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Spatiotemporal modelling for policy analysis: Application to sustainable management of whale-watching activities ☆

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ABSTRACT

Anticipating the impacts of a new policy before implementation on a complex social–ecological system is a challenging task for managers and policymakers. This paper reports on the development and use of an agent-based model (ABM) dedicated to support marine park managers in their effort to devise policies to sustainably manage whale-watching activities. The ABM, called the Marine Mammal and Maritime Traffic Simulator (3MTSim), represents the spatiotemporal dynamics of marine mammals and navigation activities in and around the Saguenay–St. Lawrence Marine Park in Canada. In the context of updating the current regulations on whale-watching in the Marine Park, 3MTSim was run to evaluate the merits of a proposed set of rules compared to the current regulations. To do so, a set of variables related to policies' impacts on the three spheres of sustainable development, namely the impact on whales (Environment), on whale-watching companies (Economy), and tourist experience (Society) was analysed. 3MTSim's simulations highlighted that the proposed rules are expected to improve the situation regarding whale conservation and tourist experience with only marginal impact on the whale-watching industry. In the proposed regulations, one rule is expected to be very influential on whale-watching activities. This rule limits to 10 the number of whale-watching boats allowed to stand within 926 m of any boat in observation mode. Assuming efficient law enforcement, 3MTSim predicts a significant decrease in overall boat concentration around whales in the Marine Park, which is one of the management objectives benefiting both whales and tourists. Interestingly, 3MTSim reveals that this rule could indirectly force some boats to observe second-choice whales present in higher abundance rather than some more attractive species scarcer in the region. This highlights the following management tradeoffs: Reducing boat exposure for the humpback whale and *endangered* blue whale is likely to increase it for the more abundant fin whale listed as *of special concern* (Canada's Species at Risk Act) and minke whale. This work demonstrates the utility of ABMs to support policy analysis in the context of sustainable management in a Marine Park. ABMs developed in close relationship with end-users are unarguably a tool of choice to manage complex social–ecological systems since they provide insight into phenomena hard or impossible to measure in the real system. Despite the labour intensive nature of their implementation, this investment is worth the effort.

☆ Except for the main author of this research, Clément Chion, all co-authors (starting with Guy Cantin) are listed in alphabetical order to reflect their equal importance in this work.

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1. Introduction

Whale-watching, designating observation activity directed toward any marine mammal species, is a flourishing industry which is worth more than US$ 2 billion/year worldwide [1,2]. The International Whaling Commission's moratorium on commercial whaling that took effect in 1986 and growing public interest in whales favoured its development in many communities [3–6]. However, decades of commercial whaling left several whale populations severely depleted in many waters across the world [5–9]. Despite the obvious conservation benefits of shifting from whale hunting to whale-watching, many animals targeted by excursion boats belong to post-hunting unhealthy populations and require special management efforts for them to recover. This need for management of activities is supported by a growing number of studies highlighting the negative impact of inappropriate whale-watching practices on the ecology of target animals [10–12]. In the case of depleted marine mammal populations, when biological functions of individuals are affected (e.g. reproductive rate [10]) this may jeopardise the recovery of the entire population. Along with wildlife viewing ethics considerations, this underscores the need to adequately manage whale-watching activities by setting rules dedicated to protect target animals and enhance tourist experience [13,14].

In the context of whale-watching activities management, rules frequently encountered include boat speed limits, distance limits, restriction of boat number in the vicinity of animals, and limits of observation duration. Additional measures are sometimes taken in particular contexts, including the establishment of a permit system for whale-watching companies, spatiotemporal zoning, as well as species-specific rules (see [15] for a worldwide review of regulations and voluntary measures).

Despite the efforts to devise efficient management rules, unanticipated side-effects may occur when regulations are enforced on complex social–ecological systems [16, 17, p. 47]. Agent-based models (ABMs) are computational simulation tools that can be used to test the efficiency of management scenarios and policies in various social–ecological contexts [18,19], offering the opportunity to unveil potential side-effects hard to foresee otherwise. ABMs are suitable to simulate the spatiotemporal dynamics of complex systems made of interacting autonomous entities [20]. The underlying principle is that the dynamics of the whole system being modelled emerges from the interactions and decisions made by entities that make it up, without the intervention of any centralised control. ABMs coupled with Geographical Information Systems (GIS) have been developed in a variety of contexts including ecosystem management [21], park management [22], wildlife ecology and management [23], and in the study of land use/land cover changes [24]. Although numerous ABMs have been developed to study the dynamics of marine ecosystems [25], they have been underused so far to support the management of intensively used marine areas [26].

The Saguenay–Saint-Lawrence Marine Park (hereafter referred to as Marine Park) is located in the Province of Quebec, Canada (cf. Fig. 1). Marine Park managers have the complex mandate to increase the protection level of the ecosystems of a representative portion of the Saguenay River and the St. Lawrence Estuary for conservation purposes, while encouraging its use for educational, recreational, and scientific purposes, in line with the principles of sustainable development. To support manager decisions in this context, an ABM called the Marine Mammal and Maritime Traffic Simulator (3MTSim) was developed, dedicated to anticipate the impacts of different management scenarios on human activities at sea [27]. The objective of this study is to evaluate the merits of a proposed set of rules on whale-watching activities in the Marine Park compared to the currently enforced regulations. To this end, 3MTSim was used to simulate boat and whale movements in space and time in the Marine Park region [27].

After a presentation of the context in the Marine Park area, 3MTSim is described along with the experimental plan for simulations. The results obtained from simulations are presented and discussed.

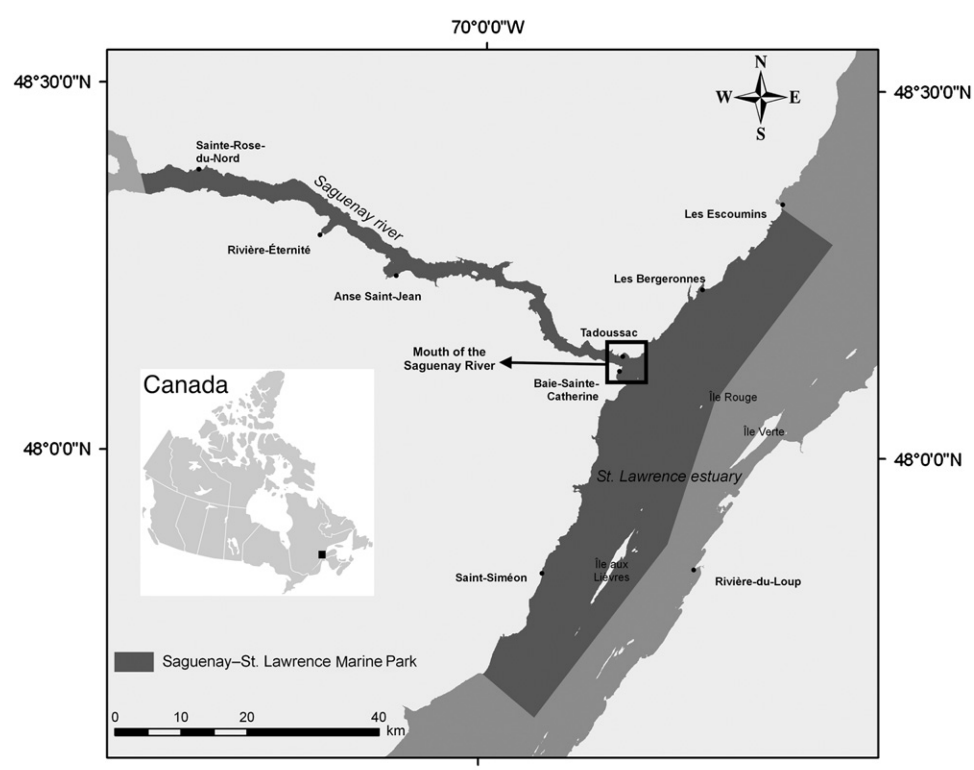

Fig. 1. Map of the Saguenay–St. Lawrence Marine Park.

2. Context and study area

The 1245 km^2 Saguenay–Saint-Lawrence Marine Park (Fig. 1) is part of the Canada's National Marine Conservation Areas network as well as part of Québec's network of provincial parks. The park, jointly managed by federal (Parks Canada) and provincial (SEPAQ[1] , MDDEP[2]) governments, was designated in 1998 following several years of favourable public pressure, consultation, and negotiation [28–30]. This federal-provincial arrangement reflects the fact that the coasts and seafloor of this estuarine region are under the province's jurisdiction and that each government acts within the scope of its responsibilities regarding water bodies.

The Marine Park is an upwelling region which hosts several rich marine and fluvial ecosystems characterised by the regular presence of marine mammals [31,32]. The Marine Park creation was largely motivated by the necessity to protect the highly depleted resident population of St. Lawrence belugas (*Delphinapterus leucas*) whose summer spatial distribution is centred at the confluence of the Saguenay and St. Lawrence Rivers, located at the core of the Marine Park [30]. This beluga population bears the *threatened* status according to the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) [33] and is listed under Canada's Species at Risk Act [34]. Due to persistent oceanographic processes that favour the aggregation of whale prey at the head of the Laurentian Channel [35], several migratory whale species are attracted to the Marine Park region to feed during summertime.

The regular and predictable presence of whales close to the shores in the Marine Park region along with the relative proximity of urban centres favoured the emergence of a whale-watching industry which grew rapidly in the early 1990s and was worth US$ 98 million in 2009 (Daniel Gosselin, personal communication). Every summer, more than 10 000 boat-based excursions [36] bring nearly 275 000 tourists offshore to observe marine mammals [37], making the region one of the world busiest whale-watching areas [38].

The five whale species most regularly observed in the area are (in decreasing order [39]), the *threatened* St. Lawrence Beluga whale [33], fin whale (*Balaenoptera physalus*) listed as *of special concern* [40], minke whale (*Balaenoptera acutorostrata*), humpback whale (*Megaptera novaeangliae*), and the *endangered* blue whale (*Balaenoptera musculus*) [33]. Beluga and blue whales belong to post-whaling highly depleted populations, whose recovery has been assessed to be limited by multiple human-induced threats, including disturbance from whale-watching [41,42].

To mitigate the potential detrimental impact of whale-watching activities on target whale species, Marine Park managers created the Saguenay–St. Lawrence Marine Park Regulations on marine activities[3] (REG-2002) in 2002 and fixed a cap on commercial permits, attributed to boats, for whale-watching companies operating on a regular basis [43]. Rules present in the REG-2002 were designed over a three-year process involving whale-watching companies, NGOs, and community representatives reflecting the three spheres of sustainable development. REG-2002's rules were designed according to local scientific studies [44], worldwide standards of wildlife viewing ethics [15], and the precautionary principle. These rules are summarised in Table 1.

Using an adaptive management approach, Marine Park managers are currently revising the REG-2002, planning to release a new version of the Saguenay–St. Lawrence Marine Park Regulations on marine activities in 2012 (REG-2012) [45]. In early 2011, a set of candidate rules was considered for inclusion in the revised REG-2012; these rules are presented in Table 1.

The original REG-2002 consists of a series of rules dedicated to mitigate the impact of whale-watching activities on target whales. The emphasis was made on the protection of endangered or threatened species according to the list of Canadian wildlife species at risk [34], namely belugas and blue whales. Another priority was to limit the concentration of boats. Boat speed is limited to 25 knots at any place and time in the Marine Park (rule #1). Additionally, within 1-nautical mile (nm) of one or more boats in observation (i.e. observation site), speed is limited to 10 knots (rule #2). Finally, when a whale is within a species specific distance from the boat (400 m for endangered and threatened whales, 100 m for others under certain conditions, 200 m otherwise), the captain must adopt the lowest speed to ensure boat manoeuvrability (i.e. 5 kt maximum), as per rules #3 and #4.

Regarding REG-2002's distance and boat densities restrictions, no boat may get closer than 100 m from a marine mammal (400 m for endangered and threatened species) at any time (rules #7 and #9). If by any circumstance a boat is closer than the appropriate limit distance (e.g., whale surfacing closer), it must stay still (rule #8). Finally, if four boats are already observing a group of marine mammals and an additional (fifth) boat comes to observe the same pod, the minimum pod-boat distance increases to 200 m (rule #10).

The last REG-2002's category of rules stipulates duration restrictions for observations. During the same excursion a captain cannot stay in the same observation zone for more than 1 h if in observation mode (rule #15). A captain cannot enter the 200-metre radius zone around the same group of marine mammals more than once during the same excursion (rule #14). Finally, after a first hour has passed and a captain has exited a given observation zone, he must wait at least one hour before returning to the same observation zone (rule #16).

In the proposed REG-2012, most of REG-2002's rules are maintained or modified and some new rules are added (cf. Table 1). New rules are mostly proposed to enhance the protection of belugas (rules #5 and #12) and a small portion of their critical habitats at the mouth of the Saguenay River near Tadoussac and Baie-Sainte-Catherine (rule #6) where traffic is the most intense in the population range [36]. The proposed modification of rule #2 reduces the 10 knots speed restriction to 1/2 nautical mile from other observing boats, the 10-year experience with the original regulations REG-2002 demonstrating this distance as being sufficient and appropriate for facilitating compliance. This also allows its implementation in the narrow Saguenay River, an important habitat for belugas where episodes of boat concentration have emerged over the past 10 years [46]. Another proposed rule is to forbid approaches within 200 m from cetaceans at rest or ones accompanied by a calf. Finally, in order to avoid large aggregations of boats around popular whales, the proposed REG-2012 fixes a maximum of 10 boats within 1/2 nautical mile from any boat in observation (rule #11).

3. Materials and methods

This paper presents 3MTSim simulations run to assess the merits of the proposed REG-2012 compared to the active REG-2002. All rules were tested except rule #13 since 3MTSim's whale agents do not have activity and age attributes in the current version [47]. This comparison was done on the basis of proxy variables standing for the three spheres of sustainable development, namely the Environment (i.e. relative to whale protection), Economy (i.e. relative to whale-watching activities),

[1] *Société des Établissements de Plein Air du Québec.*
[2] *Ministère du Développement Durable, de l'Environnement et des Parcs.*
[3] SOR/2002-76.

Table 1
Current (REG-2002) and proposed rules (REG-2012) applying to whale-watching boats in the Marine Park (nm, nautical mile; kt, knot; m, metre).

Rule category	Rule number	2002 Active regulations (REG-2002)	2012 Proposed set of rules (REG-2012)
Speed limits	1	25 kt throughout the park.	Maintained
	2	10 kt within 1 nm of another boat in observation, everywhere but in the Saguenay.	10 kt within 1/2 nm of another boat in observation, everywhere including the Saguenay
	3	Manoeuvrability speed (∼3–5 kt) between 100 m and 400 m from a cetacean.	Maintained
	4[a]	Manoeuvrability speed (∼3–5 kt) within 400 m of an endangered or threatened marine mammal.	Maintained
	5[a]	–	5–10 kt within 1/2 nm from a beluga whale
	6	–	15 kt in the mouth of the Saguenay River
Distances and boat densities restrictions	7[a]	No approach closer than 100 m from a cetacean other than endangered or threatened (cf. rule #10).	Maintained
	8	The boat must stay in a stationary position if a cetacean approaches within a distance less than 100 m.	Maintained
	9[a]	The operator of a vessel must maintain a minimum distance of 400 m between the vessel and any endangered or threatened marine mammal.	Maintained
	10	The operator of a vessel must not permit the vessel to approach closer than 200 m from a cetacean at any time when there are more than four vessels within a radius 400 m from that vessel.	Maintained
	11	–	Maximum of 10 whale-watching boats allowed within 1/2 nm of any boat in observation mode (observation zone)
	12[a]	–	If not already in observation mode, do not switch to this mode if a group of belugas approaches closer than 400 m
	13[b]	–	Not allowed to approach a cetacean at rest or a cetacean with a calf closer than 200 m
Observation time restrictions	14	Not allowed to approach between 100 m and 200 m a cetacean more than once in the same observation zone.	Maintained
	15	Not allowed to stay in observation more than 1 h, or to stay more than 1 h in the same observation zone.	Maintained
	16	At least one hour before penetrating the same observation zone.	Maintained

[a] These rules are intended to protect *threatened* and *endangered* species, as listed in the Species At Risk Act [34].
[b] This rule has not been tested in the model since activity and age are not among whale model attributes.

and Society (i.e. relative to visitor experience onboard whale-watching boats).

3.1. Marine mammal and maritime traffic simulator (3MTSim)

An overview of 3MTSim is available in [48]. For an in-depth description of 3MTSim's whale-watching excursions submodel, the reader can refer to its complete description in [27].

3MTSim is a spatially explicit ABM implemented in Java with Repast Simphony libraries [49]. It represents the main components of maritime traffic and whale movements in the St. Lawrence Estuary and the Saguenay River during the peak season of boat–whale interactions, from May to October (cf. Fig. 2). Boat and whale agents can move freely on a continuous space with their positions being updated every minute. The environment submodel is characterised by attributes (e.g., tides, visibility extent) and layers of information such as bathymetry, with a 100 m spatial resolution (cf. Fig. 2). A large amount of quality data were used to implement, calibrate, and validate the ABM [47,48]. For whale-watching excursions, data include interviews with captains, and over 2100 sampled excursions for which GPS tracks, boat activities, and neighbourhood composition (i.e. boats and whales) were available. Regarding the model of whale movements, the data used include VHF and shore-based tracking data, as well as transect-derived abundance. A comprehensive list of data used to implement 3MTSim can be found in [27].

The five most important whale species for the whale-watching industry (enumerated in the introduction) were implemented in 3MTSim (cf. Fig. 2). They account for nearly 99% of the whale-watching activities [50]. The submodel of whale movements has been developed following the pattern-oriented modelling approach

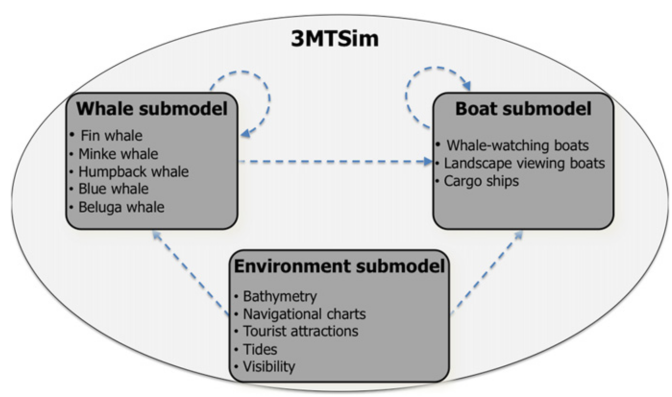

Fig. 2. 3MTSim structure.

[47,51] making use of available data summarised in [27]. Patterns reproduced by the simulated whales are movement parameters (turning angle, step length, and net displacement), aggregation pattern as a function of tides, species spatial distribution, and diving/surfacing patterns. The whale submodel has been validated independently since whales do not respond to boats in the model. Additional details on the whale submodel can be found in [47].

The whale-watching excursions submodel was developed focusing on captain agents' decision making processes and outcomes. The bounded rationality paradigm was used to ground both the investigation [50] and the modelling of whale-watching captains' decisions [48]. The main objective of captain agents is to locate and observe whales to satisfy onboard tourists. To do so, captains may explore the space or use available information to achieve their goal.

In the real system, collaboration via communication between captains appeared to be a major driver of excursion dynamics [48] and this was implemented in the model. Following interviews with captains and analyses carried out on available data [50], captain strategies and preferences were elicited and subsequently implemented in 3MTSim [48]. Additionally, vessel characteristics (size, cruise speed, and maximum speed) and attributes of planned excursions (duration, port of departure, special activities offered) were also included. Seasonal variability in companies' number of departures was derived from a specific study [36], also implemented within the model. 3MTSim has an end-user interface along with a visualisation interface shown in Fig. 3.

3.2. Model input parameters

Several parameters needed to be set before running 3MTSim and comparing the proposed REG-2012 to the current REG-2002. A summary of these parameters is given in Table 2 followed by an explanation for their selection.

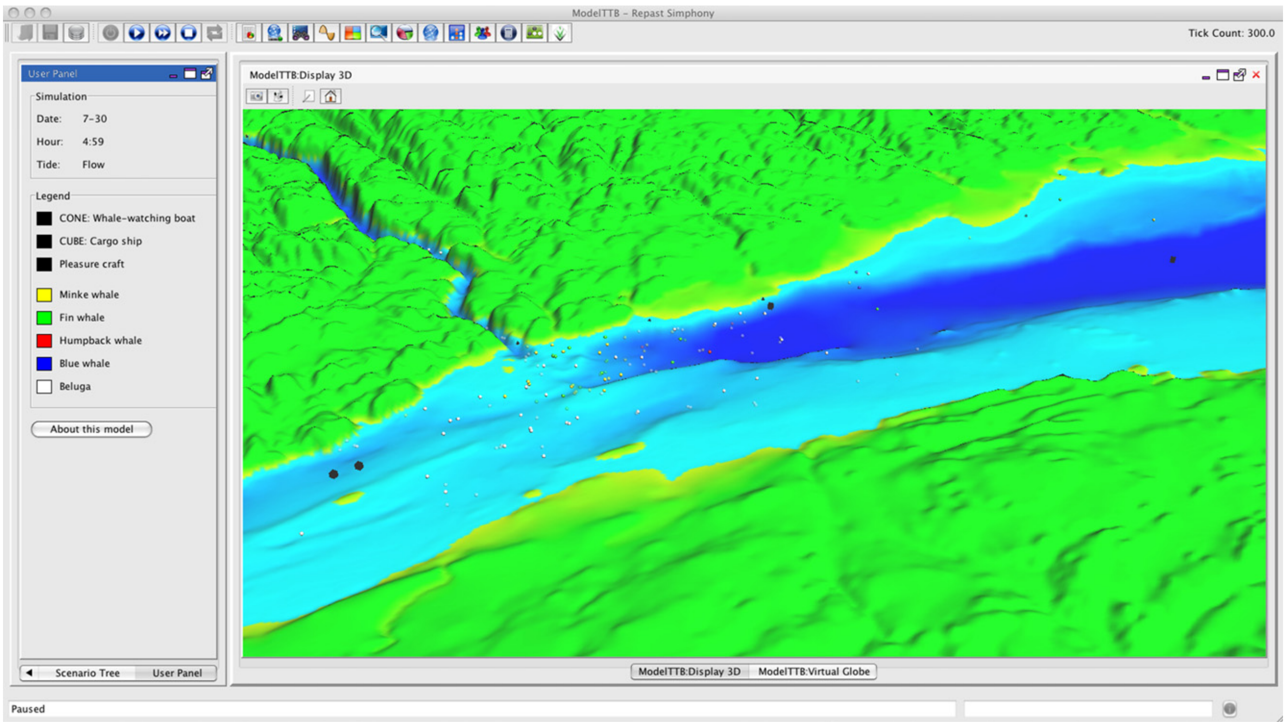

Fig. 3. 3MTSim 3D visualisation mode.

Table 2
Summary of 3MTSim parameters for simulations.

Parameter	Value	Comments
Whale species abundances	Minke whales: 47	Averages over (2005–2009)
	Fin whales: 23	
	Blue whales: {0; 3}	
	Humpback whales: 2	
	Beluga whales: 800	
Whale distribution	Species-dependent distribution maps	Averages over (1994–2008)
Blue whale presence	Presence: *With blue whales*	Likely to disperse boats from Les Escoumins and Bergeronnes when blue whales are in the region
	Absence: *No blue whale*	
Companies' schedule	Year 2007	Little inter-annual variation
Tourist season	Peak season (July 15th–August 15th)	Highest traffic level
Captain behaviour	Respectful of the regulations	Ideal case assuming a 100% efficient law enforcement
Whale-watching excursion homeports	Saint-Siméon, Tadoussac, Baie-Saint-Catherine, Bergeronnes, Les Escoumins, and Rivière-du-Loup (cf. Fig. 1)	All homeports offering excursions in the Marine Park
Fleet size	Forty-one whale-watching boats	Capacity: (7–800) passengers
Simulation duration	Eight simulated days	For each model replication, the first day is withdrawn from analysis to remove any model transient states
Number of replications	10	For each of the four configurations: • REG-2002, no blue whale • REG-2002, with blue whales • REG-2012, no blue whale • REG-2012, with blue whales
Untested rules	Rule #13	The whale model does not integrate whales' age and activity

Regarding marine mammals, the five most important species for whale-watching were instantiated in the model space according to a probability drawn from their spatial distribution. For each species, abundance and spatial distribution was averaged over years using available data (cf. Table 2). These parameters were fixed for a given simulation. However, two separate cases were distinguished regarding whether or not blue whales are in the region. The blue whale is an attractive species for whale-watching since it is the largest animal ever to exist on Earth and also because individuals of this endangered population are scarce. When present in the area, blue whales mostly congregate in the downstream part of the Marine Park, or outside it where the Fisheries Act [52] applies but does not prescribe distances to respect such as the rule #19 in the Marine Park (cf. Table 1). Their presence in this area is known to have an influence on the dispersion of whale-watching excursions since boats leaving from Les Escoumins and Bergeronnes ports (cf. Fig. 1) may decide to stay in this area instead of congregating with the large fleet from Tadoussac between Bergeronnes and Tadoussac where attractive humpback and fin whales are often observed [39]. Consequently, REG-2012 is assessed under two "whale contexts", namely the *With blue whales* and *No blue whale* contexts.

The year 2007 was chosen as a reference year for companies' daily departure schedules since the highest level of information on the whole system is available for that season. In fact, companies' schedules show only minor variations over the last few years.

The tourist season period must be fixed since it has an influence on the schedules of some companies as well as on tourist affluence. The number of small boats (<24 passengers) chartered by several companies is adjusted by owners to fit the tourist demand. During the peak of the tourist season from mid-July to mid-August, the number of boats at sea reaches its climax [36], making this period one of the most critical regarding companies' operations, level of marine mammals' exposure to boats, and the number of tourists involved. Consequently, the peak period of the tourist season was chosen for simulations.

Simulated captains in 3MTSim are programmed to comply with regulations. Indeed, what is assessed with 3MTSim is the impact of the proposed REG-2012 compared to REG-2002 and not the park wardens' ability to enforce it. Captain decision making processes are explicitly modelled in 3MTSim, with all details about the validation of their implemented behaviours given in [48].

In order to account for the variability induced by stochastic processes at play in 3MTSim (e.g., random number generation), 10 replications of each model configuration were run to assess the merits of the proposed REG-2012. As mentioned earlier, two cases were considered (i.e. whether or not blue whales are present in the area) combined with REG-2002 and REG-2012 for a total of four different configurations. Each of the 40 simulations lasted eight simulated days, with the first day systematically removed from analyses to eliminate the model's transient state.

Finally, belugas account for approximately 3% of all observations during the peak whale-watching period [50]. They are relatively small whales compared to rorquals and assuming that captains comply with the 400-meter distance imposed by the regulations (cf. model hypothesis in Table 2), observations would mostly be opportunistic. In a context where rorqual species are present in the area (cf. Table 2), the contribution of belugas to excursion observations would certainly fall below the current 3%. Therefore, belugas' contribution to observations is considered marginal for this study and were excluded. Running simulations for the early (May) or late (October) season, when other whale species are rarely present in the estuary, would not allow such a simplification.

3.3. Model output variables

Raw outputs returned by 3MTSim are mostly boat and whale agents' positions, attributes (e.g. boat speed, excursion activity, whale depth), and neighbourhood composition (e.g., number of whales by species, number of boats by category) at each time step. In order to compare REG-2012's merits to the current REG-2002, several composite variables were constructed from 3MTSim's raw outputs. These composite variables are proxies for one or several of the three spheres of sustainable development, namely Environment, Economy, and Society.

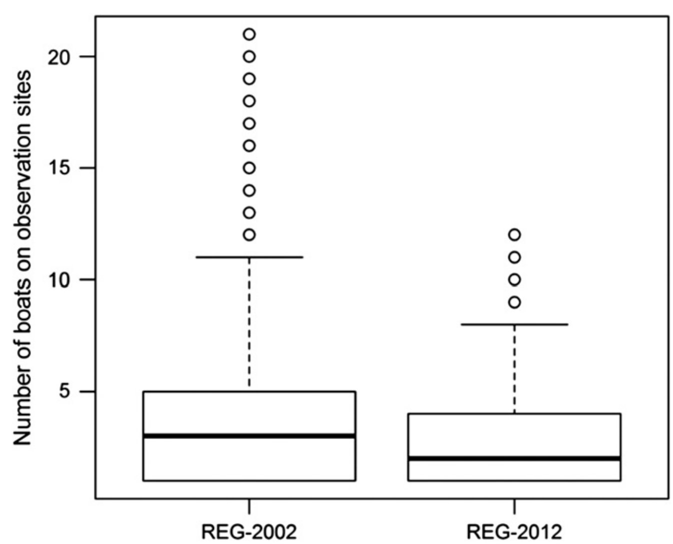

Fig. 4. Boxplots representing the number of excursion boats on observation sites.

Table 3
Expected trends from 3MTSim simulations relative to the enforcement of REG-2012 compared to REG-2002. "=" indicates no significant change; "☹" indicates a cost (i.e., deterioration of the situation); "☺" indicates a benefit (i.e., improvement of the situation); "na" means that the proxy variable is not applicable. "*" indicates that the amplitude of the change is greater than 10%.

Proxy variables	Three Spheres of Sustainability		
	Environment *Whale protection*	**Economy** *Whale-watching activities*	**Society** *Visitor experience*
Excursion success	na	☹	☹
Distance covered by excursions	na	=	na
Boat aggregations around whales (400 m and 1000 m)	☺*	☺*	☺*
"Alone with whales"	☺*	☺*	☺*
Total time of whale exposure to boats at 1000 m	☹*	na	na
Species contribution to observation activities	☺	na	na
Proportion of excursion duration observing whales	☺	☹	☺

All tests of statistical significance for similarity/difference between proxy variable distributions are conducted using the Kolmogorov–Smirnov test ($\alpha = 0.05$), referred to as KS-test in the rest of the paper.

3.3.1. Environment proxy variables

In the context of Marine Park management, environmental proxies were relative to whale exposure to whale-watching boats. The proxy output variables considered are (1) the number of boats on observation sites (i.e. in a 400-metre radius circle around the target animal), (2) the number of boats in observation zones (i.e. in a 2000-metre radius circle around the target animal), (3) the total duration of whale exposure to boats at 1000 m, and (4) the species contribution to observations made during excursions.

Large boat aggregations mostly occur around whales in *observation zones* and on *observation sites* [44] and have a negative impact on whale behaviours [53]. According to REG-2002 definitions [43], an *observation zone* is delimited by a 1-nautical mile radius circle (rounded to 2000 m in the analyses) around any boat in observation mode (i.e., observing a pod of marine mammals at a distance closer than 400 m). Additionally, in the model an *observation site* is defined as an area delimited by a 400-metre radius circle around a marine mammal currently observed by at least one boat, thus representing more accurately boat dynamics in the close vicinity of observed whales.

Even whales not targeted by observation activities may be exposed to whale-watching boats, thus subject to disturbance by

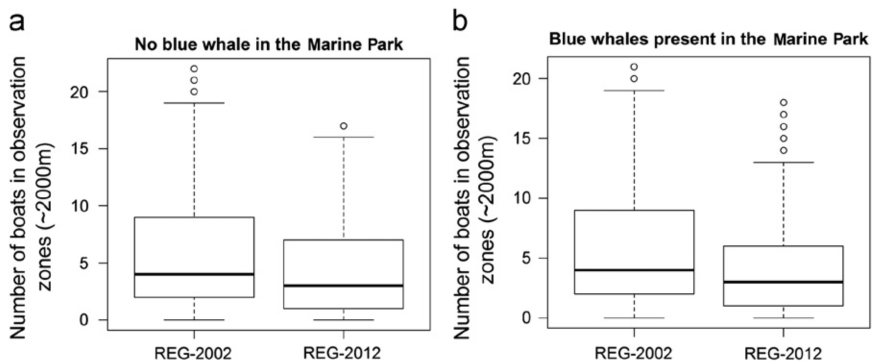

Fig. 5. Boxplots of the number of whale-watching boats in observation zones (~2000 m) in the (a) absence and (b) presence of blue whales.

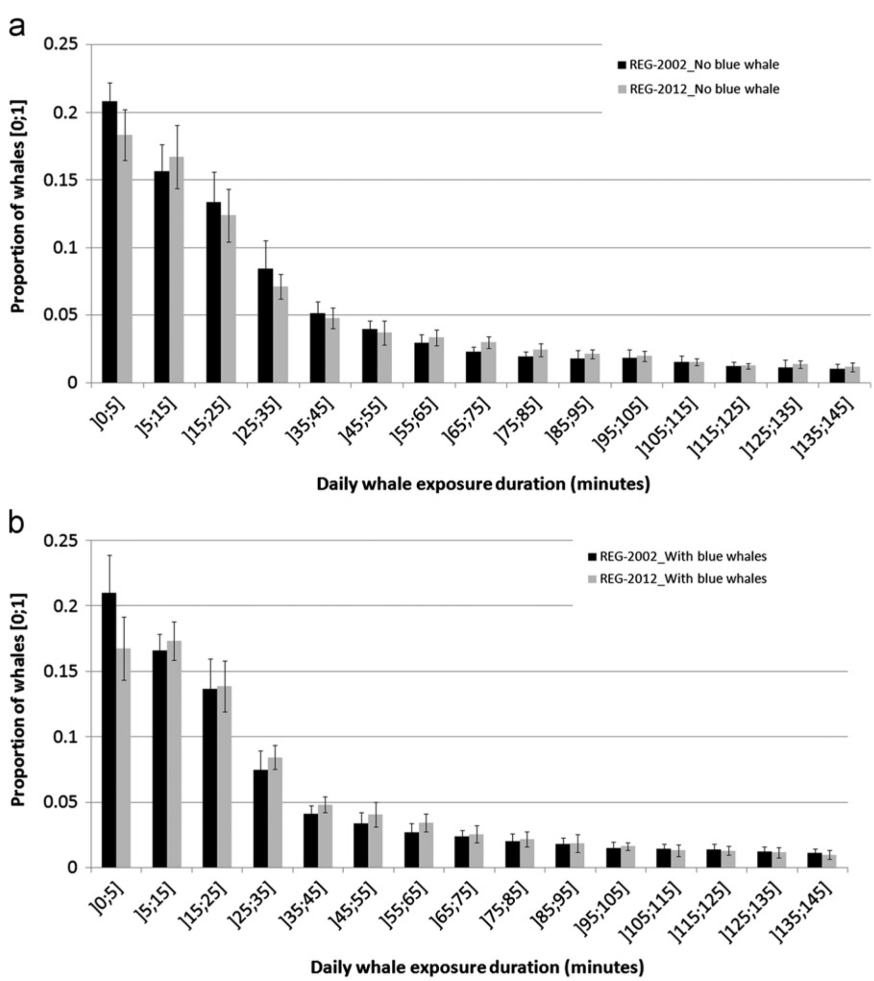

Fig. 6. Whale exposure to whale-watching boats at less than 1000 m in the (a) absence and (b) presence of blue whales.

engine noise and risks of collision. To gain insight into how whales present in the area are exposed, the cumulative duration all whales (all species combined) exposed to boats within 1000 m is computed. Finally, to get an insight into species-specific disturbance by observation activities, the contribution of each species to the cumulative budget of excursions' observation activities is assessed.

3.3.2. *Economy proxy variables*

Economy proxy variables are intended to measure any change in whale-watching activities that could be linked to the quality and interest of excursions themselves. The underlying assumption is that a decrease in excursion quality could result in a decrease in tourist affluence, potentially causing economic losses. Consequently, economic proxy variables mostly relate to the content of whale-watching excursions. The proxy variables considered were (1) distance covered by the excursion, (2) boat spatial distribution (core areas), and (3) excursion success.

For a given excursion, the distance covered to search for and observe whales is informative on the fuel consumption, a significant economic cost for whale-watching companies. The core area of boat spatial distributions gives insight into whether or not some proposed rules could force captains to modify their spatial coverage in a major way to make observations. Finally, an excursion is considered successful when at least one observation of a whale occurred. Since several companies have a reimbursement policy in case of empty-handed excursions, this variable is linked directly to excursion quality as well as potential economic costs for companies.

3.3.3. *Society proxy variables*

Social proxies that can be assessed using 3MTSim are relative to visitor experience onboard whale-watching boats. The proxy output variables considered were (1) the percentage of total excursion duration spent observing whales; (2) the percentage of observation time where the boat is alone with the target pod (i.e., wilderness experience); and (3) the success of whale-watching excursions (also defined in Economy proxy variables).

Time spent in observation can be linked to tourist satisfaction since observing whales is their fundamental expectation before getting onboard. Many tourists go whale-watching to experience wilderness. One way to achieve this experience is to make observations with no other boats in the vicinity of the target pod. Finally, the success of the excursion is also directly associated to tourist satisfaction.

Additionally, satisfied tourists on the way back from a quality excursion indirectly represent benefits for the whale-watching economy since they may convince undecided tourists to embark in upcoming excursions.

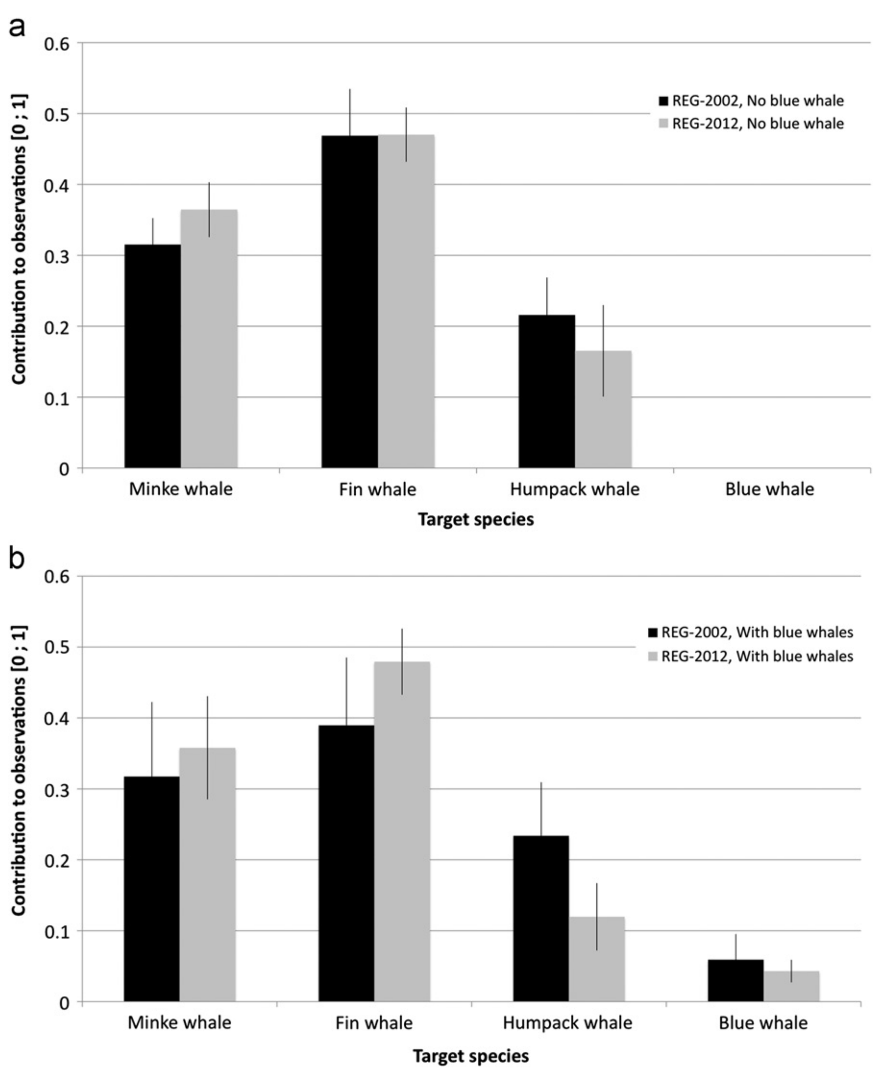

Fig. 7. Species contribution to observation activities in the (a) absence and (b) presence of blue whales.

4. Results and discussion

A synthetic qualitative analysis of the simulation results is presented in Table 3. If at least one proxy variable shows a statistically significant improvement or deterioration of the situation under REG-2012 compared to REG-2002, a benefit "☺" or cost "☹" symbol is respectively placed in Table 3 to reflect the change on the target sphere. If in addition to being significant, the difference along a proxy variable under REG-2012 is expected to be greater than 10%, a star "*" is added beside the arrow. These results are explored and discussed in more detail thereafter.

4.1. Impact on the three spheres of sustainable development

4.1.1. Environment: whale exposure

Boat aggregations: significant decrease: Both variables displayed a statistically significant decrease under the proposed REG-2012 compared to REG-2002 (cf. Figs. 4 and 5). This decrease is due to the proposed rule #11: By setting a maximum of 10 boats within observation zones, this prevents large boat aggregations.

Whale exposure: significant increase in total exposure duration: The number of whales exposed at least once a day to a boat at a distance of less than 1000 m is unchanged under REG-2012.

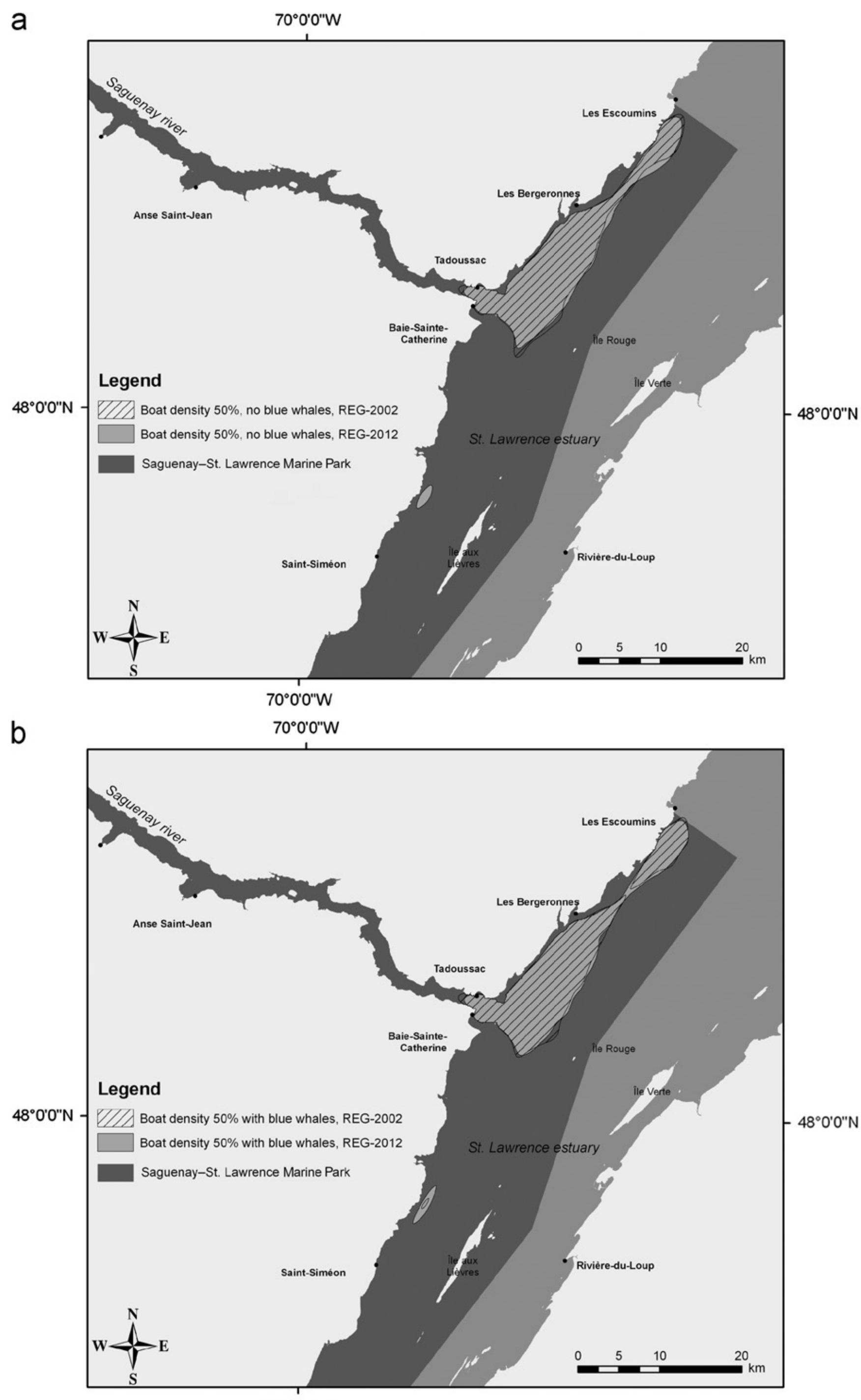

Fig. 8. Boat repartition (home range 50%) in the (a) absence and (b) presence of blue whales in the Marine Park area under REG-2002 and REG-2012 (each map).

However, histograms shown in Fig. 6 illustrate that exposures tend to last longer under REG-2012. This results in an increase in total duration of whale exposure (sum of all durations of whale exposures to boats) by 12% under REG-2012: This could be a result of REG-2012's rule #11 that limits the number of boats to 10 on an observation zone, forcing newcomers to observe other whales in the vicinity, whales that might have been left alone otherwise. This persistent pattern in model simulations sheds light on a management tradeoff: Reducing the number of boats around low-abundant rorqual species results in an increase in the total amount of time whales (all species combined) are exposed to boats in the Marine Park. By indirectly orienting whale-watching boats towards the most abundant species (i.e. fin and minke whales), the absolute amount of time whales are exposed to boats is expected to increase significantly under REG-2012.

Species contribution to observations: slight change (*cf.* Fig. 7): What is observed in general is that REG-2012 tends to reduce the contribution of scarce attractive whales in observations (i.e. humpback and blue whales), while the contribution of abundant species tends to increase (i.e. fin and minke whales). The rule #11, imposing a maximum number of 10 boats around observed whales, gets some captains to observe second choice whales. The probability of observing abundant species is high, explaining why the contributions of the most abundant fin and minke whales increase while those of low-abundant humpback and blue whales decrease (cf. Fig. 7). As a matter of fact, this increase in the pressure on individual whales from highly abundant species in the area is likely to reduce the pressure on low-abundant ones (as shown in Fig. 7). Regarding species at risk, REG-2012 might then help to enhance the protection of *endangered* blue whales but would not be of benefit to fin whales listed *of special concern* in the Species at Risk Act [34].

4.1.2. Economy: whale-watching activities

Distance covered by excursions: no overall difference: The distance covered by whale-watching excursions does not show any significant change whatever the management regime. These results indicate that there is no expected increase in fuel consumption owing to REG-2012. These results also suggest that speed limits proposed are not expected to be restrictive for companies. Whereas the mouth of the Saguenay River (an area of most intensive traffic within belugas' high residency area) is an obligatory passage for excursion boats from Tadoussac and Baie-Sainte-Catherine (cf. Fig. 1), a 15 knots speed limit in this relatively small region (rule #6) has virtually no impact on excursion dynamics as a whole. This area is known to be mostly a transit area for tourist boats between Tadoussac and Baie-Sainte-Catherine, and between the Saguenay River and the St. Lawrence Estuary. In the worst case, slowing down from the current limit of 25 knots to the proposed 15 knots, a boat transiting the area four times would add around 6 min considering an average 1-nautical mile distance per crossing. Considering that excursions last more than 2.5 h on average, the application of this rule for whale-watching companies would have a marginal impact on these excursion dynamics. Moreover, the current speed averaged by boats in the mouth of the Saguenay River is slightly over 15 knots, making rule #6 mainly a way to prevent occasional dangerously fast traffic, thus reducing risks of boat–whale collisions and enhancing safety amongst a variety of users (e.g., kayaks frequently using this area).

Spatial distribution: no overall difference: The spatial distribution of excursion boats is mostly driven by the location of past observation sites and by whales currently targeted. Consequently, after a few excursions the core areas visited by excursion boats tend to overlap the core home ranges of whale species. Whether or not blue whales are present in the Marine Park only slightly affects the average boat spatial distribution under both management regimes, as illustrated in Fig. 8.

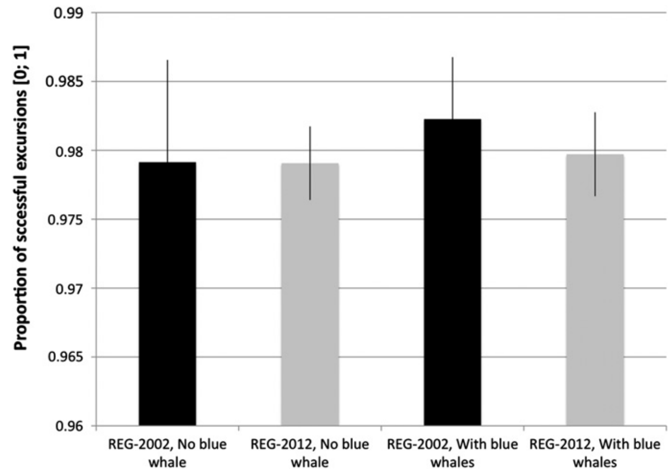

Fig. 9. Success of whale-watching excursions.

Excursion success: minor decrease: The proposed REG-2012 is expected to have only a minor impact on the capability of excursions to make observations (cf. Fig. 9). The only statistically significant difference at 95% is between *REG-2002 With blue whales* and *REG-2012 No blue whale* (KS-test, p-value$=$0.04677). Whale abundance may influence this result: In a context of whale scarcity, the rule #11 in REG-2012 could prevent some excursions from observing whales. In such critical contexts for the whale-watching industry, the 1-hour maximum observation duration (rule #15) could be lowered to 30 min to allow more excursions to have the chance of observing rare whales.

4.1.3. Society: tourist experience

Proportion of time spent in observation during excursions: slight decrease (*cf.* Fig. 10): A slight decrease in the total time spent in observation is obtained for simulations under the REG-2012 regime (cf. Fig. 10), but the only statistically significant difference at 95% is between *REG-2002 No blue* and *REG-2012 No blue* configurations (KS-test, p-value$=$0.03026), with an average 3% decrease. It should be noted that 3% of a 2.5-hour excursion represents 4.5 min, which is expected to be a marginal change for onboard tourists.

"Wilderness experience": significant improvement: Observation sites with only one whale-watching boat represent 26.6% of total observation time under REG-2002 versus 34.5% under REG-2012, suggesting an improvement for visitor experience (KS-test, p-value <0.0001). Here again, rule #11 is expected to force some captains to avoid overcrowded observation sites, thus creating opportunities for discovering new whales.

Excursion success: minor decrease: As described in the previous section, a marginal decrease can be expected regarding excursion success (cf. Fig. 9). Since most companies reimburse customers or offer them a free ticket in case of empty-handed excursions, given the low amplitude of the expected decrease in excursion success, tourist satisfaction should not be affected.

5. Conclusion

In this study, the dynamics of boat-based whale-watching excursions under two distinct management regimes using a spatially explicit ABM were simulated and compared. Under the assumptions listed in Table 2, 3MTSim simulations support that

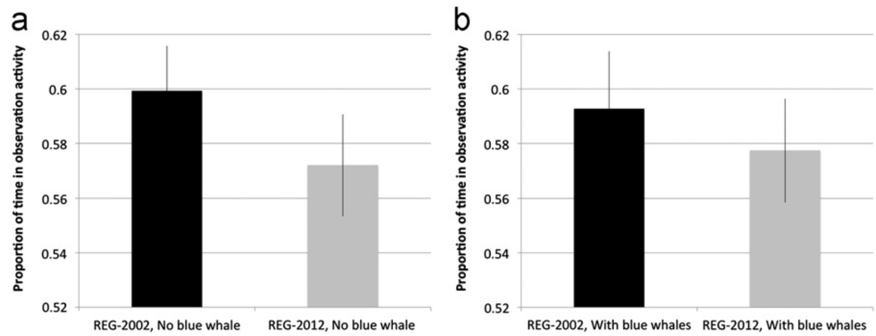

Fig. 10. Proportion observation activities in excursions, in the (a) absence and (b) presence of blue whales.

the proposed REG-2012 compared to the active REG-2002 is expected to bring benefits to some important aspects of whale conservation and visitor experience with no major costs on whale-watching operations. Of the rules assessed by 3MTSim, the most influential one proposed in REG-2012 is likely to be rule #11 which sets a maximum number of 10 boats in the vicinity of observed whales (cf. Table 1). Since reducing boat density around whales is an objective of park managers, the enforcement of this rule is likely to help in reaching management goals. Additionally, 3MTSim's simulations revealed that REG-2012's merits do not seem to be sensitive to the presence/absence of blue whales in the Marine Park. To go further into 3MTSim's use as an informative tool, it could be interesting to run simulations in different contexts (e.g., whale scarcity, off-peak tourist season, other policies) and explore additional proxy variables. For instance, the minimum distance and the maximum speed for close encounters could be an indicator of risks of boat–whale collisions. Scientific studies have demonstrated that short encounter distances and high boat speeds increase risks of collisions [54], whale death in case of collision [55], and animal changes of behaviours (e.g., [56,57]). From the standpoint of whale conservation, monitoring the evolution of these variables under various management regimes could add another piece of information relevant in Marine Park manager decisions.

Complex social–ecological systems such as the Marine Park whale-watching system are challenging to study and manage. ABM is a tool of choice to support these efforts insofar as quality data are available to characterise entities and processes driving the system's dynamics. In this paper, it was demonstrated that ABMs can provide quantitative support to managers dealing with such complex situations where their actions are expected to balance the three spheres of sustainable management. Unarguably, a hybrid approach involving ABM, spatial analysis, cartographic representations, and statistics can offer flexibility to analyse policies and derive results of interest for park managers. 3MTSim allowed to (1) regroup a large amount of knowledge and data in the same modelling environment, (2) shed light on important management tradeoffs by testing proposed rules, and (3) quantify some important phenomena hard to collect in the real system (e.g. whale exposure to boats). Although the building of a valid empirically based ABM is labour intensive, its benefits for management purposes are real and this project demonstrates that it deserves the investment. However, the true involvement of managers during the model's implementation and testing processes is a sine qua non condition for them to get the maximum benefit of it.

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