

# Environmental and economic implications of alternative cruise ship pathways in Bermuda

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## ARTICLE INFO

### Keywords:

Cruise ships  
Marine spatial planning  
Coral sedimentation  
Tourism  
Dredging

## ABSTRACT

As the cruise ship industry moves towards ever larger vessels, many tourist destinations are faced with dilemmas about how to accommodate the latest generation of ships, which require deeper and wider shipping pathways. The location of nearshore shipping channels traveled by cruise ships has important environmental and economic implications, as dredging larger lanes damages habitat, ship traffic produces sediment plumes that can smother adjacent sensitive habitats (e.g., coral reefs, seagrass beds), and dredging costs vary spatially. These environmental and economic costs should ideally be evaluated in the context of projected benefits from increased tourism. To inform decision-making on cruise ship pathway design, we evaluated tradeoffs among tourism revenue to the local economy, dredging costs, direct coral damage and sedimentation impacts to coral reefs of alternative cruise ship approach channels for the island of Bermuda. We compiled economic data on cruise tourism and dredging costs and developed a sediment particle tracking model, overlaid on maps of coral cover, to track the spread of sediment particles and resulting coral sedimentation caused by cruise ships. Using our models we compared two viable routes, if dredged, for larger ships to reach Bermuda, along with a scenario of no dredging in which the next generation of larger ships is not accommodated. Our tradeoff analysis shows that the status quo (no dredging; no larger ships) scenario performs relatively well except for the risk of a significant loss in tourism revenue. When selecting between the two channel upgrade scenarios, the south channel upgrade is preferable if dredged material can be reused, thereby recouping dredging costs; otherwise, there is a strong tradeoff between upgrade costs and coral sedimentation. While developed with data layers and inputs specific to Bermuda, this analytical approach could easily be configured to other locations facing similar spatial planning decisions about whether and where to allow pathways for larger cruise ships.

## 1. Introduction

The cruise ship industry has been growing, providing an important source of revenue for many coastal tourism destinations (Lester and Weeden, 2004; Macpherson, 2008; UNWTO, 2010). The industry as a whole has been moving towards increasingly larger ships (Clancy, 2008; Johnson, 2002), with the largest ships stretching longer than 350 m and accommodating over 6000 passengers (e.g., Royal Caribbean International's Oasis class ships).

Many tourist destinations lack the infrastructure, including deep enough shipping lanes and harbors, to accommodate these mega-ships, and developing the infrastructure is expected to be costly and come with adverse environmental impacts (Brida and Zapata, 2010; Johnson, 2002). There are also concerns about more significant environmental impacts from the larger ships themselves (Davenport and Davenport, 2006; Johnson, 2002; Lester and Weeden, 2004). However, given competition among tourism destinations to be on the schedules of the major cruise lines, many coastal tourism economies will decide to upgrade their shipping pathways and prepare for the likely effects of larger ships in order to maintain or develop cruise ship tourism.

Cruise ships can cause a range of environmental impacts for the

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coastal locations where they visit and dock, including pollution from sewage and waste disposal (Butt, 2007; Caric and Mackelworth, 2014), introduction of non-native species (Gollasch, 2002), impacts resulting from developing on-land infrastructure to accommodate the docking of large ships and short-term influxes of thousands of visitors (Davenport and Davenport, 2006; Macpherson, 2008), disturbance to marine wildlife such as turtles and cetaceans (Denkinger et al., 2013; Laist et al., 2001), and destroying critical marine habitats (e.g., coral reefs, seagrass beds) when dredging for shipping lanes, harbors and docks (Gayle et al., 2005; Jones et al., 2016; Walker et al., 2012). Additionally, ship traffic in nearshore waters suspends bottom sediments into the water column, resulting in sediment plumes that are able to spread away from the shipping pathway (Jones, 2011; Rapaglia et al., 2015; Smith et al., 2008). This sediment can smother corals, seagrass and other sensitive species and habitats (Erfteimeijer and Lewis, 2006; Rogers, 1990; Walker et al., 2012), causing continuous stress and damage to the ecosystem beyond that which occurs from the initial channel dredging. These sedimentation impacts are more difficult to predict than direct impacts from dredging (Erfteimeijer et al., 2012), and thus are less likely to be taken into account when planning for cruise ship traffic.

Preparing for larger ships is often a marine spatial planning (MSP) issue, as there can be different spatial options for the shipping channel approach to a given destination. MSP is a comprehensive approach for determining where and when human activities can take place in different areas of the ocean, ideally resulting in a plan that minimizes conflicts among users and among different management objectives (Douve, 2008). In the case of planning for larger cruise ships, if there are alternative spatial options under consideration, decision makers should take into account the pros and cons of those options (e.g., due to spatial variation in dredging costs, the distribution of sensitive habitats, and sediment transport from shipping channels to these habitats). The best option from the perspective of the cruise ship industry or a government department tasked with public works and engineering might not be the best option from the perspective of minimizing environmental impacts or conserving critical species or habitats and the ecosystem services and functions they provide. MSP can ideally help mitigate these tradeoffs by providing a planning process for weighing these different perspectives and making decisions that balance competing objectives.

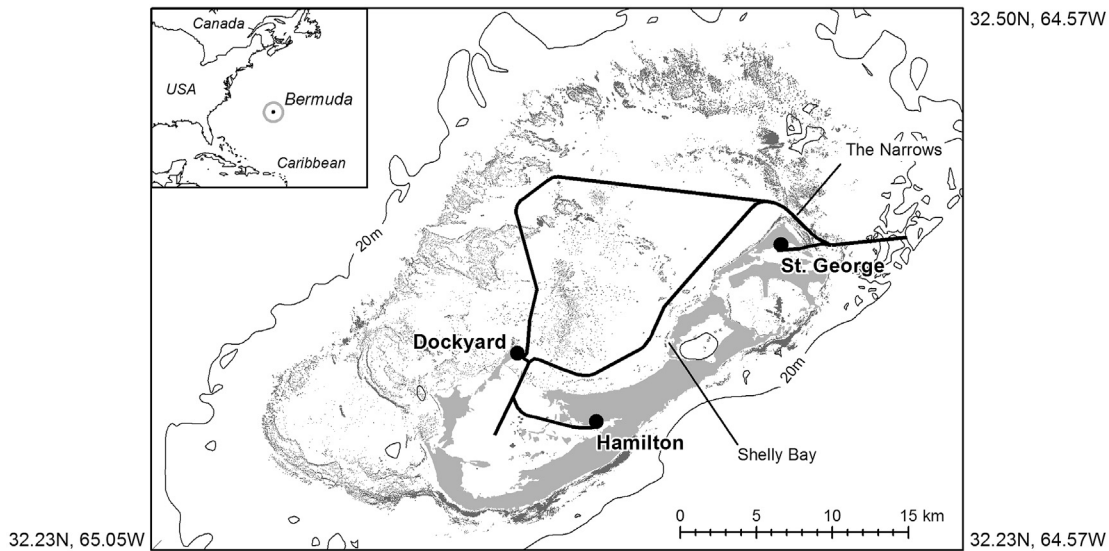
Tradeoff analysis is a useful analytical tool for evaluating alternative MSP options (Lester et al., 2013; White et al., 2012). By modeling or compiling data on the outcomes of different spatial plans and comparing different dimensions of these outcomes in terms of management objectives and ecosystem services, spatial planning options can be identified that minimize tradeoffs and optimize spatial plans for a suite of objectives. This enables more transparent decision-making and more explicit consideration of tradeoffs among management goals, stakeholder interests, ecosystem benefits, and environmental impacts. Tradeoff analysis can be especially useful for MSP because it can quantitatively compare the costs and benefits of different ocean uses that are valued in distinct terms or units, rather than requiring that they be translated into a common unit (e.g., dollars) (Lester et al., 2013). In the context of the cruise ship industry and evaluating alternative spatial plans for ship approaches to coastal locations, tradeoff analysis elucidates the tradeoffs among economic costs (i.e., dredging costs to upgrade shipping channels), economic benefits (i.e., tourism revenue), and environmental impacts that may not be easily quantified in economic terms (i.e., habitat destruction from dredging new channels; sedimentation impacts from cruise ship traffic).

Bermuda is an ideal case study for evaluating alternative cruise

ship approach channels. Bermuda has a significant tourism industry, of which cruise ship tourism comprises an increasingly large percentage. For example, in 2014, 60% of visitors to the island arrived on cruise ships, up from 43% ten years earlier (BTA, 2014). Additionally, Bermuda's marine environment has high conservation value as it includes the most northerly coral reefs in the Atlantic (Burke and Maidens, 2004), its reefs are in good health relative to those of Caribbean islands (Jackson et al., 2014), sedimentation impacts from dredging and cruise ship traffic are an important concern (Jones, 2011; Sarkis et al., 2010), and its reefs are an important draw for tourism (e.g., a recent study estimated an average annual value of Bermuda's reefs to tourism of US\$406 million; van Beukering et al., 2015).

Bermuda was traditionally visited by smaller cruise ships, which entered via the south shipping channel that runs along the northern coast of the island. Larger ships cannot navigate the south channel, however, and instead use a more northerly approach (Fig. 1). Both routes traverse the reef platform in order to reach the western ports. However, until recently, even the north channel was not sufficiently deep in some stretches to accommodate the next generation of cruise ships, thus creating pressure for Bermuda to upgrade one of its approaches to avoid losing tourism business in the future. The selection of a primary pathway (north or south) to upgrade would result in different environmental impacts, including direct impacts and indirect impacts from sediment resuspension and spreading resulting from ship traffic along each approach (Jones, 2011). Maintaining the status quo (i.e., not upgrading either pathway) could reduce future tourism revenue but would also prevent added environmental impacts. At the end of 2015, following an engineering study (MottMacDonald, 2014) and environmental impact assessment (BEC, 2014, 2015), Bermuda upgraded the north channel, realigning an elbow and deepening the channel in shallower stretches. In observing the decision-making process in Bermuda, we hypothesized that important factors were not being considered and a tradeoff analysis would have been informative in the planning process. Specifically, these studies did not quantify impacts to tourism revenue or sedimentation impacts to corals from ongoing ship traffic that would be expected to result from the channel upgrade options, and did not consider a status quo (i.e., "do nothing") option (BEC, 2015). Alternative plans that could have been pursued – either upgrading the south channel approach or maintaining the status quo – provide a convenient example for how the decision-making process of cruise ship pathway design could have been addressed more objectively and comprehensively using a marine spatial planning approach and tradeoff analysis.

In this study, we evaluated tradeoffs among tourism revenue, dredging costs, direct coral damage, and sedimentation impacts to coral reefs from ship traffic resulting from alternative cruise ship approach channels to Bermuda. Using as a starting point the status quo conditions prior to the upgrade at the end of 2015, we compared the northern and southern routes that, if dredged, would allow larger cruise ships to reach the island. We also considered a scenario of no dredging in which larger ships are not accommodated, with a possible consequent reduction in cruise ship tourism in the future. For our analysis, we compiled economic data on cruise ship tourism and dredging costs and developed a sediment particle tracking model, overlaid on maps of coral cover, to track the spread of sediment particles and resulting coral sedimentation caused by cruise ship traffic. We anticipate that this analytical approach will be useful for other locations, for example in the Caribbean, facing similar spatial planning decisions about whether and where to allow pathways for larger cruise ships (e.g., Diedrich, 2007).



**Fig. 1. Bermuda's shipping channels and ports.** The Bermuda islands (light grey) are shown with surrounding visible reefs (dark grey) and shipping channels (black lines), prior to dredging at the end of 2015. The 20 m isobath shown roughly delineates the edge of the reef platform; much of the inner platform averages around 10 m depth.

## 2. Methods

### 2.1. Shipping lane scenarios

For ships entering Bermuda ports, there is a single charted approach from the east of the island. To reach the western ports of Hamilton and Dockyard, ships pass through a narrow channel (“The Narrows”) before rounding the northern land tip of Bermuda and turning west. At this point, the route splits between the north channel and south channel, both ending up at the entrance to the Great Sound and Dockyard (Fig. 1). The southern channel is the more traditional route, although the north channel has become more popular with the advent of larger ships and currently none of the regular caller cruise ships use the south channel. The south channel route has an elbow near the Shelly Bay area (Fig. 2). Smaller ships will sometimes bypass this elbow in favor of a straighter route to the west, which has sufficient depth. In considering an upgrade to the south channel route, we include a realignment of the channel following this straighter route. Similarly, the north channel includes a small elbow through a reef patch that would be straightened in an upgrade (as was done in the actual upgrade in 2015) (Fig. 2).

We used three shipping lane scenarios for this study (Table 1), assuming a decision starting point prior to the north channel upgrade that took place at the end of 2015: 1) status quo, in which the north channel is used without dredging or realignment, 2) upgrade of the north channel with a realignment to straighten the elbow, and 3) upgrade of the south channel with a realignment to straighten the elbow. Centerline data for these shipping lane routes were digitized from an existing nautical chart (UKHO, 2007), with route lengths of 23,715 m, 23,650 m, and 17,560 m, respectively.

### 2.2. Biophysical data

To create a more complete bathymetric model, a 30 arc-second bathymetric grid was obtained from the British Oceanographic Data Centre's General Bathymetric Chart of the Oceans (GEBCO) 2008 data set (GEBCO, 2008) and clipped to the Bermuda Exclusive Economic Zone, and was then combined with digitized depth soundings compiled from nautical charts (BDCS, 2014) and a

bathymetric survey of the shipping channels (BDWE, 2014). A regular 25-m grid was then created from the bathymetry points using spatial interpolation tools in ArcGIS for Desktop software (Esri, Version 10.2), and the resultant grid was clipped to the study area. Coral coverage data were obtained from the Bermuda Department of Conservation Services and the Bermuda Zoological Society, using the best available coral reef spatial distribution data for Bermuda (Murdoch et al., 2007). The data include reef heads as polygonal shapes that were digitized from 50-cm visible aerial photography from 1997, and thus may exclude some deeper coral not visible in aerial photographs.

To determine direct coral destruction by dredging, we assumed a channel width of 185 m for the south channel and 215 m for the north channel, as these are the minimum widths required for operation of larger vessels for channel turns (MottMacDonald, 2014); we applied the widths required for turns to the entire channel pathway for simplicity. Coral reef heads within these channel pathways were classified as destroyed by dredging operations and were quantified as meters squared of coral destroyed.

### 2.3. Channel upgrade costs

Channel upgrade (i.e., dredging) costs were taken from an engineering study commissioned by the Government of Bermuda's Ministry of Public Works that identified the channel upgrades needed to allow larger cruise ships to visit Bermuda (MottMacDonald, 2014). This study calculated costs for various operating conditions, and we used their projected costs for the broadest range of operating conditions: normal operation plus night and/or daytime storm operation. This would allow ships to approach Bermuda in conditions with up to 35 knot winds and up to 0.8–1.0 m significant wave height during the night; and up to 45 knot winds and up to 1.3–2.2 m significant wave height during the day. The cost estimates we used included the engineers' overall contingency allowance to account for estimated uncertainty given project complexity and risk; this contingency is 35% for the north channel and 20% for the south channel, with a higher value for the north channel due to factors such as more dredging of hard materials and a more exposed location (MottMacDonald, 2014).

We considered different cost scenarios for each shipping

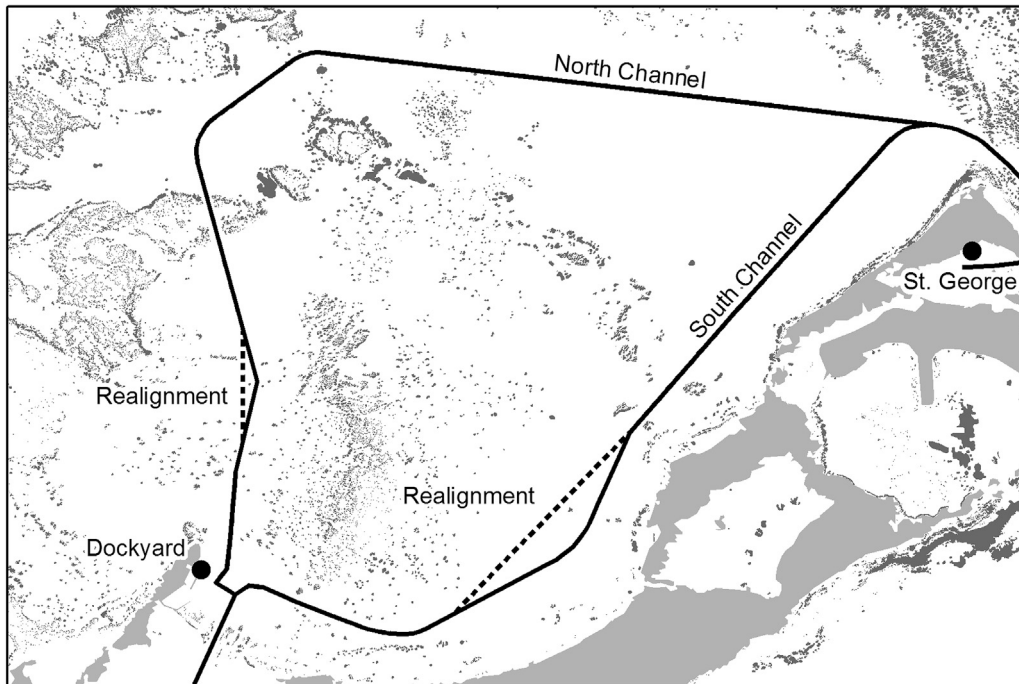


Fig. 2. South and north channel shipping lane upgrade options. Proposed realignments of each option shown by dashed lines.

Table 1  
Summary of all scenarios.

Scenario	Description	Reuse dredge (affects upgrade costs)	Relocate coral (affects upgrade costs and coral dredged)	Tourism scenario
1a	Status quo (use north channel, no dredging or realignment)	NA	NA	2015 cruise ship visitation maintained as is (SQ)
1b	Status quo (use north channel, no dredging or realignment)	NA	NA	2015 cruise ship visitation continues but loses Liberty of the Seas (SQ - ship loss)
2a	Upgrade north channel, with realignment	Yes	Yes	2015 cruise ship visitation continues with Anthem of the Seas replacing Liberty of the Seas (N or S upgrade)
2b		No	Yes	
2c		Yes	No	
2d		No	No	
3a	Upgrade south channel, with realignment	Yes	Yes	
3b		No	Yes	
3c		Yes	No	
3d		No	No	

channel upgrade option (Tables 1 and 2). We considered scenarios in which dredged material is reused (e.g., as landfill) and thus has a value, and those in which dredged material is not reused and thus has no value (Table 2). Dredged material for a small, isolated island like Bermuda, which must often import aggregate, can have considerable value, but without specific plans to store or immediately use the material following dredging, this value is highly speculative and the material could be more of a liability than a benefit (BEC, 2014). We also considered capital costs of dredging that either included or did not include costs for relocating corals in the dredging pathway (Table 2). If coral relocation is mandated and done successfully, coral relocation could eliminate direct damage to corals caused by dredging. However, given that coral relocation may not be mandated in all places, and may not be successful for all coral species (Garrison and Ward, 2008; Yap, 2004), we also considered a scenario where there was no coral relocation (and thus no cost for such activity), and therefore coral directly destroyed by dredging is an environmental impact. Overall, considering reusing or not dredging material and relocating or not coral provide book-ends across the range of possible outcomes

within our analysis, ensuring that our results are robust to these uncertainties.

#### 2.4. Tourism revenue

Annual revenue to the local economy from cruise ship tourism was calculated using data from the 2015 cruise ship schedule compiled by the Government of Bermuda Department of Marine and Ports Services (BDMPS, 2015), focusing on regular callers (i.e., contract ships) (Table 3). We focused our analysis of annual revenue on the regular callers and did not take into account occasional callers since the vast majority of cruise ship visits to Bermuda are from regular callers. Royal Caribbean International (RCI) has replaced the Liberty of the Seas with the larger Anthem of the Seas (Quantum class) for service to Bermuda in 2016, following the required upgrade to accommodate this size vessel (MottMacDonald, 2014).

For tourism revenue, we considered three hypothetical scenarios: 1) no dredging was done to allow for larger ships and thus the 2015 cruise ship tourism schedule continues for the regular

**Table 2**  
**Channel upgrade costs.** Scenarios from Table 1 indicated in parentheses (with and without coral relocation).

Channel scenario	With coral relocation	Without coral relocation
North channel, no reuse of dredged material (2b, 2d)	\$ 35,041,950	\$ 33,330,750
North channel, reuse dredged material (2a, 2c)	\$ 31,297,950	\$ 29,586,750
South channel, no reuse of dredged material (3b, 3d)	\$ 53,534,400	\$ 53,311,200
South channel, reuse dredged material (3a, 3c)	\$ 17,534,400	\$ 17,311,200

callers, including continued visitation by Liberty of the Seas (“status quo”), 2) no dredging was done to allow for larger ships and we assume that RCI stops sending Liberty of the Seas because it has been replaced by a ship that cannot approach the island, but that all other 2015 regular callers continue on an identical schedule (“status quo with ship loss”), and 3) dredging is conducted to upgrade a channel and thus RCI is able to replace all Liberty of the Seas calls with calls from Anthem of the Seas and all other regular callers continue on an identical schedule to that in 2015 (Tables 1 and 4). This last tourism revenue scenario can be realized with either the south channel or north channel upgrades.

For each of the above tourism scenarios, we calculated annual tourism revenue to the local economy as the sum of total passenger expenditures, total crew expenditures, and total cruise cabin taxes for a calendar year (Table 4). For total passenger expenditures, we multiplied the total number of passengers (passenger capacity for each ship multiplied by the number of visits in a year) by an assumed average per passenger expenditure of \$118 (the average of the per passenger expenditure range, \$112–\$124, reported for 2013 (TRA, 2014)). In reality, passenger spending is unlikely to be constant and may not be independent of cruise ship capacity and visitation rates. However, we did not have sufficient data to make a more complex prediction about changing spending patterns with changes in numbers of tourists and so were forced to assume linear increases in revenue. Passenger capacity for each ship is based on the projected number of passengers listed in the 2015 cruise ship schedule (BDMPS, 2015). For the Anthem of the Seas, we used the median number of passengers based on the minimum and maximum passenger numbers (<http://cruise-international.com/cruise-search/ShipDetailsQuery?nShip=555&nLine=26&nOperator=Royal+Caribbean>). For total crew expenditures, we divided the total number of crew (number of crew for each ship multiplied by the number of visits in a year) by two to assume a 50% disembarkment rate (TRA, 2014) and then multiplied that number by an assumed average per crew expenditure rate of \$50.50 (the average of the per crew expenditure range of \$50–\$51 (TRA, 2014)). Crew size for each ship is from the 2015 cruise ship schedule. For the Anthem of the Seas, we determined the crew size by using a linear regression of minimum passenger capacity predicting crew size for the entire Royal Caribbean fleet ( $R^2 = 0.986$ ) and used this model to calculate the crew size for Anthem based on their minimum number of passengers (4180 passengers; 1644 crew). For total cruise cabin taxes, we used the Bermuda Passenger Cabin Tax rates per cabin per night of \$14 for ships arriving May 1–August 31 and \$10 for ships arriving

September 1–April 30 ([http://www.bermuda-attractions.com/bermuda\\_0001b7.htm](http://www.bermuda-attractions.com/bermuda_0001b7.htm)), determining the number of nights for each ship based on the 2015 cruise ship schedule and the number of cabins for each ship as posted on [http://cruise-international.com/cruise-search/Cruise\\_Ship\\_CL](http://cruise-international.com/cruise-search/Cruise_Ship_CL). See Table 4 for values used in calculations.

### 2.5. Sediment particle tracking model

In order to quantify the environmental impact of cruise ship traffic for the different shipping lane options, we developed a numerical particle tracking model (PTM). The PTM simulates the spread of sediment particles, which are assumed to be suspended during the passing of cruise ships, using a simplified model that incorporates turbulent diffusion and particle sinking. We used the PTM to estimate the cumulative environmental impact of the following three scenarios (Table 1): no upgrade and continued use of the north channel (“status quo”), upgrade of the north channel, and upgrade of the south channel. Using spatial data on coral cover, environmental impact was quantified by counting the number of sediment particles that diffuse away from the shipping channel and sink onto a bathymetric point with coral cover (i.e., coral sedimentation).

Based on published and projected cruise ship speed estimates, we assumed that the cruise ships are traveling in the shipping channels with speeds in the range of 10–16 knots with the ratio of the ship draft to average channel depth typically around 0.6 (e.g., 8 m draft in 14 m deep shipping channel) (MottMacDonald, 2014). Using the aforementioned values, the estimated bottom stress generated by the passing ships is several orders of magnitude greater than the critical shear stress needed to mobilize fine sand sediment like that of coral sand (see next paragraph) (Berenbrock and Tranmer, 2008; Fischer et al., 1979). Therefore, sediment particles are assumed to be mobilized from the bottom and released near the surface of the shipping channel locations in the model. Surface release represents a conservative approach for estimating the worst-case environmental impact since the particles are allowed to diffuse over greater areas. A random walk model was used to simulate a particle’s movement in response to turbulent diffusion in three-dimensions, as is commonly done (e.g., Batchelder et al., 2002; Moniz et al., 2014; Ross and Sharples, 2004; Visser, 1997). The vertical settling velocity of particles was estimated using Stokes’ law,

**Table 3**  
**Ship characteristics for regular callers to Bermuda.** Information provided by cruise line websites.

Ship name	Cruise line	Ship length (m)	Gross tonnage	Draft (m)	Passenger capacity
Grandeur of the Seas	Royal Caribbean International	279.2	74,000	7.6	2172
Summit	Celebrity Cruises	294.1	91,000	7.9	2181
Norwegian Dawn	Norwegian Cruise Line	294.1	92,250	8.2	2593
Norwegian Breakaway	Norwegian Cruise Line	325.6	146,600	8.2	4094
Liberty of the Seas	Royal Caribbean International	338.9	160,000	8.5	3894
Anthem of the Seas	Royal Caribbean International	347.8	168,666	8.5	4543

**Table 4**

Values used to estimate annual tourism revenue. The last three columns are calculated as described in Section 2.4.

Ship	Included in scenario?		# Visits per yr	Passenger capacity	Crew size	# Cabins	Total passenger expenditures per yr	Total crew expenditures per yr	Total cabin tax per yr	
	SQ	SQ – ship loss								N or S upgrade
Liberty (RCI)	Y	N	N	21	3894	1397	1814	\$ 9,649,332	\$ 740,759	\$ 497,036
Grandeur (RCI)	Y	Y	Y	12	2172	840	975	\$ 3,075,552	\$ 254,520	\$ 304,200
Breakaway (NCL)	Y	Y	Y	26	4094	1566	2000	\$ 12,560,392	\$ 1,028,079	\$ 1,312,000
Dawn (NCL)	Y	Y	Y	22	2593	1181	1126	\$ 6,731,428	\$ 656,046	\$ 657,584
Summit (CEL)	Y	Y	Y	19	2181	965	975	\$ 4,889,802	\$ 462,959	\$ 503,100
Anthem (RCI)	N	N	Y	21	4543	1644	2400	\$ 11,257,554	\$ 871,731	\$ 657,600

$$w_s = \frac{2 \rho_s \rho_f g r^2}{9\mu} \quad (1)$$

where  $\rho_s$  is the density of the settling particle,  $\rho_f$  is the density of seawater,  $g$  is the acceleration due to gravity,  $\mu$  is the dynamic viscosity of seawater, and  $r$  is the particle's radius. Coral sand was used for the density of the particles ( $\rho_s = 1567 \text{ kg/m}^3$ ), while the radius ( $r = 1 \text{ }\mu\text{m}$ ) was chosen to match the approximate median radius of sediment collected in a sediment plume after the passage of a cruise ship in Bermuda (see Fig. 8b in Jones, 2011). Consideration of larger particles does not change the qualitative results. Note that the particle Reynolds number was sufficiently small such that Stokes' law is a reasonable assumption (Tchobanoglous and Schroeder, 1985).

Using a random walk model for turbulent diffusion in three-dimensions and Stokes' law for the settling velocity, a particle's position is calculated as follows:

$$X_i = X_{i-1} + \zeta_{ix} \sqrt{2K_x \Delta t} \quad (2)$$

$$Y_i = Y_{i-1} + \zeta_{iy} \sqrt{2K_y \Delta t} \quad (3)$$

$$Z_i = Z_{i-1} - w_s \Delta t + \zeta_{iz} \sqrt{2K_z \Delta t} \quad (4)$$

where  $(X, Y, Z)_{i-1}$  and  $(X, Y, Z)_i$  are the initial and final positions in the horizontal and vertical directions,  $\zeta_i$  is a random variable with unit variance in each respective direction,  $K_{x,y,z}$  is the turbulent diffusivity in each respective direction,  $w_s$  is the vertical settling velocity determined from Stokes' law (Eq. (1)), and  $\Delta t$  is the model time step (Batchelder et al., 2002; Moniz et al., 2014; Ross and Sharples, 2004; Visser, 1997). Turbulent diffusivities were characterized using a local bed friction velocity ( $u_*$ ) based on the ship's speed (where the ship speed is assumed to be the free-stream velocity in the channel), the average shipping channel depth ( $H$ , characteristic length scale), and empirical constants based on channels with meanders and strong bends such as those observed here (Table 5; cf. Fischer et al., 1979 and reference therein). The shipping channel depth ( $H$ ) was calculated by taking the average depth over the entire shipping channel, neglecting the deep portion of the east channel approach since these points are in offshore waters with no adjacent coral cover. A spatially uniform turbulent diffusivity was used, in each respective direction, in order to prevent spurious aggregations of particles (Batchelder et al., 2002; Ross and Sharples, 2004; Visser, 1997).

The shipping channel routes were converted to a series of points at 25-m spacing along the length of each route (Table 6). In the PTM, 500 sediment particles were released at each shipping channel point (>1000 points for each scenario; see Table 6) and

allowed to diffuse and settle according to Eqs. (1)–(3). The spatial location where a particle settled was recorded, and if the closest bathymetric point contained coral cover, then the particle was tagged in the model. The cumulative environmental impact of a shipping channel scenario on coral sedimentation was then calculated as the total number of tagged particles in the model run. The model time step ( $\Delta t = 0.05 \text{ s}$ ) and number of particles (500) were chosen based on convergence of the final cumulative impact (i.e., total number of particles landing on coral did not change by more than a few percent). Finally, we ran the PTM using the minimum and maximum shipping speeds, in order to provide lower and upper bounds on the model diffusivities (Tables 5 and 6). These bounds on the diffusivities are also intended to account for variable background environmental conditions not captured in the PTM, as this was more tractable than attempting to include information about ocean circulation patterns around Bermuda which are highly variable over a range of time-scales (Coates et al., 2013).

## 2.6. Tradeoff analysis

For the tradeoff analysis, we focused on four outcomes (axes) of interest: 1) predicted annual tourism revenue to the local economy, 2) cost of upgrading a channel, 3) area of coral destroyed by dredging, and 4) coral sedimentation impact from cruise ship traffic. With the exception of tourism revenue, for which the goal is to maximize the value, the objective for the other three axes is to minimize their values. In relation to these four axes, we compared outcomes of different shipping pathway scenarios (Table 1): the status quo in which the north channel is used without dredging or realignment (and thus larger ships like Anthem of the Seas cannot visit the island; 1a,b), scenarios in which the north channel is upgraded (2a–d), and scenarios in which the south channel is upgraded (3a–d).

## 3. Results and discussion

The relative expense of dredging the north versus south channel depends highly on whether or not the dredged material is reused (Table 2; (MottMacDonald, 2014)). If dredged material is not reused (i.e., its value is not realized), the north channel is significantly less costly to dredge compared with the south channel (~\$33 M vs. ~\$53 M). On the other hand, if dredged material is reused, the south channel is the more cost effective solution given the more extensive dredging required (~\$29.5 M for north, ~\$17 M for south). Coral relocation cost is higher for the north channel than the south channel because there is more coral in the proposed channel pathway. However, including coral relocation cost does not change the qualitative pattern of total cost between north and south channel upgrades, because in both scenarios it represents a relatively small portion of the total cost. We assume that if coral is

**Table 5**  
Parameters used in the particle tracking model.

$K_x \frac{m^2}{s}$	$K_y \frac{m^2}{s}$	$K_z \frac{m^2}{s}$	$w_s \left[ \frac{m}{s} \right]$	$u \left[ \frac{m}{s} \right]$	$\Delta t[s]$	# Particles at each shipping point
3.4u-H	3.4u-H	$\frac{1}{15}u$ H	1.1E-06	0.1(Ship Speed)	0.05	500

**Table 6**  
Particle tracking model results highlighting the cumulative environmental impact, measured by the number of particles released that land on coral, for each of the three shipping channel upgrade options considered.

Shipping channel	Channel depth (H) [m]	Ship speed [knots]	# Shipping points	Environmental impact [# particles on coral]
Status Quo (North)	14.12	10	1290	9231
Status Quo (North)	14.12	16	1290	9284
North Upgrade	14.4	10	1287	9642
North Upgrade	14.4	16	1287	9764
South Upgrade	13.56	10	1043	7942
South Upgrade	13.56	16	1043	7965

relocated, there is 100% success and thus no coral damage, which is admittedly optimistic; however, we were limited by a lack of information about actual success rates for this system. If we assume that coral is not relocated prior to dredging, 59,098 m<sup>2</sup> of coral cover is destroyed by dredging for the north channel upgrade, compared to 46,636 m<sup>2</sup> for the south channel upgrade.

Annual tourism revenue resulting from the five regular caller cruise ships is predicted to be \$45,222,546 for the channel upgrade scenarios (either the north or south channel; Table 4). If there is no dredging to upgrade a channel to allow for larger ships, the predicted annual tourism revenue drops to \$43,322,789 for the status quo scenario or to \$32,435,661 for the status quo with ship loss scenario (which only includes four regular caller ships).

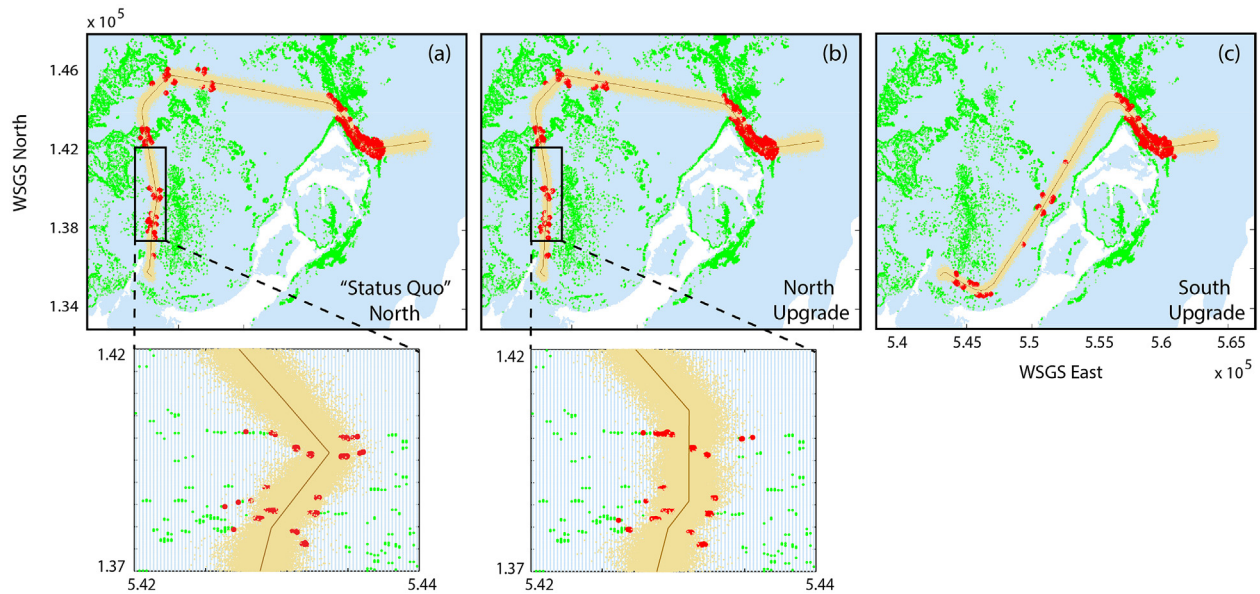
The particle tracking model indicates that all three shipping options result in the highest levels of coral sedimentation in the shallow, eastern portion of the shipping channel, due to the proximity of the shipping channel lane to areas with high density coral cover (Fig. 3). Upgrading the south channel has the smallest environmental impact in terms of coral sedimentation (Fig. 3c; Table 6), mainly due to this channel extending through areas with less coral compared to the north channel options. For the two north channel options, the status quo (no dredging) scenario has a slightly smaller sedimentation impact relative to the upgraded channel scenario with dredging and realignment. Differences between the two north channel options included the area of channel realignment (see Fig. 3 insets) and the upgrade resulting in deeper channel routes with larger diffusivities that increase the spread of particles away from the channel center. The upper and lower bounds for the ship speed did not significantly affect the levels of coral sedimentation for any of the options (Table 6), indicating that the proximity of the shipping channel center to existing coral largely determines the resulting coral sedimentation values.

Comparing the four dimensions of our tradeoff analysis together (i.e., the four bar plots in Fig. 4a–d), maintaining the no-dredging status quo has no cost in terms of channel upgrade and no direct dredging damage to coral, but has a high amount of uncertainty with respect to future tourism revenue, with a possible loss of over \$12 million/year in revenue to the local economy if one of the regular caller ships ceases visits to the island. The status quo scenario also has a relatively high degree of coral sedimentation. If the status quo was not deemed an acceptable outcome, for example because of the risk of a significant drop in tourism revenue, the best option based on our analysis is to upgrade the south channel, reusing the dredged material, and relocating coral to avoid direct damage. Reusing the dredge recoups a large portion of the dredging

costs for the south channel, and relocating coral is a small percentage of total upgrade costs. As a result, the total cost of this option is less than the expected extra tourism revenue generated in just two years with the larger ships, making it a compelling option economically. Furthermore, upgrading the south channel results in much lower sedimentation to corals relative to either of the north channel options. If dredged material is not able to be reused, the decision is much more difficult because of the tradeoff between upgrade cost and coral sedimentation: the north channel upgrade scenarios come with moderate costs (equal to ~3 years extra revenue from the tourism it will generate) and high coral sedimentation, and the south channel scenarios have even higher upgrade costs (>4 years recoup time from tourism revenue) but lower coral sedimentation (Fig. 4e).

We made some simplifying assumptions that could limit the utility of our results. In particular, our tourism scenarios only consider the replacement of one ship (Liberty of the Seas). The other cruise lines could also decide to replace existing ships with larger ships, in which case the status quo with ship loss scenario could be underestimating the loss of tourism revenue from failing to upgrade an approach channel, while the upgrade scenarios could be underestimating the increases to tourism revenue. Cruise ship schedules are driven by factors such as consumer demand and port availability and capacity, and we examined only two simple although plausible outcomes if Bermuda had failed to upgrade one of its channels. Additionally, we assumed linear changes in revenue with changes in visitor numbers, ignoring possible income effects whereby increased cruise ship supply makes cruises cheaper and thus lower income tourists can visit Bermuda but may spend less on island. However, we did not have data to support more complex assumptions, and thus assumed linear changes, which are likely to be more accurate over the short-term. Lastly, we did not account for possible negative environmental and economic repercussions of potentially exceeding the tourist carrying capacity of the island or of diminished tourist experience from crowding, and also were not able to quantify potential economic gains from encouraging development of other forms of tourism that might have lower environmental impacts (e.g., smaller cruise ships or air-arrivals).

Our analysis was also limited by a lack of a direct measure for damage to coral from sedimentation and smothering. We do not have a rigorous methodology to estimate the absolute quantity of sediment that is suspended during cruise ship passage in the channels, and thus our PTM is not attempting to predict the total amount of sediment that is deposited in any one location on the



**Fig. 3. Particle tracking model results highlighting the differences in coral sedimentation between the three scenarios.** a) North channel with no dredging or realignment (“status quo”), b) north channel upgrade with dredging and realignment, and c) south channel upgrade with dredging and realignment. The inset panels on a and b highlight the spatial differences between the north channel scenarios in the channel realignment region. The dark brown line indicates the shipping channel lane, the light brown dots represent the sediment plume, the green dots represent locations with coral cover, and the red dots represent sediment particles that settled in a grid point with coral (i.e., coral sedimentation). The model output shown is for an assumed ship speed of 16 knots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reef. Additionally, it is difficult to assess what absolute levels of sedimentation would lead to coral mortality, as this varies by sediment type, coral species, and duration of smothering, among other factors (Jones et al., 2016; Rogers, 1990). Instead, we developed a method to determine the relative sedimentation impacts across space; although indirect, we argue this approach still is useful for comparing alternative development plans and offers an advance over current practice which is typically to ignore likely sedimentation impacts from ship traffic.

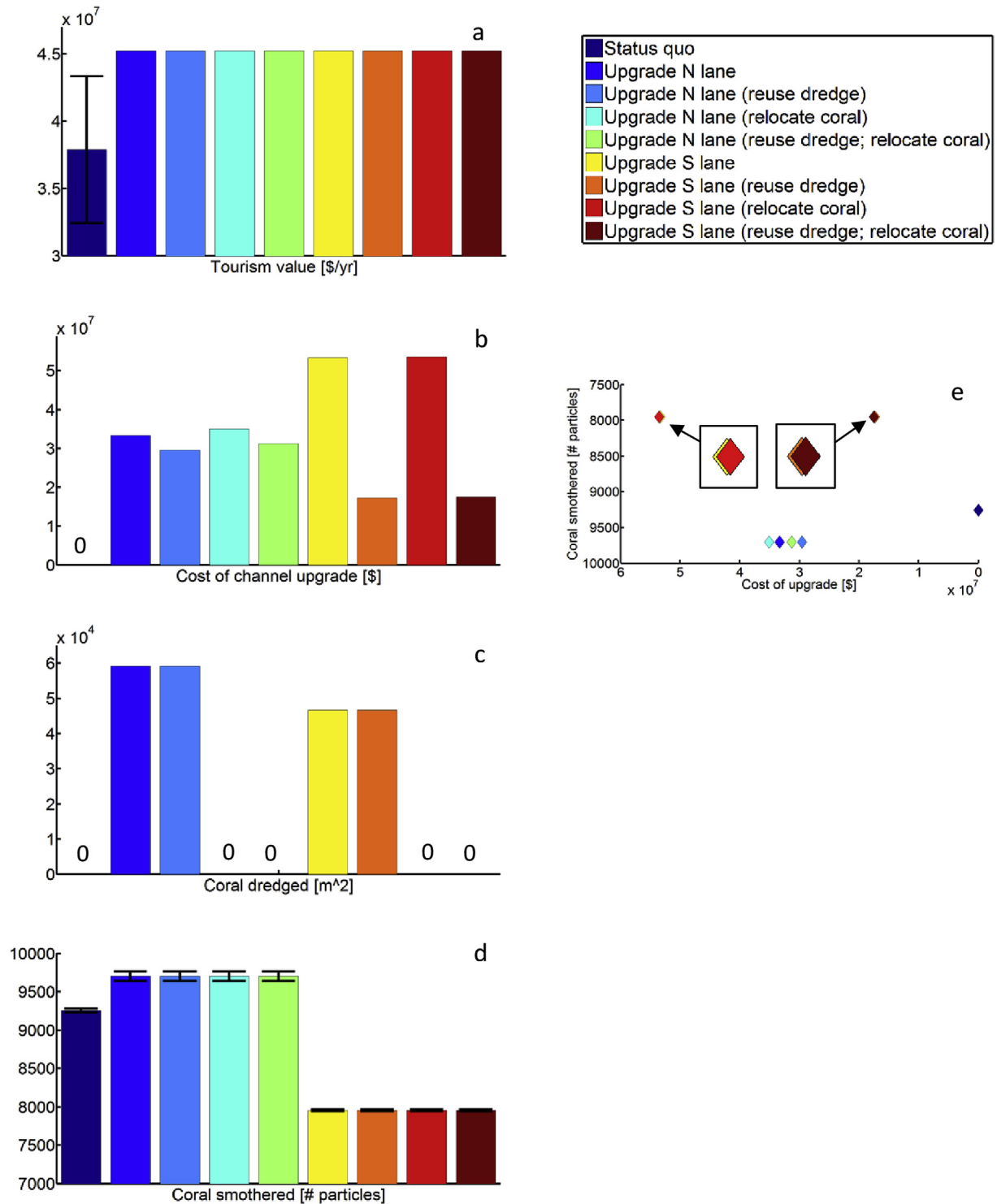
It is also important to note that we have not accounted for all factors that might be important in making a channel upgrade decision. Specifically, there are other environmental impacts that could vary among the scenarios, such as pollution from ships (Caric and Mackelworth, 2014), sedimentation to other key species like seagrasses (Cabaco et al., 2008; Erfteimeijer and Lewis, 2006), and disruption to marine life from ship traffic (Denkinger et al., 2013; Laist et al., 2001). We also did not take into account future maintenance costs of the channels, safety of navigation, or required upgrades to ports or harbors (not a factor in this decision since all scenarios use the same port). Additionally, while we examined potential sedimentation impacts to corals and tourism revenue from cruise ships, we did not attempt to quantify how negative impacts to coral reefs could feedback to influence tourism or other sources of economic value. For example, healthy reefs are a contributing factor to attracting tourists to Bermuda, and reef degradation could negatively impact tourism demand and thus revenues, for both cruise and air arrivals (Glasson et al., 1995; van Beukering et al., 2015). Lastly, there are a number of factors we did not examine that could have further favored the status quo scenario, including economic revenue from other forms of tourism, environmental impacts of potentially exceeding the tourist carrying capacity of the island, and the distribution of costs and benefits to difference segments of society. One would ideally account for all of these factors in a tradeoff analysis. Ignoring key dimensions, or considering some tradeoffs only implicitly, is likely to result in

inferior decisions during marine planning (Lester et al., 2013; White et al., 2012).

The Government of Bermuda has already dredged the north channel. A status quo option was not on the table because of a government commitment to accommodate the Quantum class of cruise ships (BEC, 2015). The rejection of the south channel option was guided by the scale and financing of the dredging, the lack of an identifiable project that would utilize the large volumes of dredge material, less safe conditions for residents on nearby beaches (e.g., Shelly Bay) due to ship surge, and the expected future maintenance costs of re-dredging the channel. Although our analysis left out some of these factors that favored the north channel upgrade, the factors we did consider indicate that the status quo option or dredging the south channel could have been equally good or even better options. The Environmental Impact Statement commissioned by the government examined economic and environmental costs of dredging (BEC, 2015), but did not examine the environmental effects of ship traffic. While dredging impacts are important, they are an intense one-time disturbance and we argue that the continuous impact from sedimentation caused by ship traffic is equally important due to the cumulative damage it can cause to adjacent coral communities.

In summary, despite some limitations, our analysis represents an important advance in multi-objective decision making for cruise ship tourism development, offering an approach for simultaneously considering economic costs of accommodating larger ships, local economic benefits from tourism revenue, and environmental impacts to sensitive habitats from dredging and ship traffic. This approach is intended as a general framework—that could be expanded to include additional factors—to support spatial planning for cruise ship approach channels in tourist destinations around the world. Our methodology can be parameterized with local data and expanded to include additional factors, to help to make important tradeoffs among infrastructure costs, tourism revenue, and environmental impacts more explicit and transparent.





**Fig. 4. Tourism revenue, dredging cost, and direct (dredged) and indirect (smothered by sediment) coral impacts from status quo and eight alternative cruise shipping lane upgrade scenarios.** Bars and fences in panels a–d indicate mean and minimum/maximum values, respectively. Fences in panel a refer to status quo with and without ship loss and fences in panel d refer to results for two ship speeds. e) Tradeoff between mean dredging cost and mean coral smothering impact for each of the shipping lane scenarios (note inverted axes). Inset boxes with arrows show magnified results to facilitate differentiation between nearly-overlapping symbols. In all of the panels bar/symbol color corresponds with the label indicated in the legend.

This should be applicable and useful for a wide variety of tourist destinations that depend on or are hoping to attract cruise tourism, including Latin America and the Caribbean (Luxner, 2014; Sheller, 2009), Asia and the Pacific (Dwyer and Forsyth, 1996; UNWTO, 2012), and Africa (PWC, 2014).

#### Acknowledgements

We thank A. Dan and E. Ruff for assistance with literature review, J. Ward and A. Glasspool at Bermuda Environmental Consulting Ltd for assistance with aligning the study with the

actual decision to the extent possible, R. Johnson at BIOS for helpful discussions, Bermuda Department of Conservation Services for assistance with bathymetric and coral cover data, and useful feedback from anonymous referees. Financial support was provided by the Waitt Foundation.

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