite database for organization and analysis purposes (see Appendix C2).

After both AIS and whale presence data were prepared in the appropriate formats, we explored the spatial relationship between vessels and whales. By visually and statistically analyzing vessel and whale abundance and distribution, we designed a marine spatial plan that best suits the vessel traffic patterns and the local sperm whale community off the west coast of Dominica.

Data Analysis

A combination of maximum entropy modeling (MaxEnt) and geographic information system (GIS) software (ArcGIS and QGIS) were used to analyze and visualize data on sperm whale presence and vessel traffic to identify and mitigate ship strike threats to the eastern Caribbean sperm whale community. MaxEnt predicts species occurrences by finding the distribution that is most spread out, or closest to uniform, while taking into account the limits of the environmental variables of known locations. ArcGIS and QGIS are geographical information systems used in map-making, spatial data analysis, and database management.

Species Distribution Model Using MaxEnt

Species distribution modeling is a type of spatial analysis used to find likely locations of a species. MaxEnt was used to create a species distribution model (SDM) predicting suitable areas for sperm whales off the west coast of Dominica. Species distribution modeling requires two sets of data inputs: 1) species presence points; and 2) environmental data related to the species of interest. MaxEnt requires that environmental data are in plain text format, and that all data are identical in resolution, extent, and projection. MaxEnt uses these presence-only species data and environmental conditions data to model species geographic distributions (Phillips, Anderson, & Schapire, 2006).

For the environmental inputs to the SDM, we used publicly available bathymetry, temperature, salinity, chlorophyll, and primary production data (see Appendix D1).

Bathymetry, temperature, and primary production were referenced in the literature as being important to sperm whales, but salinity and chlorophyll were included to see if they were also relevant to the SDM. We used the bathymetry layer as a mask for all other environmental layers, assuring that the extent, projection, and resolution were the same for all inputs (see Appendix D1, Figure D1).

We input sperm whale presence points to the SDM using seasonal data collected by DSWP off the west coast of Dominica from 2005-2018, excluding years 2006 and 2013 (see Appendix B2). The sightings data were assigned GPS coordinates from the research vessel by matching up the timestamp from the sightings photographs with the closest GPS coordinates from the research vessel track data (see Appendix C1).

We then converted the whale presence data to shapefile and raster datasets within ArcGIS according to the appropriate coordinate system and resolution for our study area. We also used ArcGIS to prepare the whale presence data to bring into MaxEnt (see Appendix D1).

We then loaded the sperm whale presence, bathymetry, temperature, salinity, chlorophyll, and primary productivity data into MaxEnt. We completed two MaxEnt runs, one using the maximum values for salinity, chlorophyll, and primary productivity environmental layers, and the second using the mean values for salinity, chlorophyll, and primary productivity. The minimum value for temperature was used for both model runs as female sperm whales are restricted by temperatures above 15°C. As the model run using maximum values had a better fit, we chose these parameters for our MaxEnt analysis (see Appendix D2).

Vessel Traffic Visualization and Density Analysis

We filtered the AIS data to include merchant, cruise ship, and high speed ferry categories, as these vessel types pose the greatest lethal ship strike risk due to their large size and fast speeds. We also filtered the AIS data to include only vessel positions at speeds of 10 knots or greater (see Appendix E). We used the comprehensive AIS data from 2012-2019 (excluding 2016) to visualize vessel traffic patterns for vessels traveling over 10 knots. To get a representative example of vessel traffic patterns for each category, 2018 data were used to map each category (Figure 4; see Appendix E1). We completed a density analysis for all vessels traveling greater than 10 knots in all years (2012-2019; excluding 2016) at a resolution of 1km^2 and distributed into quantiles (Figure 5; see Appendix E2).

Creating Vessel Traffic Recommendations

We created recommended shipping lanes and a vessel speed reduction zone based on current vessel traffic patterns and sperm whale habitat suitability. We created the vessel speed reduction zone to encompass the high habitat suitability area from the MaxEnt SDM output. Vessels would be required to travel 10 knots or less in the recommended speed reduction zone. We created offshore northbound and southbound lanes along the offshore perimeter of the speed reduction zone, which could be used by merchant and cruise ship vessel types transiting through Dominica's coastal waters. We created inshore northbound and southbound lanes along the inshore perimeter of the speed reduction zone. The inshore lanes encompass the current path that high speed ferries utilize to travel between Portsmouth and Roseau, as well as between surrounding islands. For vessels coming into port at Portsmouth and/or Roseau, there are no established recommended lanes, but vessels would be required to slow down to 10 knots or less if they transit through the speed reduction zone on their way to port (see Appendix F1).

Quantifying Vessel Time Cost in Vessel Speed Reduction Zone

Once the speed reduction zone was created based on sperm whale habitat suitability, we calculated the time cost to vessels slowing down through this zone. The time cost was quantified by calculating the additional time that would be added to a vessel's route due to having to slow down to 10 knots through the proposed vessel speed reduction zone. The total time cost was calculated for all vessels traveling faster than 10 knots from 2012-2019 (excluding 2016) off the west coast of Dominica (see Appendix F2).

Shiny App Visualizing Whale Presence and Vessel Traffic

Shiny is a framework for R that allows you to build interactive web applications (Chang et al., 2020). With this tool we designed an interactive mapping application in R that users will be able to access online (see Appendix G). The Shiny app visualizes sperm whale and vessel abundance and location over time and includes three tabs:

1. Tab 1: Project summary.
2. Tab 2: Interactive map where users can select a year for whale cluster sightings to visualize their distribution in the study area for each year 2005-2018.
3. Tab 3: Interactive map where users can choose a range of vessel speeds and visualize the vessels traveling at specific speeds, displayed over a static map of the sperm whale presence points. An interactive line graph is also included at the bottom of the tab, where users can choose to graph whale abundance, total vessels, and individual categories of vessels from 2012-2018.

Results

Economic Valuation

Survey

The survey had a 14.5% response rate, with a total of nine survey responses (two tour booking companies, four whale watching tour operators, and three swim-with-whale tour operators) out of 62 survey recipients (see Appendix A1).

Survey responses from tour booking companies were not complete enough to calculate annual net profit estimates for this group. Therefore, tour booking operators were not included in total annual net profit calculations for the sperm whale tourism industry. One of the survey responses for whale watching tour operators was not complete enough, so was not included in calculations for this group.

Total Annual Net Profit Model

Two sets of estimated total annual net profit values for the sperm whale tourism industry were calculated using Equations 1-3 described in the methods section. The results include both available data and extrapolated values (Table 1).

Table 1 includes total annual net profit estimates for each of the whale tourism sector groups we were able to collect data for in Dominica. Estimates include values calculated from both survey and online data as well as values extrapolated from the combination of survey and online data. For values used in calculations, see Appendix A2. Table 1 includes the annual net profit values found using a combination of survey and online research results. Due to the anonymity of the survey, there is no way of knowing whether operator information found online had already been accounted for in the survey results; this may have produced duplicates. However, combining these two available data sources was necessary to obtain an estimate of total annual net profit using the best available data. See Appendix A3 for estimated annual net profit values calculated using only survey results or online research results, respectively (Table A1 and Table A2).

Only extrapolated annual net profit values are displayed for cruise lines as the extrapolated number of annual whale watching tourists was used in the calculation.

Table 1. Total Annual Net Profit Generated From Whale Tourism in Dominica. These results include combined survey and online research data and represent direct expenses only. All values are in USD.

	Available Data	Extrapolated
Whale Watching Low	$78,496	$130,827
Whale Watching Mean	$500,623	$826,372
Whale Watching High	$1,285,000	$2,141,667
Swim-With-Whale Low	$642,700	$1,948,600
Swim-With-Whale Mean	$1,021,690	$2,043,380
Swim-With-Whale High	$1,102,080	$2,204,160
Cruise Line Surplus Low	N/A	$21,906
Cruise Line Surplus Mean	N/A	$43,812
Cruise Line Surplus High	N/A	$65,718
Average Whale Tourism Net Profit	**$1,522,313**	**$2,913,564**

Economic Benefits to Dominica

The total estimated annual economic benefits to Dominica amount to $1,082,985 USD. We calculated this value using Equation 4, described in the methods section. All profit generated from whale watching tourism can be considered a direct economic benefit to Dominica because all of the whale watching operators are local to Dominica (see Table 1). International swim-with-whale tour operators share the profits with Dominica. We calculated the economic benefits to Dominica from swim-with-whale research permits ($3,000 USD/each) and daily boat charter prices (dependent on operator and boat size). The number of swim-with-whale trips per year is the average of survey and online results (28.5 trips), multiplied by the minimum number of days a boat could be chartered (5 days, because swim-with-whale operators fit two 5-day trips into every 10-day permit). To see the separated survey and online research results refer to Appendix A4.

Marine Spatial Plan

Species Distribution Model

The SDM created in MaxEnt from whale presence data and environmental factors demonstrates the areas of highest predicted habitat suitability for sperm whales off the west coast of Dominica. The SDM output is visualized in Figure 2, with Figure 3 also displaying sperm whale presence data (2005-2018). Since the environmental data used in the SDM was downloaded on a global scale, the output had a low resolution, causing the map to display coarse pixels, evidenced in Figure 2 and Figure 3.

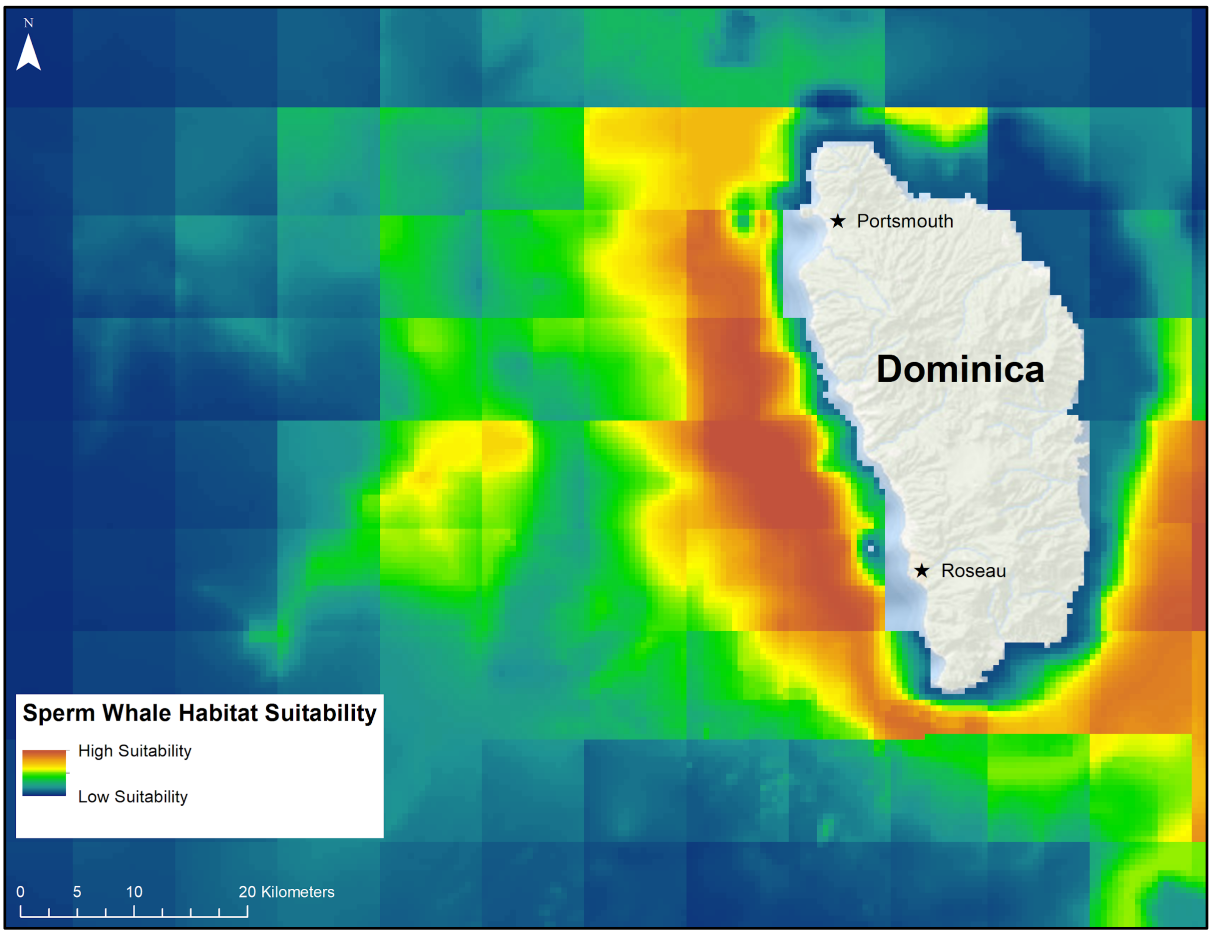

Figure 2. Species Distribution Model Output. MaxEnt output of the point-wise mean of the model using maximum values for salinity, chlorophyll, and primary productivity. Sperm whale presence data with temperature, bathymetry, salinity, chlorophyll, and primary productivity environmental variable inputs. Jackknife analysis determined primary productivity and bathymetry to be the most influential factors on sperm whale distribution. The scale in the legend indicates habitat suitability, with red areas representing high suitability, and blue areas representing low suitability.

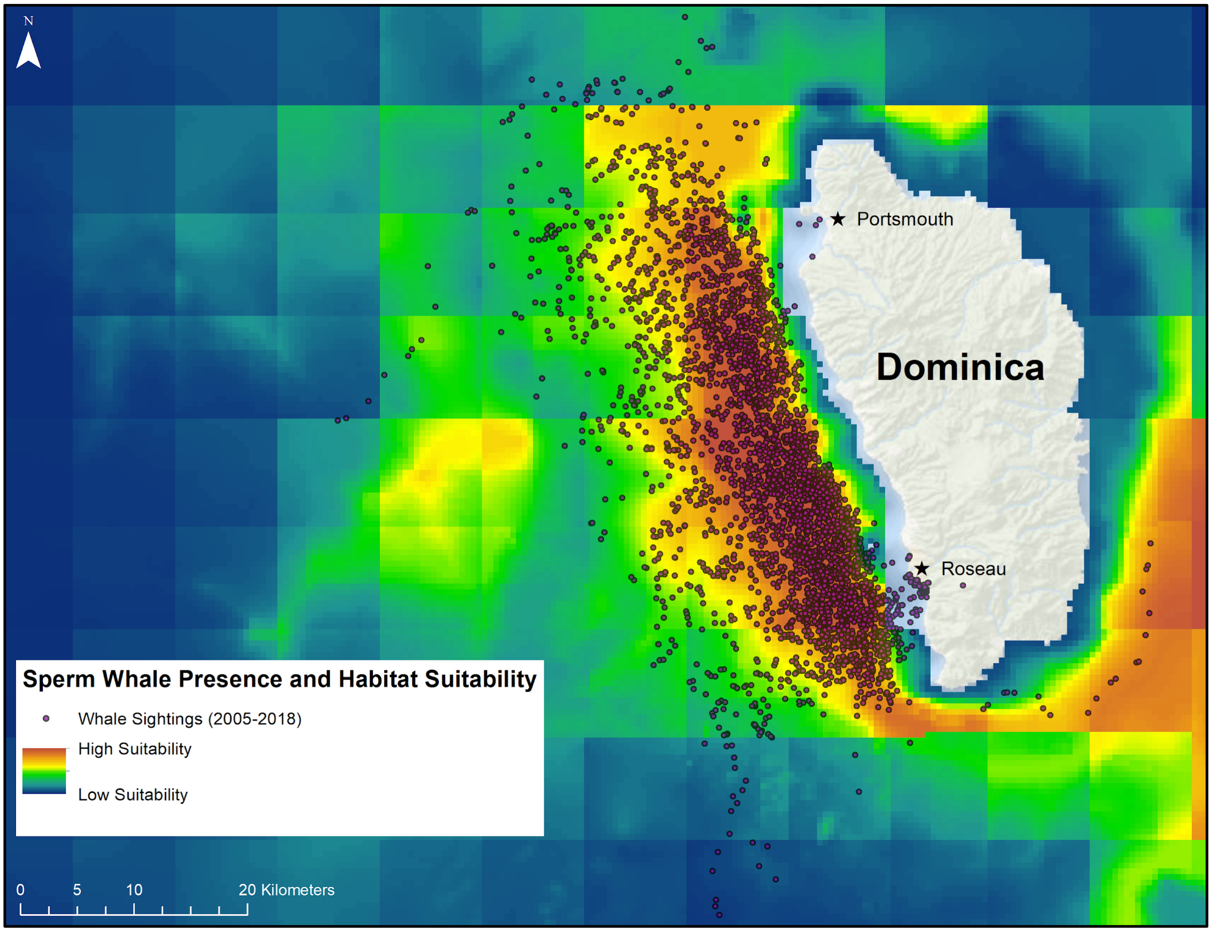

Figure 3. Sperm Whale Presence and Species Distribution Model Output. Whale sightings points collected from the Dominica Sperm Whale Project from 2005-2018 are overlaid on the habitat suitability MaxEnt output indicating areas of high (red) and low (blue) suitability.

Vessel Traffic Analysis

To visualize how each vessel category of interest utilizes the west coast of Dominica, we used data for 2018 only to get a representative sample of annual travel patterns of high speed ferries, cruise ships, and merchant vessels (Figure 4).

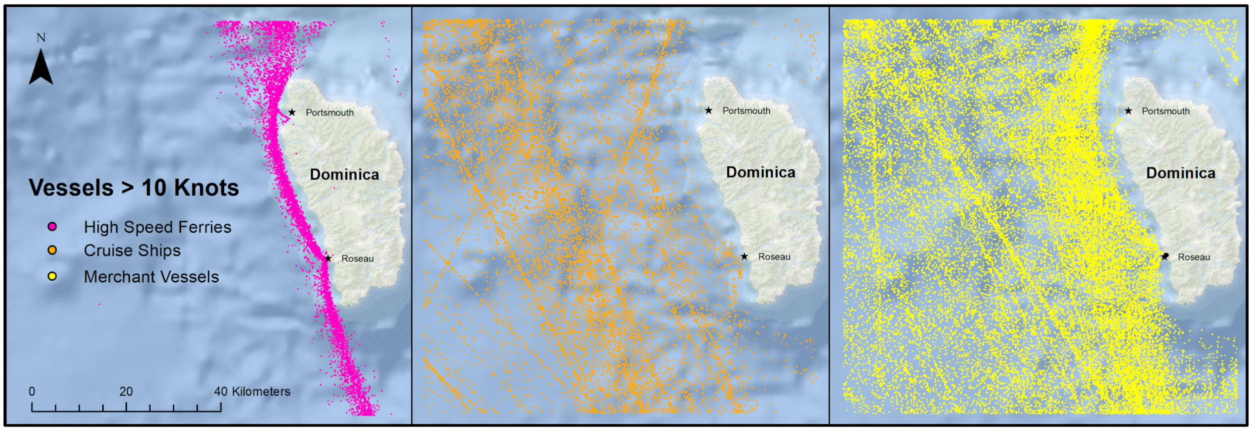

Figure 4. Vessel Traffic Visualization (2018). The left panel visualizes high speed ferries traveling greater than 10 knots in 2018 (pink). The middle panel visualizes cruise ships traveling greater than 10 knots in 2018 (orange). The right panel visualizes merchant vessels traveling greater than 10 knots in 2018 (yellow). High speed ferries tend to stay close to shore and stop frequently at both Portsmouth and Roseau. Cruise ships tend to travel further offshore, and not as many stop at the ports in Dominica. While merchant vessels also pass by Dominica further offshore, there are also a number of vessels that visit both ports.

Vessel Density Analysis

To visualize locations of highest vessel density on the west coast of Dominica, we completed a density analysis of merchant vessels, cruise ships, and high speed ferries traveling over 10 knots for 2012-2019. The grid represents 1km^2 cells with a count of vessels found in each cell for all years analyzed (Figure 5). The highest density of vessels traveling over 10 knots occurs relatively close to Dominica's west coast, within areas of high sperm whale habitat suitability.

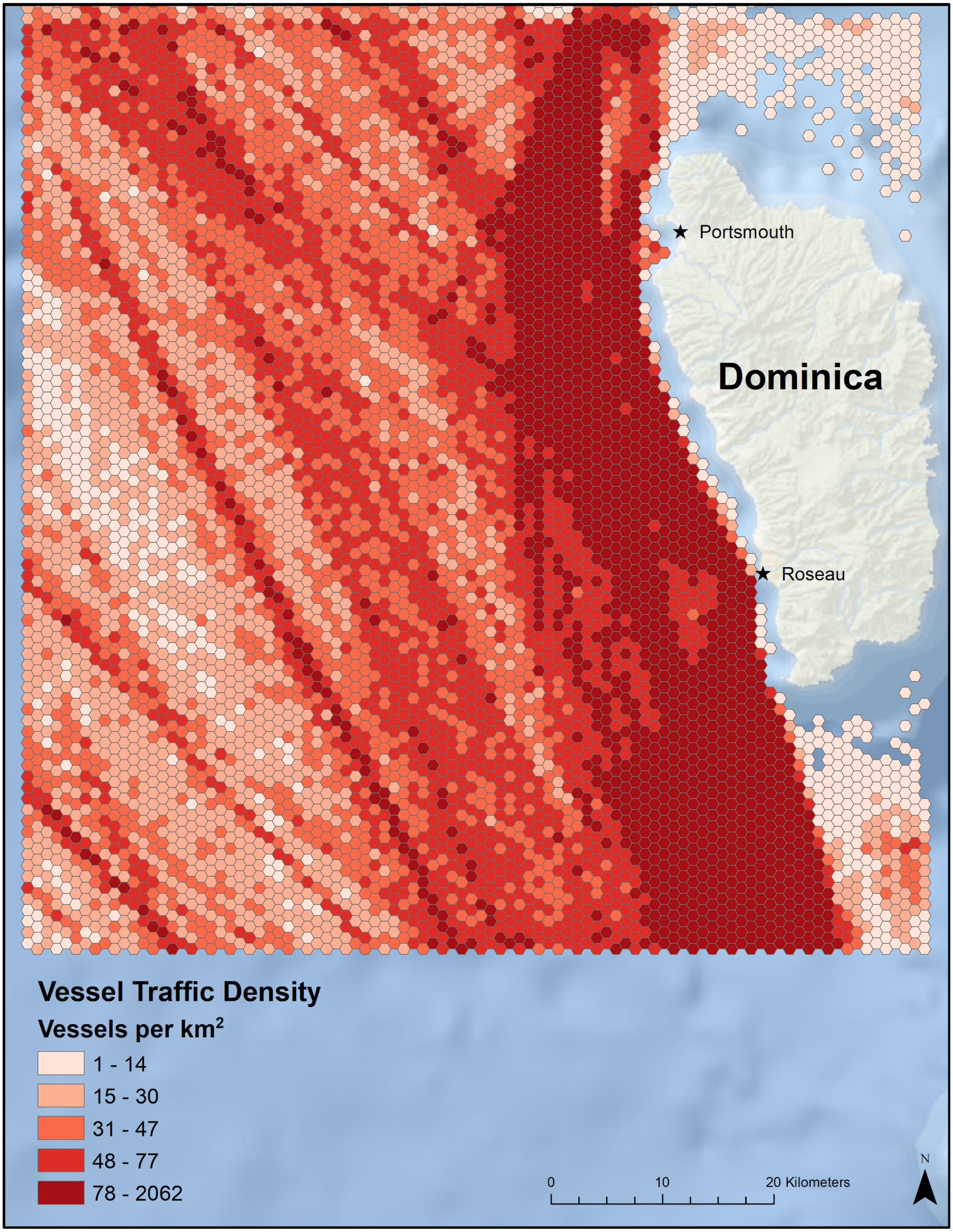

Figure 5. Vessel Abundance Density per km^2 (2012-2019). Vessel abundance per km^2 from 2012-2019 distributed into 20% bins. The darkest red represents the highest density of vessels, or the top 20% of vessel points traveling greater than 10 knots.

Vessel Traffic Recommendations

We recommend that the Dominican government implement three vessel traffic schemes to regulate and manage vessel traffic off the west coast of Dominica. By separating the vessels from whales where possible, and reducing speeds in areas where it is not feasible to separate, we hope to reduce ship strike threats to the local sperm whale community. As mentioned earlier, the North Atlantic right whale case study involved a similar slow speed regulation and has been successful in reducing the threat of ship strikes to this population (Abramson et al., 2011). Our marine spatial plan is designed by taking into account sperm whale distribution and habitat suitability and vessel patterns. Due to lack of data on FAD placement, they are not incorporated in the vessel traffic schemes outlined below.

Vessel Speed Reduction Zone

The vessel speed reduction zone is mapped to encompass the high habitat suitability area from the SDM output (Figure 6). Any vessel transiting through this speed reduction zone would be required to reduce its speed to 10 knots or less.

- Area: 588km^2
- Perimeter: 135km
- Maximum width: 15km

Offshore Shipping Lanes

The offshore shipping lanes are separated from the vessel speed reduction zone by 1nm to avoid areas of high sperm whale suitability. The northbound and southbound offshore lanes are also separated by 1nm to reduce vessel traffic conflicts (Figure 6). These lanes would be used mainly by merchant vessels and cruise ships either traveling past Dominica, or to one of Dominica’s ports, Portsmouth or Roseau.

Inshore Shipping Lanes

The inshore shipping lanes are separated from the vessel speed reduction zone by 0.5nm to avoid areas of high sperm whale suitability. The northbound and southbound inshore lanes are also separated by 0.25nm to reduce vessel traffic conflicts (Figure 6). These lanes would be utilized mainly by high speed ferries traveling between Dominica's ports, or between neighboring islands.

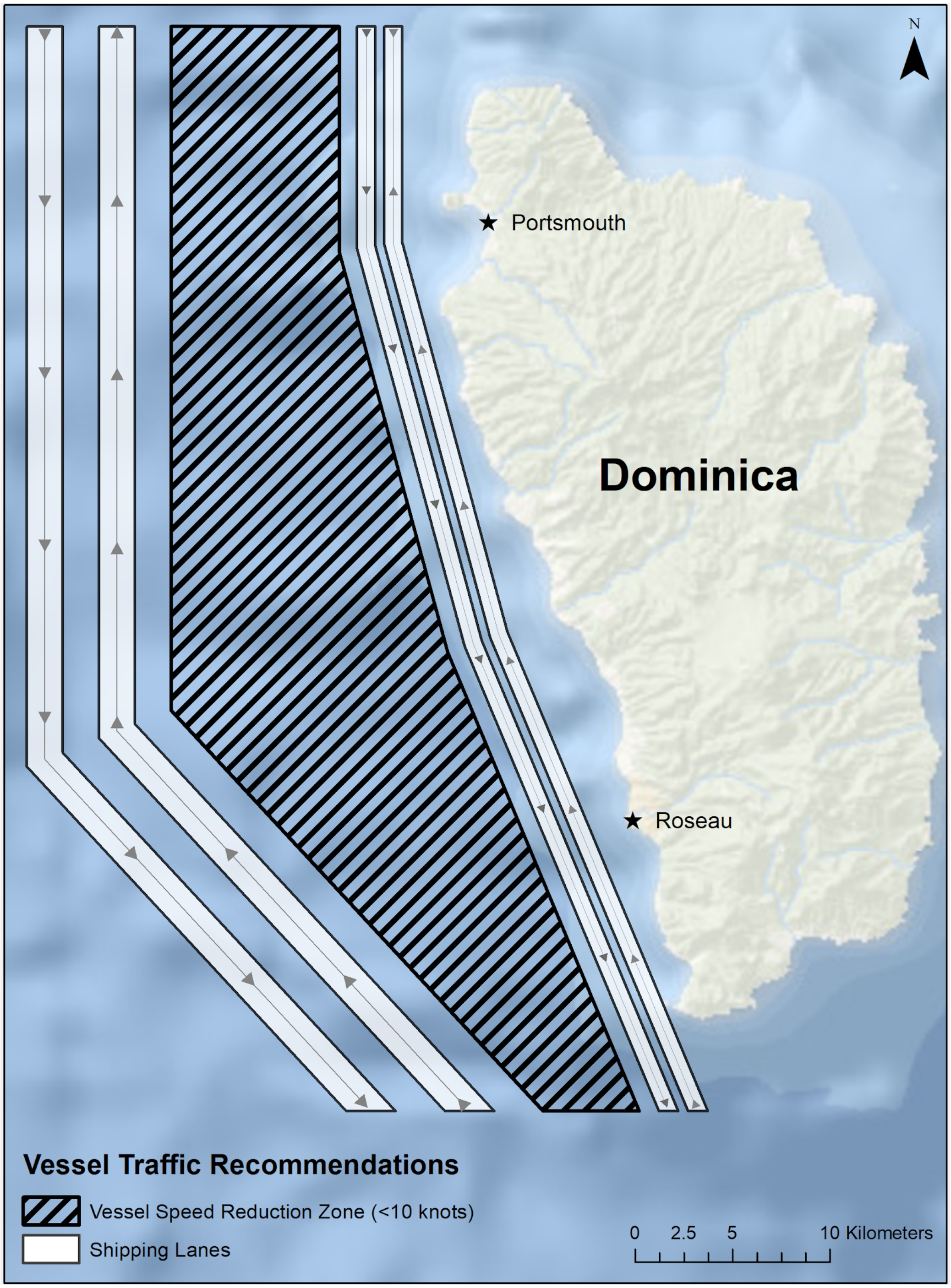

Figure 6. Vessel Traffic Recommendations. Marine spatial plan for suggested vessel traffic management off the west coast of Dominica. Offshore and inshore shipping lanes (white) avoid high sperm whale habitat suitability and are split into southbound and northbound lanes (arrows). The vessel speed reduction zone (black lines) encompasses high sperm whale habitat suitability.

Vessel Time Cost in the Vessel Speed Reduction Zone

We quantified the time cost for vessels traveling greater than 10 knots within the proposed vessel speed reduction zone for each year AIS data were available (2012-2019; excluding 2016). The results are shown in Table 2 and Figure 7. Overall, merchant vessels have the largest time cost, followed by cruise ships, and high speed ferries have the smallest time cost.

Table 2. Annual Time Cost for Vessels Traveling > 10 knots in Vessel Speed Reduction Zone.

Year	Vessel Category	Time Cost (hours)
2012	Merchant	59
2012	Cruise Ship	20
2012	High Speed Ferry	1
2012	**All**	**80**
2013	Merchant	930
2013	Cruise Ship	145
2013	High Speed Ferry	13
2013	**All**	**1088**
2014	Merchant	985
2014	Cruise Ship	209
2014	High Speed Ferry	12
2014	**All**	**1206**
2015	Merchant	863
2015	Cruise Ship	150
2015	High Speed Ferry	10
2015	**All**	**1023**
2017	Merchant	750
2017	Cruise Ship	54
2017	High Speed Ferry	17
2017	**All**	**821**
2018	Merchant	1250
2018	Cruise Ship	231
2018	High Speed Ferry	19
2018	**All**	**1500**
2019	Merchant	584
2019	Cruise Ship	184
2019	High Speed Ferry	11
2019	**All**	**779**

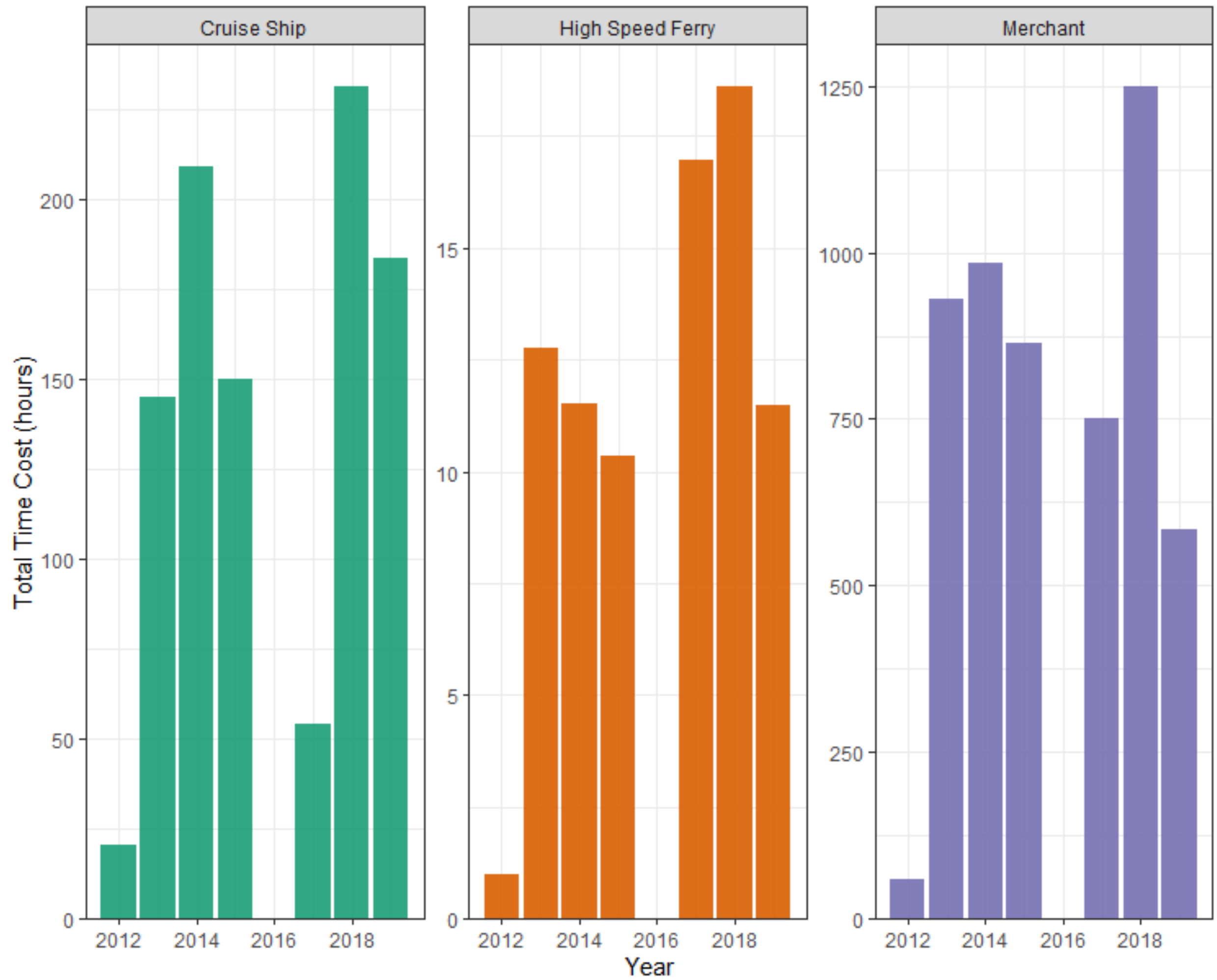

Figure 7. Vessel Time Cost in Vessel Speed Reduction Zone. Graphs show total time cost each year for vessels traveling through the 10 knot vessel speed reduction zone. The y-axis is scaled to each vessel type. Merchant vessels experience the largest time cost in a vessel speed reduction zone, cruise ships experience slightly less, and high speed ferries experience the least time cost. No vessel AIS data were available for 2016 due to Hurricane Maria.

Shiny App Visualizing Whale Presence and Vessel Traffic

Figures 8-11 below showcase the Shiny app, which visualizes sperm whale presence and vessel traffic off the west coast of Dominica.

Figure 8. Shiny App Tab 1: Summary. The summary tab helps users understand the contents, limitations, and sources of the whale presence and vessel data.

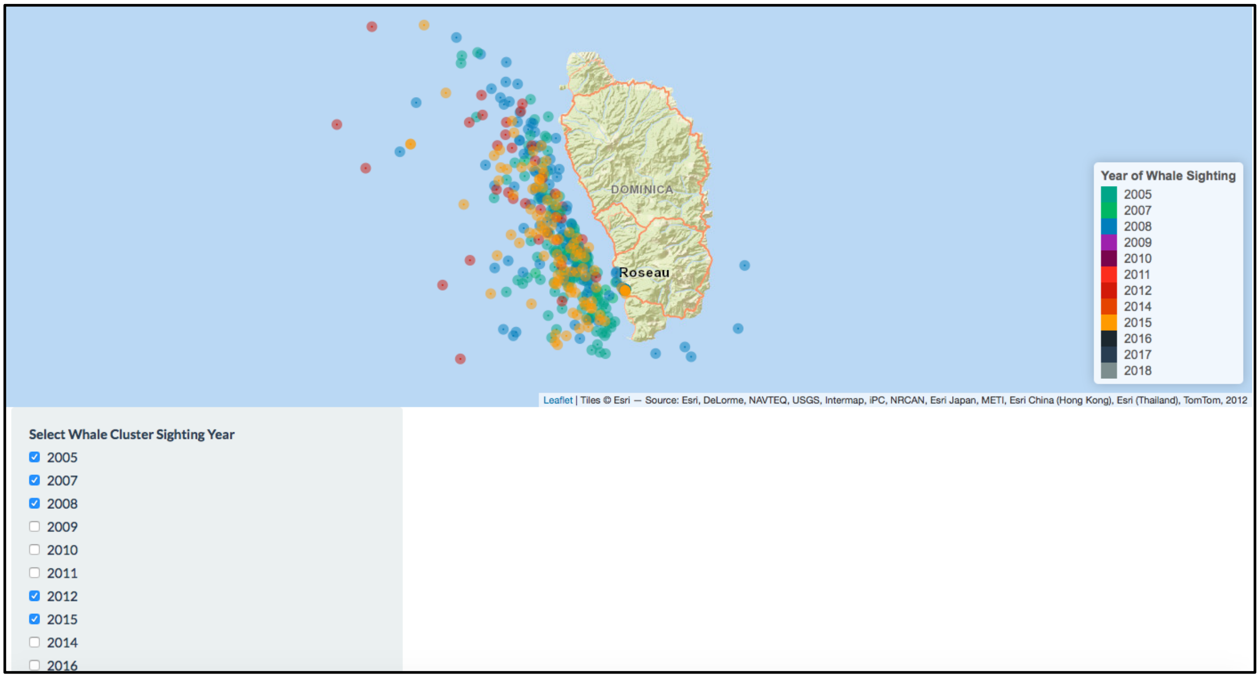

Figure 9. Shiny App Tab 2: Meet the Whales. This tab has a check box option for users to select years of interest, with whale cluster sightings displayed in a different color for each year 2005-2018 (excluding 2006 and 2013).

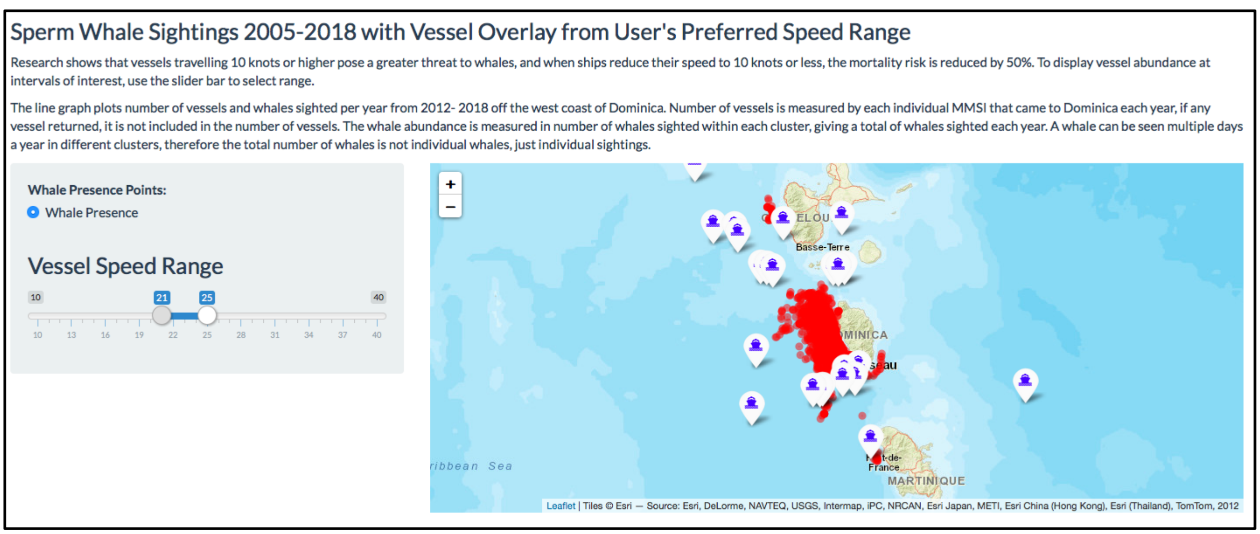

Figure 10. Shiny App Tab 3: Whale and Vessel Abundance and Interactions. This tab allows users to select a speed range of vessels (travelling over 10 knots) and display their location on a static map of whale sightings from 2005-2018 (excluding 2006 and 2013). This visualizes where vessels overlap with sperm whales.

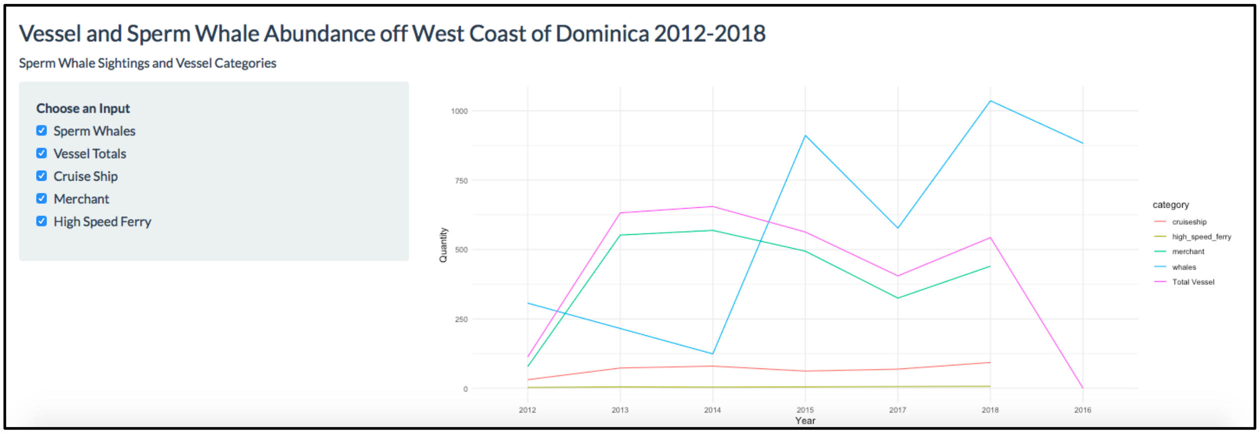

Figure 11. Shiny App Tab 3: Interactive Line Graph of Vessel and Sperm Whale Abundance. Tab 3 also includes an interactive line graph that displays total values of sperm whales sighted within clusters each year, individual vessels that visited Dominica each year, as well as total values for each vessel category of interest: cruise ships, high speed ferries, and merchant vessels. (Note that vessel totals only include unique vessels that visited the west coast of Dominica each year; if the vessel returned within that same calendar year, it is not counted in the totals).

Discussion

Economic Valuation

Limitations and Assumptions

Other Approaches Considered

An alternative analysis could have used a preexisting input-output model that showed all the linkages throughout the different sectors of Dominica's economy. This would have allowed an analysis to account for "knock on" effects of whale tourists indirectly contributing to the economy through expenses such as meals and hotels that are paid in addition to the fees for their whale tourism experience. However, an input-output model does not exist for Dominica. In addition, since a lot of tourism comes from cruise ships, there actually may not be a substantial "knock on" effect for cruise ships, as these tourists eat and sleep on the cruise ship. In contrast, the "knock on" effects for swim-with-whale operators are likely to be high as these tourists rely heavily on services provided on the island such as hotels, restaurants, and land-based tourist activities, so the economic impact from these indirect costs is most likely underestimated. Lastly, the small sampling size from whale watching operators most likely underestimates the economic impact of this group as well.

Intrinsic Value

The community of eastern Caribbean sperm whales off the west coast of Dominica are valued as an iconic species and part of Dominica's cultural identity. Sperm whales have existence value and locally-recognized aesthetic value in the form of tourist attractions for Dominica (Ocean Health Index, 2020). This community of sperm whales has also been the subject of highly publicized media and press coverage, such as BBC, National Geographic, TEDx, and The New York Times (DSWP, 2020). These sperm whales have intrinsic value as well as monetary value from the whale tourism industry.

In order to account for the intrinsic value of this sperm whale community, a "willingness to pay" analysis could be completed in the future. While a willingness to pay survey was beyond the scope of this project, it is important to recognize that the resident community of sperm whales have an existence value for the residents of Dominica and their identity as the "Whale Watching Capital" and the "Nature Island" of the Caribbean.

Survey

The survey imposes several limitations on the economic valuation. There were a total of nine responses from different whale tourism businesses, out of 62 survey recipients. Respondents who did answer the survey did not answer all the questions asked. There were no responses from cruise lines, and the two responses from tour booking agencies were not complete enough to use. All the information gathered for cruise lines was found online and then extrapolated from whale watching survey answers. The survey also had to be sent out later than originally intended: the survey was completed in June 2019, but was not sent out until October 2019 for technical reasons.

As a backup plan for the survey, cold calls were administered to cruise lines and international swim-with-whale tour operators. Cruise lines especially did not wish to disclose any information to us. Alternatively, some of the cruise lines we contacted have limited trips to Dominica and/or did not know their tour itinerary and costs so far in advance.

Economic Model

We extrapolated cruise line data with the assumption that all whale watching operators cater to cruise lines. The proportion of whale watching tours related to cruise ships was taken from the average of the two whale watching operator survey respondents who stated they have clients from cruise lines. We also assumed that tour operators all have the same weight within the calculations, meaning that no matter the size of the operator, the survey results get treated equally when calculating their contribution. There is one large whale watching operator who caters to a larger proportion of tourists, but without complete survey data, assigning appropriate weights for each operator was not feasible. Due to the survey being anonymous, there is also a chance of duplication between the survey responses and the supplemental public online data. For this reason, separate, less complete analyses have been done to show any discrepancy between survey and online results (see Appendix A3, Table A1, and Table A2). These findings can be updated in the supplemental spreadsheet if more complete data is acquired in the future (see Appendix A2).

Benefit to Dominica

Calculations for the economic benefits to Dominica received from swim-with-whale operators assumed that a typical trip consists of 5 days, and that operators would need to pay for a daily local charter boat during the entirety of the trip (see Appendix A2). The 30 total trips per year used for the survey estimate only came from the 2 swim-with-whale operator survey respondents who provided that information, which significantly limits our data. In addition, it is important to note that this floor estimate of economic benefit to Dominica does not take into account the various indirect costs (e.g., hotels, food and beverage purchases, etc.) that we were unable to acquire information for. Therefore this estimate is most likely a floor value, and has the potential to be much higher with a more complete set of data.

Economic Model Spreadsheet: Total Annual Net Profit

As survey responses were minimal and incomplete, we did not have a robust sample to use in our annual net profit model. Should DSWP and/or the Dominican government conduct future surveys to gather more complete information from whale watching tour operators, swim-with-whale tour operators, and cruise lines, those values can be added into the economic model spreadsheet. The spreadsheet currently includes example data taken from our survey results and online research, however, once values for operators are updated, the sheet will automatically calculate new estimates for annual net profit. With a greater amount of data from businesses related to their economic activity in the sperm whale tourism sector, annual net profit estimates could be substantially larger and more accurate.

Relevance

Determining the economic contribution of the resident community of eastern Caribbean sperm whales can provide an incentive for their protection. The economic valuation will shed light on the monetary value sperm whales contribute to Dominica's economy. Dominica's GDP was approximately $500 million USD in 2017 (Worldometer, 2018). Table 1's total annual net profit extrapolated result of approximately $3 million USD generated from whale tourism in Dominica from combined survey and online research accounts for almost 1% of the total GDP. More complete economic data could provide greater accuracy as to the exact monetary value of whale tourism in Dominica. A more accurate percentage of whale tourism's contribution to Dominica's GDP could also be calculated if all direct and indirect costs to whale tourism operators and their customers become available, suggesting that the true economic impact is much larger than our estimates. Our economic model spreadsheet will allow DSWP and/or the Dominican government to complete this analysis (see Appendix A2).

Marine Spatial Plan

Limitations and Assumptions

Whale Presence Data

Whale sightings data were collected on an almost daily basis (weather permitting) from 2005-2018, generally between January and June for around six weeks (see Appendix B2, Table B2). However, whale sightings data from July to December each year were not available. While the sightings data are seasonally biased, the same sperm whales use the waters off the west coast of Dominica year-round. Additionally, there is generally less vessel traffic from whale watching boats and cruise ships during the summer months due to the hurricane season discouraging tourists from visiting Dominica.

Species Distribution Model

A key assumption in using MaxEnt is that species individuals have been sampled randomly across the landscape and are proportional to the actual population density. However, as the whale sightings data were collected in a bounded space, this contributes to bias in the MaxEnt results (Merow, Smith, & Silander, 2013).

The MaxEnt technique using presence-only data has been extensively used with terrestrial species, but is not often used for marine species. The primary concern when using MaxEnt is the spatial biases that can occur due to data being collected opportunistically rather than systematically. MaxEnt models with pseudo-absences have shown altered spatial patterns of predictions compared to MaxEnt models with observed absence and presence. The opportunistic sampling bias extends through the study area with the projection of the model in geographic space. When using MaxEnt with presence-only data, spatial bias must be addressed, as it will return biased predictions (Fiedler et al., 2018). We recognize the results from our SDM using MaxEnt may have spatial bias due to the reasons outlined above.

Vessel Traffic Recommendations

As mentioned above, the IMO frequently implements routing measures, whereas vessel speed restrictions are rarely implemented and generally have low compliance (Frantzis et al., 2019). Our proposed marine spatial plan implements both routing measures and a vessel speed reduction zone, capturing the benefits of separating vessels from whales where possible, and slowing vessels down where separation is not an option. If the vessel speed reduction zone with a speed limit of 10 knots is implemented, it could reduce the risk of lethal ship strikes by approximately 50%, while remaining safe for large vessels such as cargo ships to maneuver accurately (Vanderlaan & Taggart, 2007).

Fish Aggregating Devices

This project originally aimed to take into account FADs when developing proposed vessel traffic recommendations, however, comprehensive data on FAD placement was not available. Therefore, our marine spatial plan does not take into account FAD locations. These devices are inherent to the livelihood of the Dominican people as a means of income and food security and are known to occupy the same areas where sperm whales and vessels are present. To the extent feasible, shipping lanes should avoid FAD locations to decrease conflicts with vessels cutting up FADs with their propellers. When FADs are destroyed, they also become an entanglement danger to sperm whales. Therefore, future work addressing the spatial and temporal implications of FADs is recommended, both for the benefit of Dominica fisheries and the sperm whales.

Relevance

These results have important implications for the conservation of the unique and vulnerable community of eastern Caribbean sperm whales off the west coast of Dominica. The SDM created in MaxEnt shows there is high habitat suitability for sperm whales off the west coast of Dominica. Vessel traffic analyses show there is vessel activity within this high habitat suitability area year-round. Therefore, these results indicate the need to mitigate vessel traffic threats to sperm whales off the west coast of Dominica. Reducing speeds for vessels traveling greater than 10 knots within the proposed vessel speed reduction zone will add travel time for these vessels, which will have to be addressed by vessel operators and port authorities.

The marine spatial plan results can also be used to visualize vessel routing options into the northern port of Portsmouth and the southern port of Roseau. Areas of high whale presence outside of ideal vessel routing lanes could be designated as additional vessel speed reduction zones to minimize risk of whale strikes. This report provides a marine spatial plan for vessel traffic given sperm whale distribution in the coastal waters of Dominica. This report can also serve as a reproducible analysis of vessel and whale interactions elsewhere in the world.

Conclusions

Based on our results, the following actions are recommended:

1. DSWP and the Dominican government should continue to update the economic valuation spreadsheet with more complete data to improve the estimation accuracy of sperm whale tourism's monetary value in Dominica.
2. The Dominican government should implement IMO shipping lanes off the west coast of Dominica to regulate vessel traffic in and out of the ports of Portsmouth and Roseau and avoid high suitability sperm whale habitat to the extent feasible.
3. The Dominican government should implement a vessel speed reduction zone with a 10 knot speed limit that encompasses the area of highest sperm whale habitat suitability to reduce ship strike threats.
4. DSWP should continue to monitor the sperm whale community and update these reproducible analyses with new whale sightings and AIS data to track any shifts in threat hotspots. This will allow DSWP and the Dominican government to collaborate on updating vessel traffic schemes if necessary.
5. DSWP and the Dominican government should complete additional analyses that include the neighboring islands of Guadeloupe and Martinique, in order to create a region-wide vessel traffic network that avoids high sperm whale habitat suitability areas and mitigates ship strike risk within the larger Lesser Antilles region.
6. Vessel management decisions should incorporate the time and costs associated with vessels subject to the vessel speed reduction zone, so that vessels traveling through this zone can account for these costs.
7. DSWP and the Dominican government should obtain accurate data on FADs to account for their location in planning shipping lane locations. FAD fisheries and the sperm whales will benefit by ensuring that shipping lanes do not overlap with FAD locations.

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Appendix

Appendix A: Economic Valuation

Appendix A1: Tour Operator Survey Design and Responses

The Tour Operator Survey was designed in June 2019 and submitted to the Office of Research Application for the Use of Human Subjects at the University of California, Santa Barbara. The survey was approved in July 2019. The survey includes: Part A: Cruise ship tour coordinator; Part B: Tour booking agency/hotel; Part C1: Whale watching tour operator; and Part C2: Swim-with-whale tour operator.

Survey Design and Questions

See digital collection associated with this report.

Survey Responses Spreadsheet

See digital collection associated with this report.

Appendix A2: Economic Model Spreadsheet

The economic model spreadsheet is provided as a quantitative tool to calculate the monetary contribution of whale tourism in Dominica. The spreadsheet contains equations to input survey responses and online data to calculate net profit generated from each whale watching tour operator and swim-with-whale tour operator in Dominica. The spreadsheet can be updated with new data if the analysis is expanded in the future.

Economic Model Spreadsheet

See digital collection associated with this report.

Appendix A3: Annual Net Profit Values: Survey and Online Research Results

Table A1 displays annual net profit values calculated using only survey results. Table A2 displays annual net profit values calculated using only online research results. The N/A values in Tables A1 and A2 stem from the incomplete data from both survey and online research results.

Table A1. Total Annual Net Profit Generated From Whale Tourism With Data Collected From Survey Responses. All values are in USD.

	Available Data	Extrapolated
Whale Watching Low	$-218,204	$-272,755
Whale Watching Mean	$804,223	$1,005,279
Whale Watching High	$2,361,400	$2,951,750
Swim-With-Whale Low	N/A	N/A
Swim-With-Whale Mean	N/A	N/A
Swim-With-Whale High	N/A	N/A
Cruise Line Surplus Low	N/A	$90,928
Cruise Line Surplus Mean	N/A	$395,321
Cruise Line Surplus High	N/A	$699,715
Average Whale Tourism Net Profit	**N/A**	**N/A**

Table A2. Total Annual Net Profit Generated From Whale Tourism With Data Collected From Online Research. All values are in USD.

	Available Data	Extrapolated
Whale Watching Low	$39	$256
Whale Watching Mean	N/A	N/A
Whale Watching High	$14,173	$17,716
Swim-With-Whale Low	$-63,000	$-63,000
Swim-With-Whale Mean	$146,840	$146,840
Swim-With-Whale High	$356,680	$356,680
Cruise Line Surplus Low	N/A	N/A
Cruise Line Surplus Mean	N/A	N/A
Cruise Line Surplus High	N/A	N/A
Average Whale Tourism Net Profit	**N/A**	**N/A**

Appendix A4: Economic Benefit to Dominica

The results from survey answers and online information are completely separated here. The number of trips per year from survey answers is 27, and the number of trips per year from online information is 30.

Based on Equation 4 described in the methods section, the combined swim-with-whale and whale watching economic benefits to Dominica include:

- Survey Calculated Benefits: $1,021,473 USD
- Online Calculated Benefits: $211,998 USD

Appendix B: Data Description and Metadata

Appendix B1: Environmental Factors Data

Table B1. Environmental Factors Metadata.

Source	Data type	Data Format	Resolution	Coordinate System	Extent
GEBCO	Bathymetry	2DnetCDF (.nc)	15 arc seconds	WGS 84	Latitude: between 14.95771° and 15.9024° Longitude: between -61.1464° and -62.4688°
Bio-ORACLE	Chlorophyll, Phytoplankton, Primary Productivity, Salinity, Temperature	GEOTiff (.tif)	5 arc minutes	WGS 84	Worldwide excluding polar region latitudes between 70° North/South.

Global environmental marine data layers for ecological modeling were directly downloaded from Bio-ORACLE in Geostationary Earth Orbit Tagged Image File Format (GeoTIFF) raster file format (Tyberghein et al., 2012; Assis et al., 2018). Both surface and benthic depth layers were downloaded for the maximum and mean values of temperature, salinity, chlorophyll, phytoplankton, and primary productivity. Since the environmental data were downloaded on a global scale, the resolution was low at 5 arc minutes, causing the map output to display coarse pixels.

The marine data layers for present conditions were produced from monthly climate data of global oceans averages from 2000-2014. The polar regions contained imprecise data, so to exclude them, the rasters were cropped to latitudes between 70° North/South with a spatial resolution of 5 arc minutes (Tyberghein et al., 2012). These environmental marine layers were created from the combination of satellite data and local (in situ) observational data at both two and three dimensional spatial grids in order to capture both surface and benthic layers. Benthic layers were created by a downscaling process using the depth of cells and geographic position from the General Bathymetric Chart of the Oceans (GEBCO; Assis et al., 2018).

Gridded bathymetry data were downloaded from GEBCO for the 2019 grid data. The bathymetry data were downloaded in a 2D Network Common Data Form (netCDF) format, in World Geodetic System 1984 (WGS 84) coordinates, for latitudes between 14.95771° and 15.9024° and longitudes between -62.4688° and -61.1464°, with a spatial resolution of 15 arc seconds (GEBCO, 2019).

The GEBCO_2019 bathymetry grid is a continuous, global terrain model for ocean and land that is created from a fusion of land topography with estimated and measured seafloor topography (GEBCO, 2019).

Appendix B2: Whale Presence Data

Table B2. Whale Presence Metadata.

Source	Data type	Data Collection Intervals	Data Collection Years	Data format	Resolution	Coordinate System	Extent
Dominica Sperm Whale Project (DSWP)	Boat-based (transect) sightings	~ Daily Jan 15 - Mar 26, 2005 Jan 30 - Feb 24, 2007 Feb 8 - May 8, 2008 Jan 13 - Mar 28, 2009 Jan 20 - Apr 17, 2010 Mar 7 - Apr 10, 2011 May 7 - Jun 4, 2012 Apr 2 - May 12, 2014 Feb 8 - Apr 11, 2015 Apr 1 - May 19, 2016 Apr 5 - May 26, 2017 Mar 15 - May 25, 2018	2005 - 2019 (excluding 2006, 2013)	Microsoft Excel file (.xlsx)	Point Data	WGS 84	West coast of Dominica

Whale presence data were collected by the Dominica Sperm Whale Project (DSWP) through taking photos of individual whales or clusters of whales during boat-based surveys on either a Zodiac boat or sailboat. The search pattern of the research vessels is based on the "reach" of their hydrophones so that the researchers can find sperm whales as efficiently as possible. This is not a standardized, random, line-transect survey. This "search box" is visible in the vessel track data. The researchers leave from their dock south of Roseau and head roughly southwest towards a waypoint off the southern tip of the island; how far they actually get depends on weather (if in a smaller boat). Then they head north along a roughly straight line from which they can hear all the way inshore with their equipment. If the researchers have not heard anything by the time they reach the north end of the island, and the weather/boat permits, they move offshore about 150% of the distance they can hear so that they do a second "ribbon" back southward. The researchers do slow down for other species when they encounter them, but the goal is to be with sperm whales as fast as possible. In years when the researchers have the sailboat, they either continue driving the search box through the night, or pull close into port to sleep overnight.

The geographic coordinates of each whale sighting are calculated by matching up the time of the sighting photo with the Global Positioning System (GPS) location of the research vessel at that time. The researchers use either a self-contained handheld GPS on the Zodiac, or a boat-based GPS with an antenna on the sailboat.

Whale sightings data were collected on an almost daily basis (weather permitting) from 2005-2018, generally between January and May for approximately six weeks. From 2005-2018 there is a slow progression in field season dates more toward the spring than winter. There are no data for 2006 and 2013. The "Encounter" column in the whale presence data represents an encounter with one or more sperm whales; these encounters are numbered sequentially for each field season. Encounters start when the researchers first hear whales on the hydrophone, and end when they decide to leave them to go back to shore or have to leave due to weather. The "Cluster" column refers to a set of sperm whales together at the surface. A cluster is defined as sperm whales who are coordinating behavior and are within three body lengths of each other at the surface. Cluster numbers are unique; YYYYEE### refers to year/encounter number/cluster number. The "Males", "Adults", and "Calves" columns represent the number of these sperm whale individuals that are observed within a cluster.

All GPS devices on the research vessels use the WGS 84 geographic coordinate system. In most years the data is collected with decimal degrees, but in some sailboat years it was collected in decimal minutes and then converted.

Appendix B3: AIS Data

Table B3. AIS Metadata.

Source	Data type	Data Collection Intervals	Data Collection Years	Data format	Resolution	Coordinate System	Extent
AIS Station 1249	AIS	~ Daily Dec 1 - Dec 23, 2012 Jan 6 - Dec 31, 2013 Jan 1 - Dec 31, 2014 Jan 1 - Oct 23, 2015	2012 - 2015	Comma Separated Values file (.csv)	Point Data	WGS 84	West coast of Dominica
MarineTraffic	AIS	~ Daily Jan 6 - Dec 31, 2017 Jan 1 - Dec 31, 2018 Jan 1 - May 31, 2019	2017 - 2019	Comma Separated Values file (.csv)	Point Data	WGS84	Latitude: between 15.0° and 15.75° Longitude: between -62.0° and -61.25°

Automatic identification system (AIS) point data were collected from AIS Station 1249 on Dominica from 2012-2015 by DSWP. No AIS data were recorded for 2016 due to Hurricane Maria. Data from 2017-2019 were collected from AIS Stations 1061, 1214, and 1249 on Dominica, 1633 and 3597 on Martinique, 959 on Antigua, 1078 on St. Lucia, 3256 on Aruba, and 3627 on Guadalupe. AIS stations only collect vessel locations for vessels present in their range. The data has a temporal resolution of 10 minutes and is in point data format recorded in the WGS 84 reference coordinate system.

International vessels that are 300 tons or greater, cargo ships 5000 tons or greater, and all passenger vessels must broadcast basic information including vessel position, speed, and navigational status at regular intervals via AIS. The AIS data from 2012-2015 were provided by DSWP for the waters off the west coast of Dominica. The AIS data from 2017-2019 were requested from MarineTraffic by DSWP for an area off the west coast of Dominica encompassing latitude between 15.0° and 15.75° and longitude between -62.0° and -61.25°. Only data for vessels that met the following criteria were provided:

1. Greater than 30m in length
2. Did not have a 1 or 5 status (moored or anchored)

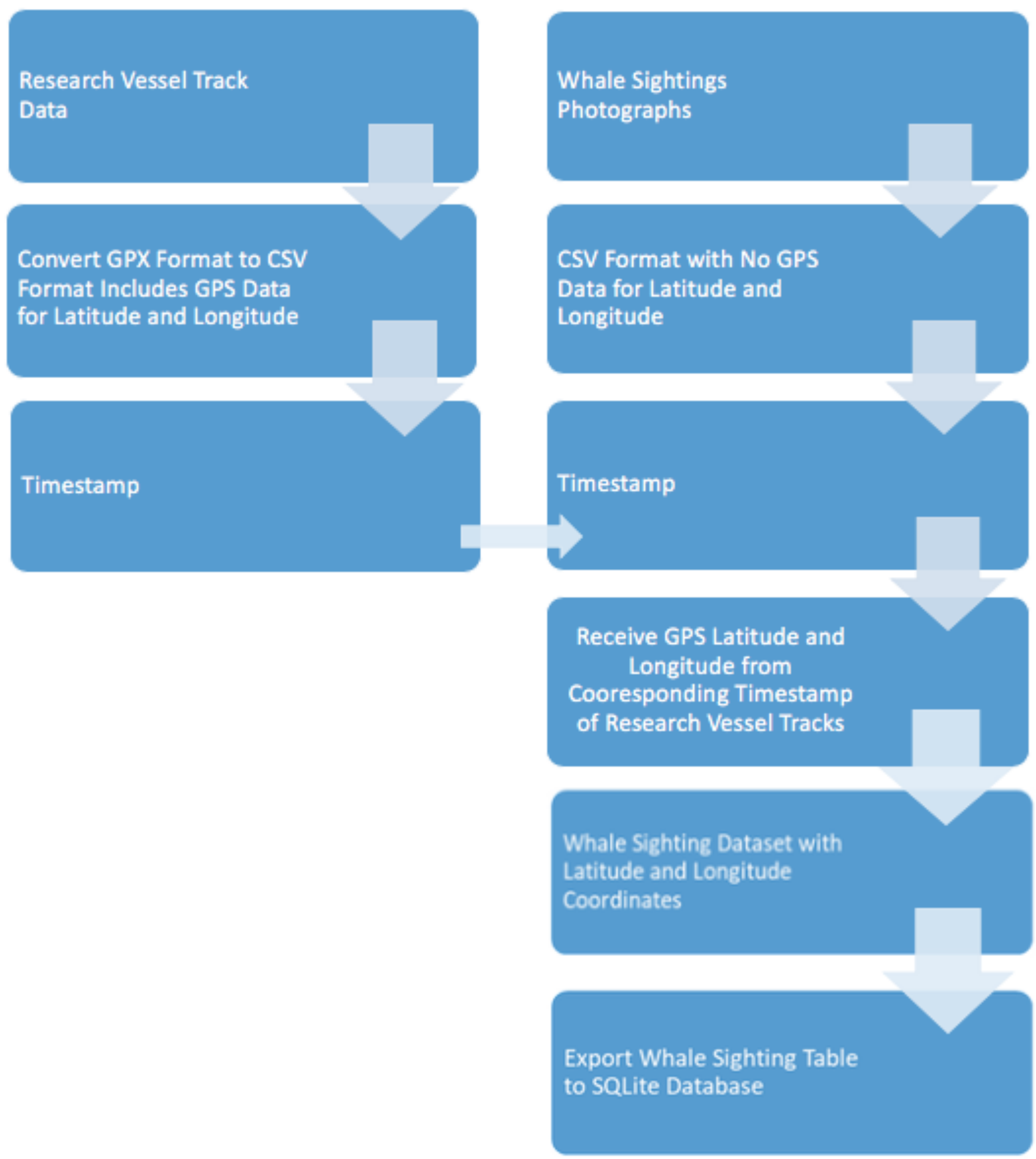
All AIS data includes the following parameters: Maritime Mobile Service Identity (MMSI) number, status, speed, longitude, latitude, course, heading, timestamp, vessel name, vessel type, length, width, and International Maritime Organization (IMO) number with a maximum resolution of 10 minutes. Longitudes and latitudes are in the WGS 84 geographic coordinate system.

Appendix C: Preparing Data in R

The following code was used to prepare whale presence data (Appendix C1) and AIS data (Appendix C2) for use in the geographic information system (GIS) software, ArcGIS and QGIS.

Appendix C1: Whale Presence Data

The chart below is a visual documentation of the workflow used to prepare whale presence data.



Some of the research vessel tracks data were given in GPS Exchange Format (GPX). These file types were converted to comma-separated value (CSV) files using a Bourne Again SHell (Bash) script and standard UNIX text processing utilities (see Listing 1).

```
# convert GPX to CSV
#

export HTML_TIDY=                    # disable local "tidy" customizations

cat "$@" |                           # gather input files
    tidy -xml 2>/dev/null |          # convert to one-line-per-XML-tag
    gawk '
        BEGIN {
            print "lat,lon,time"     # CSV header
        }

        /<trkpt/ {                   # <trkpt lat="..." lon="...">
            lat = $0
            sub(/^.*lat="/, "", lat)
            sub(/".*$/,     "", lat)

            lon = $0
            sub(/^.*lon="/, "", lon)
            sub(/".*$/,     "", lon)

            next
        }

        /<time>/ {                   # <time>...</time>
            time = $0
            sub(/.*<time>/,    "", time)
            sub(/<\/time>.*/, "", time)

            next
        }

        /<\/trkpt>/ {
            printf("%s,%s,%s\n", lat, lon, time)

            lat = lon = time = ""

            next
        }
    '
```

Listing C1. Shell Script to Convert GPX Files to CSV Format.

Once all the research vessel track GPX files were converted to CSV files, they were imported into R along with the whale cluster CSV files. One CSV was supplied for all whale clusters from 2005-2015 (excluding 2006 and 2013), and whale cluster data from 2016-2018 were supplied separately for each year. All the research vessel tracks and whale cluster data were imported into R. Timestamp columns were coded to match the research vessel tracks data to the corresponding whale cluster data and converted to Coordinated Universal Time (UTC) format in the Dominican timezone. The timestamps for the research vessel tracks and whale cluster data were then matched up in a function, so that the latitude and longitude from the research vessel track data were added to the whale cluster data, giving a location for each whale cluster sighting. Once all the whale cluster sightings were matched up with locations from their corresponding research vessel tracks, the data were directly exported into a table in the SQLite database (see Listing C2).

Vessel Tracks + Whale Clusters

WorthWhale Team

11/16/2019

Goal: Match up the photo timestamps from whale sightings data with research vessel GPS coordinates in order to assign coordinates to the whale sightings.

Combine whale sightings data with vessel track location data from 2005-2018:

```
# Create clusters tibble
clusters <- tibble(cluster = integer(),
              datetime = character(),
              lat = numeric(),
              lon = numeric()
              )

# Read in whale clusters data
cluster_files <- dir_ls(path = "Whale_Clusters", glob = "*.csv")

# Loop to wrangle clusters data
for (cluster_file in cluster_files) {
  chunk <- read_csv(cluster_file)
  names(chunk) <- tolower(names(chunk))
  chunk$datetime <- paste(chunk$date, "", chunk$truetime)
  chunk$datetime <- format(parse_date_time(chunk$datetime, "%d/%m/%Y %H:%M:%S", tz = "America/Do
minica"))
  chunk <- rename(chunk, lon = long)
  chunk <- subset(chunk, select = c(cluster, datetime, lat, lon))
  clusters <- bind_rows(clusters, chunk)
}

clusters$datetime <- parse_date_time(clusters$datetime, "%Y-%m-%d %H:%M:%S")
```

```r
# Create vessel tracks tibble
vessel_tracks <- tibble(time = character(),
              lat = numeric(),
              lon = numeric()
)

# Read in vessel tracks data
vessel_tracks_files <- dir_ls(path = "Vessel_Tracks", glob = "*.csv")

# Loop to wrangle vessel tracks data
for (vessel_tracks_file in vessel_tracks_files) {
  chunk <- read_csv(vessel_tracks_file)
  names(chunk) <- tolower(names(chunk))
  chunk <- rename_all(chunk, recode, long = "lon")
  chunk$time <- format(parse_date_time(chunk$time, c("%d/%m/%Y %H:%M:%S", "%Y-%m-%d %H:%M:%S",
"%b/%d/%Y %H:%M:%S"), tz = "America/Dominica"))
  vessel_tracks <- bind_rows(vessel_tracks, chunk)
}

vessel_tracks <- rename(vessel_tracks, datetime = time)
vessel_tracks$datetime <- parse_date_time(vessel_tracks$datetime, "%Y-%m-%d %H:%M:%S")
```

```r
# Matching times
closest <- sapply(seq(nrow(clusters)), function(i) {which.min(abs(clusters$datetime[i] - vessel_
tracks$datetime))})
clusters$lat <- vessel_tracks$lat[closest]
clusters$lon <- vessel_tracks$lon[closest]
```

Insert as “sightings” table to worthwhale SQLite database:

```r
# Inserting to SQLite database
clusters$datetime <- format(clusters$datetime)
sqlite_db_filename <- "worthwhale.sqlite"
sqlite_db <- dbConnect(RSQLite::SQLite(), sqlite_db_filename)
dbWriteTable(sqlite_db, name = "sightings", value = clusters, overwrite = TRUE, field.types=c(cl
uster="int"))
```

Listing C2. R Code to Assign GPS Coordinates to Whale Sightings.

Appendix C2: AIS Data

We used an R script to combine the 2012-2015 AIS data with the selected columns: MMSI, Status, Speed, Longitude, Latitude, Course, Heading, and Timestamp. After the years were combined with these columns, they were joined with the AIS data from 2017-2019 (see Listing C3). We obtained descriptive information for 2012-2015 from an external database of MarineTraffic satellite data (see Figure C1). We merged the data by MMSI number, adding new columns: IMO, Vessel Name, Vessel Type, Gross Tonnage, Built, Length, Width, and Country (see Figure C1). We exported finalized AIS point data from 2012-2019 into

SQLite using R: a script created AIS database files (.db) compatible with SQLite. We then used DB Browser for SQLite, an open source tool, to access, edit, and query the SQLite database (see Listing C3).

```
title: "AIS Database"
author: "WorthWhale Team"
date: "11/5/2019"
output: html_document
---

**Goal: Create a cohesive dataframe of AIS data from years 2012-2015 and bind it with AIS data from 2017-2019.**

# Removes everything in environment for faster workflow
rm(list = ls())

# Load packages
library(tidyverse)
library(dplyr)
library(purrr)
library(tibble)
library(janitor)
library(DBI)
library(RSQLite)
library(RPostgreSQL)
library(data.table)
library(lubridate)
library(fs
```

```
# Reading station data
station_files <- dir_ls(path = "RawData", glob = "RawData/station*.csv")

# Creating an empty tibble to hold the position data
positions <- tibble(mmsi = integer(),
          status = integer(),
          speed = numeric(),
          lat = numeric(),
          lon = numeric(),
          course = numeric(),
          heading = numeric(),
          timestamp = character())

# Iterating over the files and appending the data to the tibble
for (station_file in station_files) {
 chunk <- read_csv(station_file)
 names(chunk) <- tolower(names(chunk))
 chunk <- subset(chunk, select = c(mmsi, status, speed, lon, lat, course, heading, timestamp))
 chunk$timestamp <- format(chunk$timestamp)
 positions <- bind_rows(positions, chunk)
}

# Adding the 2017-2019 data. This file is in a different format
positions_2017_2019 <-read.csv("RawData/NEW_AIS2017_2019.csv")
names(positions_2017_2019) <- tolower(names(positions_2017_2019))
positions_2017_2019 <- clean_names(positions_2017_2019)
positions_2017_2019 <- rename(positions_2017_2019, speed = speed_knotsx10)
positions_2017_2019$timestamp <- format(parse_date_time(positions_2017_2019$timestamp, "%d/%m/%Y %H:%M:%S", truncated = 3))

positions <- bind_rows(positions, select(positions_2017_2019, c(mmsi, status, speed, lon, lat, course, heading, timestamp)))

# Speed is given as 1/10 of knots. Correct for this
positions$speed <- positions$speed/10

# Getting vessel info from Niklas' database
con <- DBI::dbConnect(RPostgreSQL::PostgreSQL(),
          host = "WorthWhale",
          port = "WorthWhale",
          user = "WorthWhale",
          password = "WorthWhale",
          dbname = "WorthWhale" )
```

```
query_vessels <- "SELECT mmsi, imo, name, vessel_type, gt, built, length, width, country FROM vessels WHERE mmsi IS NOT NULL"
vessels_nick <- dbGetQuery(con, query_vessels)

# Getting vessel info from positions_2017_2019
vessels_2017_2019 <- select(positions_2017_2019, c(mmsi, vessel_name, vessel_type, flag, length_meters, width_meters))
vessels_2017_2019 <- distinct(vessels_2017_2019)
vessels_2017_2019 <- rename(vessels_2017_2019, length = length_meters, width = width_meters, name = vessel_name, country=flag)

# Merging Niklas' and the AIS vessel data
vessels <-bind_rows(vessels_nick, vessels_2017_2019)

# Getting Callie's categorization
vessel_types <- read.csv("categories.csv")

# Inserting to SQLite database
sqlite_db_filename <- "worthwhale.sqlite"
sqlite_db <- dbConnect(RSQLite::SQLite(), sqlite_db_filename)
dbWriteTable(sqlite_db, name = "vessel_types", value = vessel_types, overwrite = TRUE)
dbWriteTable(sqlite_db, name = "positions", value = positions, overwrite = TRUE)
dbWriteTable(sqlite_db, name = "vessels", value = vessels, overwrite = TRUE)
```

Listing C3. R Code to Combine AIS Data. This code creates a cohesive dataset of AIS data from 2012-2015 and binds it with AIS data from 2017-2019.

Original 2012-2015 AIS data

mmsi	Vessel name	Vessel Type
012	unknown	unknown
123	unknown	unknown
234	unknown	unknown
345	unknown	unknown
456	unknown	unknown

Satellite AIS Data from Marine Traffic

mmsi	Vessel name	Vessel Type
123	Condor Express	WW
012	Flying Dutchman	Pirate
345	Black Pearl	Pirate
234	S.S Triumph	Container
456	unknown	WW

Merged 2012-2015 AIS data with Marine Traffic Data

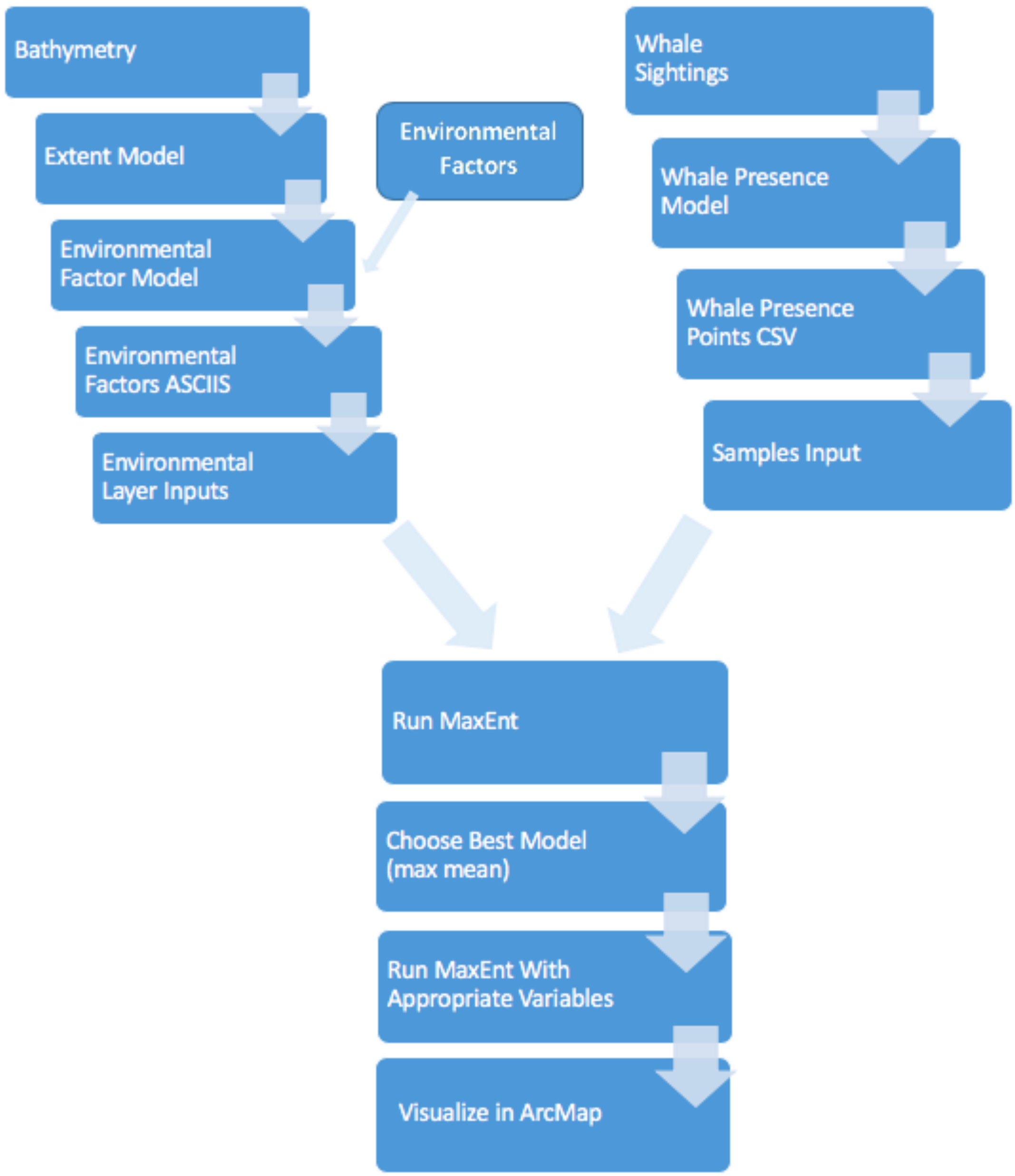
mmsi	Vessel name	Vessel Type
012	Flying Dutchman	Pirate
123	Condor Express	WW
234	S.S. Triumph	Container
345	Black Pearl	Pirate
456	**NA*	WW

**The name of vessel 456 could not be populated as that information was not available from Marine Traffic, therefore the merge returned a "NA" value for that column.*

Figure C1. Diagram of AIS Data Merging Method in R. Vessel names, types, and MMSI numbers are fictitious and should only be used for demonstration.

Appendix D: MaxEnt Analysis Methodology

The chart below depicts the workflow used to prepare data for maximum entropy modeling (MaxEnt).



Appendix D1: Preparing Data in ArcGIS ModelBuilder for MaxEnt Input

The following are the models and methods used in ArcGIS ModelBuilder to prepare the whale presence and environmental factors data for input to MaxEnt. ModelBuilder is a visual programming language for building geoprocessing workflows. In the ModelBuilder properties, the map projection was set to "Dominica_1945_British_West_Indies_Grid" and the analysis cell size was set to 0.5km^2.

Extent Model

ArcGIS ModelBuilder was used to create an extent mask raster to be applied to all other environmental data layers (see Figure D1). The extent was taken from the bathymetry layer: latitude between 14.95771° and 15.9024° and longitude between -62.4688° and -61.1464°. These data were originally in netCDF format, made accessible to ModelBuilder through the "Make NetCDF Raster Layer" tool. The data were then reprojected into the "Dominica_1945_British_West_Indies_Grid projection" and resampled to a 0.5km^2 resolution. The resulting Dominica mask layer was then used as the frame and mask for the environmental factor layers.

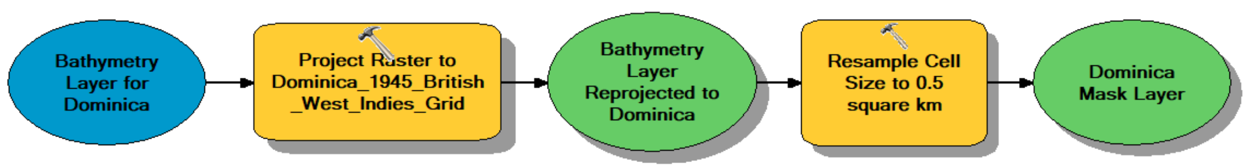


Figure D1. ArcGIS Extent Model to Create Study Area Layer for Dominica.

Environmental Factors Model

Each environmental factor layer was converted to an American Standard Code for Information Interchange (ASCII) text file:

- **Bathymetry:** Bathymetry data were downloaded from GEBCO as described in Appendix B1. The "Make NetCDF Raster Layer" tool was used to access the downloaded bathymetry. In ModelBuilder, the "Project Raster" tool was used to reproject the bathymetry raster into the local Dominica projection, followed with the "Resample" tool to change the resolution to 0.5km^2. The "Set Null" tool was used to assign all positive values as no data, so that only underwater bathymetry values were included in the raster. The new output raster was then assigned -9999 for the no data values, since MaxEnt requires all no data values to be the same. Finally, the null bathymetry raster was converted to ASCII format using the “Raster to ASCII” tool, as required for input to MaxEnt.

- **Temperature:** “Min” temperature data were downloaded from Bio-ORACLE in GeoTIFF format for a worldwide extent excluding polar region latitudes above 70° North/South. The minimum temperature values were chosen since female sperm whales are only found in sea surface temperatures greater than 15°C. In ModelBuilder, the “Extract by Mask” tool was used with the bathymetry raster as the mask. The output raster was then used as the input raster for the “Raster to ASCII” tool, converting the temperature raster into ASCII format for MaxEnt. No data values were also set to -9999 in general properties.
- **Salinity:** “Max” salinity data were downloaded from Bio-ORACLE in GeoTIFF format for a worldwide extent excluding polar region latitudes between 70° North/South. The maximum salinity values were chosen since we wanted to see if high salinity affects sperm whale distribution, perhaps in relation to buoyancy. In ModelBuilder, the “Extract by Mask” tool was used with the bathymetry raster as the mask. The output raster was then used as the input raster for the “Raster to ASCII” tool, converting the salinity raster into ASCII format for MaxEnt. No data values were also set to -9999 in general properties.
- **Chlorophyll:** “Max” chlorophyll data were downloaded from Bio-ORACLE in GeoTIFF format for a worldwide extent excluding polar region latitudes between 70° North/South. The maximum chlorophyll values were chosen since female sperm whales are usually found in areas of high primary productivity, and chlorophyll is a good indicator of primary productivity. In ModelBuilder, the “Extract by Mask” tool was used with the bathymetry raster as the mask. The output raster was then used as the input raster for the “Raster to ASCII” tool, converting the chlorophyll raster into ASCII format for MaxEnt. No data values were also set to -9999 in general properties.
- **Primary Productivity:** “Max” primary productivity data were downloaded from Bio-ORACLE in GeoTIFF format for a worldwide extent excluding polar region latitudes between 70° North/South. The maximum primary productivity values were chosen since female sperm whales are often found in areas of high primary productivity. In ModelBuilder, the “Extract by Mask” tool was used with the bathymetry raster as the mask. The output raster was then used as the input raster for the “Raster to ASCII” tool, converting the salinity raster into ASCII format for MaxEnt. No data values were also set to -9999 in general properties.

A second environmental factors model (not shown below) was created using the mean values for salinity, chlorophyll, and primary productivity rather than the maximum values, with all other values staying the same.

Figure D2. ArcGIS Environmental Factors Model to Create ASCIIs for MaxEnt Environmental Layers Input.

Whale Presence Model

The CSV file that contained all whale sightings data from 2005-2018 was brought into ArcGIS, given WGS 84 geographic coordinates, and exported as a shapefile. The shapefile was then brought into ArcGIS ModelBuilder and re-projected into the local projection for Dominica. The "Add Geometry Attributes" tool was used to add new columns for longitude and latitude that contained XY coordinates (Figure D3). Since some whale sightings points appeared on land, the "Extract Values to Points" tool was used to match the whale presence points shapefile to the extent layer, therefore excluding any erroneous points on land (Figure D4). The new attribute table was exported as a CSV containing columns for species, longitude, and latitude, and then brought into MaxEnt as the sample data.

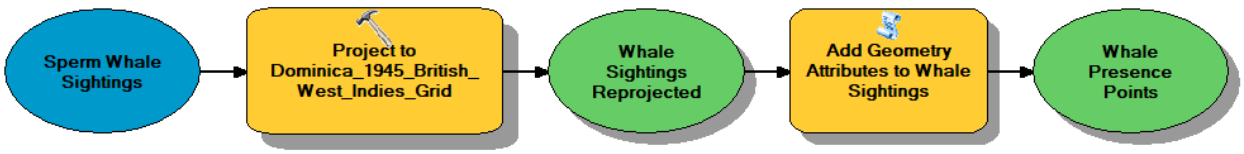


Figure D3. ArcGIS Whale Presence Model to Create Shapefile for MaxEnt Samples Input.

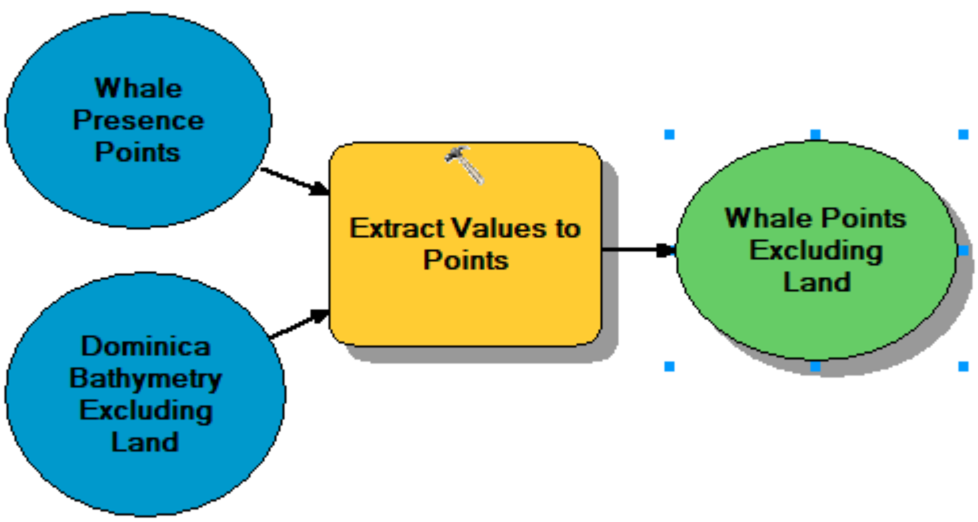


Figure D4. ArcGIS Whale Presence Model to Take Whale Sightings Off of Land.

Appendix D2: MaxEnt Inputs and Parameters

In MaxEnt, the whale presence CSV file was used as the "Samples" input file, and the environmental layer ASCII files were used as the "Environmental layers" input files. The first model run used the maximum values for salinity, chlorophyll, and primary productivity, and the minimum value for temperature. A second model run was done using the mean values for salinity, chlorophyll, and primary productivity, and the minimum value for temperature (Table D1). A jackknife test was run within MaxEnt to determine which model run had the best model fit, and which environmental variables were most important to the analysis. Higher "area under the receiver operating characteristic (ROC) curve" (AUC) values indicate better model performance, as well as a lower likelihood that the habitat suitability values were found by random chance. The first model run resulted in an AUC of 0.896, while the second model run's AUC was 0.815. Based on these results, the first model run that used maximum rather than mean values for salinity, chlorophyll, and primary productivity was chosen due to its higher AUC value and better fit. The parameters chosen for the model run using maximum values are shown in Figure D5 below. The output that was brought into ArcGIS for mapping purposes was the model output from the maximum values MaxEnt model run in ASCII format.

Table D1. Environmental Factors Tested for Inclusion in MaxEnt Model Run.

Environmental Factor	Source	Reference	Included
Bathymetry	GEBCO	bathymet_asc	Yes
Minimum annual temperature	BioORACLE	temp_min_asc	Yes
Maximum salinity	BioORACLE	sal_max_asc	Yes
Mean salinity	BioORACLE	sal_max_asc	No
Maximum chlorophyll	BioORACLE	chlor_max_asc	Yes
Mean chlorophyll	BioORACLE	chlor_mean_asc	No
Maximum primary productivity	BioORACLE	pp_max_asc	Yes
Mean primary productivity	BioORACLE	pp_mean_asc	No

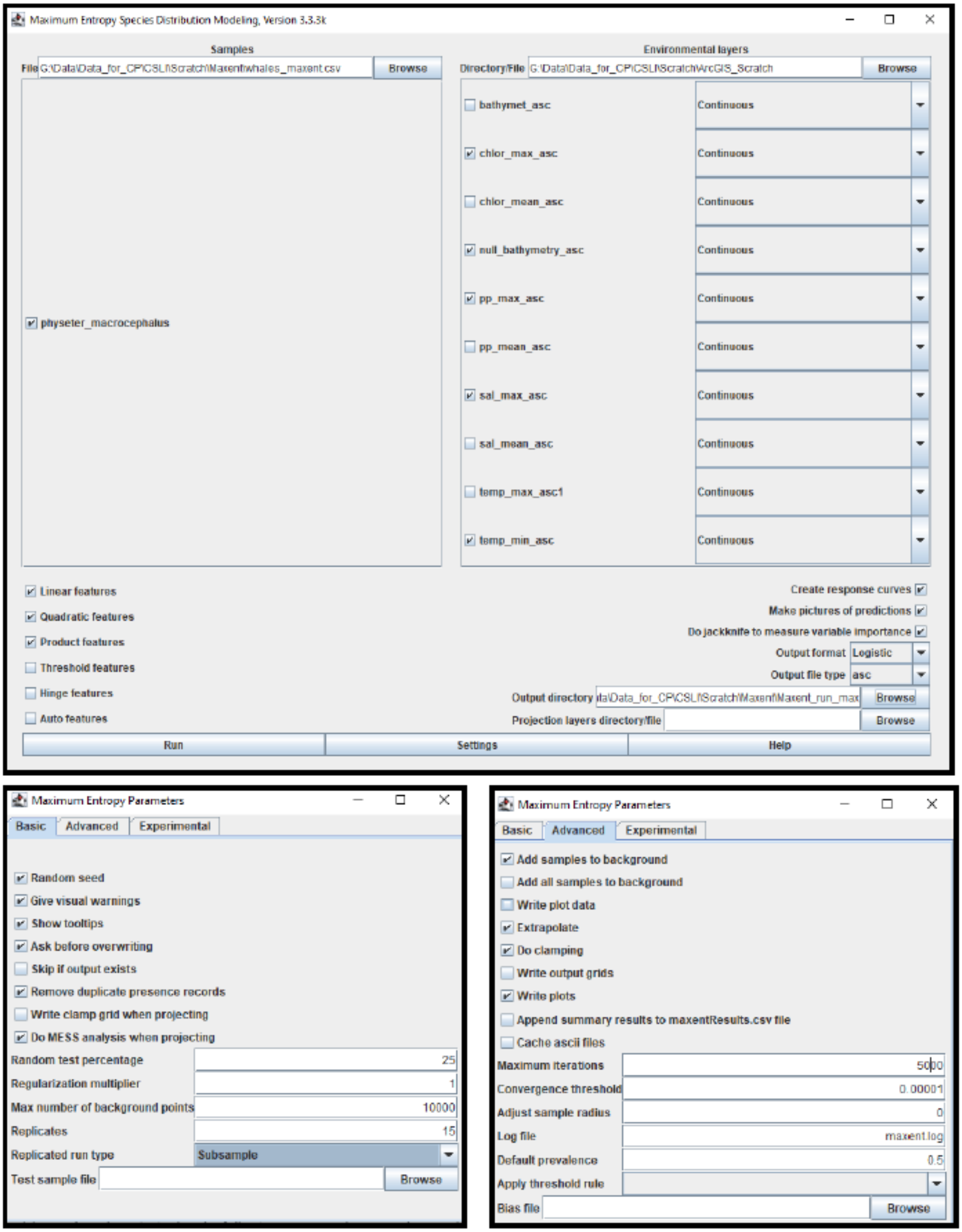


Figure D5. MaxEnt Model Parameter Settings.

Appendix E: Vessel Traffic Visualization and Density Analysis

AIS data were filtered within the SQLite database to include merchant, cruise ship, and high speed ferry vessel categories travelling at speeds greater than 10 knots from 2012-2019 (excluding 2016).

```
### Create join from columns of different tables to create one table with columns of interest and remove duplicates

SELECT positions.mmsi, positions.timestamp, positions.speed, positions.lat, positions.lon, vessels.name, vessel_types.category
FROM positions
LEFT JOIN vessels on positions.mmsi = vessels.mmsi
LEFT JOIN vessel_types on vessels.vessel_type = vessel_types.vessel_type
WHERE speed > 10 AND (category = 'merchant' OR category = 'passenger')
GROUP BY positions.mmsi, positions.timestamp, positions.speed, positions.lat, positions.lon, vessel_types.category
        ### Save result as view "merchant_passenger_noduplic_final"


### Create a table from view

CREATE TABLE fast_vessels AS
SELECT *
FROM merchant_passenger_noduplic_final


### Recategorize Passenger Ships as Cruiseships

UPDATE fast_vessels
SET
category = 'cruiseship'
WHERE (vessel_type = 'Passenger Ship' OR vessel_type = 'Passenger ship')


### Recategorize certain MMSIs as high speed ferry category

UPDATE fast_vessels
SET category = 'high_speed_ferry'
WHERE mmsi IN(377906089,367503381,341683000,329003800,329003100,329002300,329001200,257285700,235094715,228036000,228008600,226127000)


### Select categories of interest

SELECT *
FROM fast_vessels
WHERE (category = 'merchant' OR category = 'cruiseship' OR category = 'high_speed_ferry')
```

Listing E1. SQL Query Code to Filter AIS Data for Vessel Traffic Analysis.

Appendix E1: Vessel Traffic Visualization

The filtered “fast_vessels” dataset from the SQLite database was brought into QGIS for visualization. Only 2018 data were used as a representative example of vessel patterns for each category. The outputs were then saved as shapefiles to import into ArcGIS for visualization purposes (see Figure 4). Each of the vessel categories (high speed ferries, cruise ships, and merchant vessels) were visualized individually for 2018. High speed ferries tend to travel along the island’s shore, while merchant vessels and cruise lines tend to travel more offshore.

Appendix E2: QGIS Vessel Density Analysis

The filtered "fast_vessels" dataset from the SQLite database was brought into QGIS to create a density analysis through the Processing Modeler. The AIS points were brought in through "Input Points", then the "Base Layer" was added and the "Grid Size" was set to 1km^2. The layer was reprojected into WGS 84 and the grid was created to the extent of the reprojected layer. The "Extract by Location" tool extracted the points from the grid and counted each point within 1km^2. The output was an aggregated density plot, which was then distributed into 20% bins through symbology (Figure E1). The output was imported into ArcGIS to visualize the density analysis for all vessels traveling greater than 10 knots for all years (2012-2019; excluding 2016) at a resolution of 1km^2 resolution and distributed into quantiles (see Figure 5).

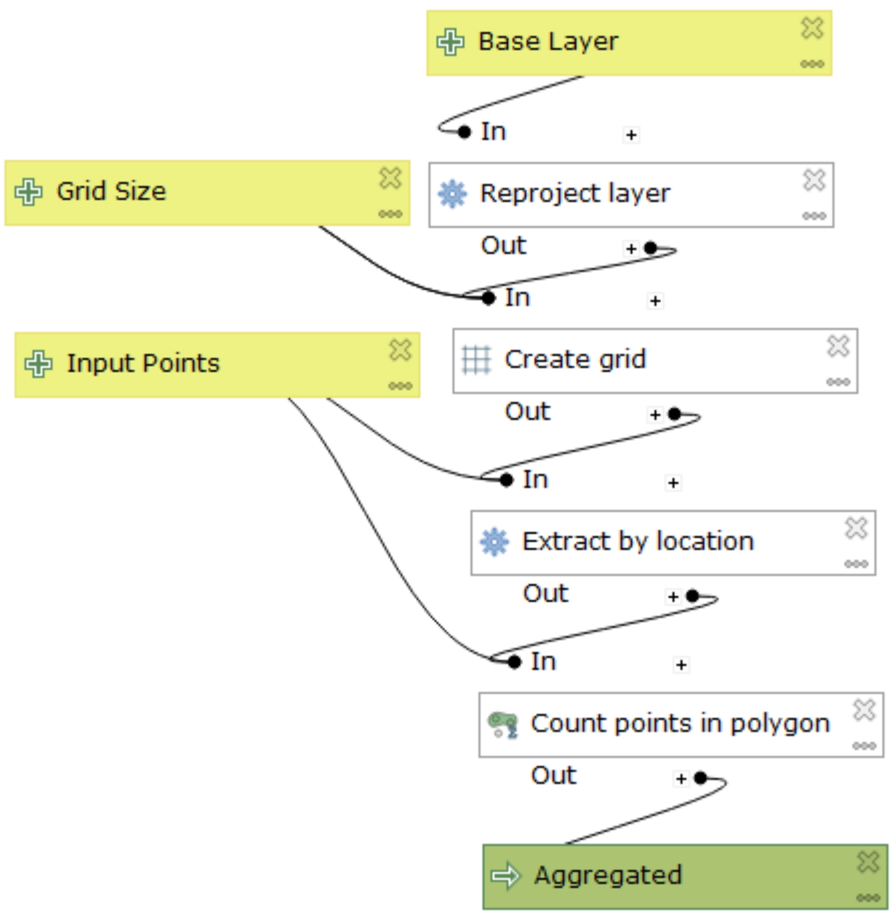


Figure E1. Vessel Density Model Built Using QGIS Processing Modeler.

Appendix F: Vessel Traffic Recommendations and Analysis

Appendix F1: Creating Shipping Lanes and Vessel Speed Reduction Zone

ArcGIS was used to create recommended shipping lanes and a speed reduction zone based on current vessel traffic patterns and sperm whale habitat suitability. The polygon tool was used to hand-draw a polygon that outlines the high sperm whale habitat suitability from the MaxEnt species distribution model (SDM) output and exported as a shapefile. This high habitat suitability area shapefile was assigned as the speed reduction zone, where vessels would be required to travel 10 knots or less. Using the same method, the offshore northbound and southbound lanes were created by hand-drawing polygons along the offshore perimeter of the speed reduction zone, using a buffer of 1nm between the offshore lanes and the speed reduction zone. These lanes could be used by merchant vessels and cruise ships transiting through Dominica's coastal waters. The inshore northbound and southbound lanes were created using the same method along the inshore perimeter of the slow speed zone, using a buffer of 0.5nm between the inshore lanes and the speed reduction zone. These lanes would be used by high speed ferries transiting between Dominica's ports and neighboring islands.

Appendix F2: Quantifying Time Cost of Vessel Speed Reduction Zone

The proposed speed reduction zone would require vessels to slow down to 10 knots or less, thereby increasing their travel time. We developed a method to quantify the time cost of this aggregate additional travel time. The method is based on the following algorithm.

1. For each vessel and each point in the AIS data, the time difference to the next reported point of the same vessel is calculated, under the assumption that the vessel speed during this duration is constant.
2. Points whose time difference duration is longer than 20 minutes are filtered out, since a gap of 20 minutes or longer likely was caused by an interruption of an individual vessel trip or a data gap.
3. All AIS points that are located outside the speed reduction zone are filtered out.
4. All AIS points that are below the speed limit (10 knots) are filtered out.
5. The traveled distance for each point is calculated under the assumption of constant speed during its duration.
6. The time that would be required to travel this distance at 10 knots is calculated.

7. The difference between the actual duration and the travel time at 10 knots is calculated.
8. The time differences across all vessels and points are summed, which results in a total additional time spent at sea due to complying with the speed reduction zone.

In order to quantify the amount of extra time vessels would have to travel to comply with the vessel speed reduction zone (10 knots or less), we used R to calculate the time cost of vessels using the proposed vessel speed reduction zone. The shapefile of the vessel speed reduction zone polygon created in ArcGIS (see Appendix F1) was loaded into R . A data frame including merchant, cruise ship, and high speed ferry vessels traveling over 10 knots was brought into R by connecting to the SQLite database and importing the "fast_vessels" dataset. The AIS data consists of GPS points of each vessel, with points reported every time an AIS station picked up a signal from that vessel. Therefore, in order to quantify the distance traveled between points for each vessel, the time difference from each AIS point to the next sequential point was calculated. In order to account for errors in the data and prevent falsely counting time differences between separate vessel trips, only time differences between 0 and 20 minutes were included. In order to quantify the amount of time vessels would have to slow down, the difference between AIS reported vessel speed and the proposed 10-knot speed limit was calculated. The difference in vessel speed was multiplied by the time difference between all AIS points to produce the difference in distance the vessels would have to make up by traveling at a speed of 10 knots instead of their actual speed. In order to get the value of time added to vessel trips due to the speed reduction zone, the difference in distance traveled was divided by the difference in vessel speed for each AIS data point. These points were then intersected with the speed reduction zone polygon. The time added for each point within the speed reduction zone was then summed to quantify the total extra time vessels would have to spend traveling through the speed reduction zone annually (2012-2019; excluding 2016). The total time cost per vessel category was visualized; merchant vessels have the largest time cost, followed by cruise ships, and high speed ferries have the smallest time cost (see Listing F1).

Vessel Time Cost Analysis

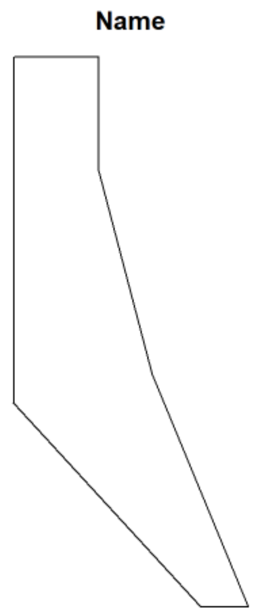
WorthWhale Team

2/28/2020

The following code quantifies the time cost to vessels traveling through the proposed vessel speed reduction zone.

```
# Load necessary packages
library(tidyverse)
library(DBI) # DBI stands for "database interface" and creates a connection between R and other database management systems
library(sf)
library(lubridate)
```

```
# Read in slow speed zone shapefile and reproject to WGS84
slowzone <- sf::read_sf("data/slowspeedzone.shp") %>%
  st_transform(crs = 4326)
plot(slowzone)
```




```
# Connect to our worthwhale.sqlite database
sqlite_con <- dbConnect(RSQLite::SQLite(), "../AIS/worthwhale.sqlite")

# Get a list of all tables
alltables = dbListTables(sqlite_con)

# Get the fast_vessels table as a data.frame
fast_vessels = dbGetQuery(sqlite_con, 'SELECT * FROM fast_vessels')
```

```r
# Create a difference in seconds, minutes, and hours columns
diff_time <- fast_vessels %>%
  group_by(mmsi) %>%
  mutate(diff_in_sec = as.POSIXct(timestamp, format = "%Y-%m-%d %H:%M:%S") - lag(as.POSIXct(timestamp, format = "%Y-%m-%d %
H:%M:%S"), default = first(as.POSIXct(timestamp, format = "%Y-%m-%d %H:%M:%S")))) %>%
  mutate(diff_in_min = as.numeric(diff_in_sec/60)) %>%
  mutate(diff_in_hr = as.numeric(diff_in_min/60)) %>%
  mutate(year = year(timestamp))


# Create master dataframe
diff_filtered <- diff_time %>%
  filter(diff_in_min > 0 & diff_in_min < 20, category != "passenger") %>%
  mutate(diff_speed = speed-10) %>%
  mutate(diff_dist = diff_speed * diff_in_hr) %>%
  mutate(diff_time = diff_dist/diff_speed) %>%
  select(mmsi, year, speed, diff_speed, lon, lat, category, diff_in_hr, diff_dist, diff_time)


# Only include vessels within the speed reduction zone polygon
point <- st_as_sf(diff_filtered, coords = c("lon", "lat"), crs = 4326)

# Intersect slowzone and point
inzone = st_intersection(point, slowzone) %>%
  select(-Name)

# Create df of total extra time spent in slow speed zone over all vessels from "fast_vessels" table
time_sum_all <- inzone %>%
  group_by(year) %>%
  summarize(year_total = sum(diff_time))

# Create df of total extra time spent in slow speed zone split between merchant, cruise ship, and high speed ferry vessel ca
tegories
time_sum_category <- inzone %>%
  group_by(year, category) %>%
  summarize(year_total = sum(diff_time))

# Create vector for 3 vessel categories
vessel_categories <- c("Cruise Ship", "High Speed Ferry", "Merchant")
names(vessel_categories) <- c("cruiseship", "high_speed_ferry", "merchant")

# Visualize total time cost per vessel category
time_cost_plot <- ggplot(time_sum_category, aes(x = year, y = year_total, fill = category))+
  geom_bar(stat = "identity", alpha = 0.9) +
  facet_wrap(~category, scales = "free_y", labeller = labeller(category = vessel_categories)) +
  scale_y_continuous(expand = expand_scale(mult = c(0,0.05))) +
  theme_bw()+
  theme(legend.position = "none", plot.title = element_text(hjust = 0.5))+
  scale_fill_brewer(palette="Dark2")+
  labs(title = "Time Cost for Vessels in 10 knot Vessel Speed Reduction Zone",
       x = "Year",
       y = "Total Time Cost (hours)")

time_cost_plot
```

Listing F1. R Code to Quantify Vessel Time Cost of Vessel Speed Reduction Zone.

Appendix G: Shiny App

The R code and files to run the Shiny app can be found on GitHub on the WorthWhale account, under the repository “ShinyApp_WorthWhale”. The R script named “app_worthwhalefinal.R” is the final code. The repository is public and can be forked and cloned by GitHub users. The link below will bring you to the repository.

- https://github.com/worthwhale/ShinyApp_WorthWhale