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Insights from agent-based modelling to simulate whale-watching tours

Influence of captains' strategy on whale exposure and excursion content

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Introduction

Multi-agent models can bear several names depending on the field they were initially developed in (e.g. agent-based model in social science, individual-based model in ecology). Agent- and individual-based models (ABMs and IBMs) are becoming tools of choice to simulate complex social–ecological systems (Gimblett, 2002; Janssen & Ostrom, 2006; Monticino *et al.*, 2007; Bennett & McGinnis, 2008). The recent development of dedicated programming platforms and libraries has also contributed to the expansion of multi-agent models coupled with geographic information systems (GIS) (Railsback *et al.*, 2006). Such models have been applied in a wide variety of natural resource management contexts where heterogeneous actors interact, including rangeland management in arid zones (Gross *et al.*, 2006), management of water use and access in river basins (Schlüter & Pahl-Wostl, 2007), control of irrigation channels (van Oel *et al.*, 2010), agriculture management (Manson, 2005), and forest clearing for agriculture (Moreno *et al.*, 2007). ABMs have also been used to support national parks and recreation areas' managers by simulating visitor movements to predict overcrowded areas along vehicular routes and hiking trails (Itami *et al.*, 2003), or along riverside rest areas and attraction sites for rafting trips on the Colorado River (Roberts *et al.*, 2002).

ABMs of social–ecological systems where natural resource management is at stake are frequently used to explore outcomes of *what-if* scenarios of policy rules (Gimblett *et al.*, 2002). Apart from testing policy rules, such models involving humans can also be used to explore the effects of alternative behaviours on the status of the natural resource. In this study, we developed a spatially explicit multi-agent model named 3MTSim (Marine Mammal and Maritime Traffic Simulator) to investigate whale-watching activities in the Saint-Lawrence Estuary and the Saguenay River, Québec, Canada (Parrott *et al.*, 2011). Whale-watching activities in this area have increased dramatically since the 1990s (Dionne, 2001), raising concerns about the impact of intensive navigation on targeted whale populations, some of which were, and still are, of special concern (COSEWIC, 2005), threatened (Demers *et al.*, 2011), or endangered (Beauchamp *et al.*, 2009) under the Species at Risk Act (2002, Canada). Public pressure on governments led to the creation of the Saguenay–Saint-Lawrence Marine Park (referred to as marine park later) in 1998 (Guénette & Alder, 2007) whose limits are shown in

Whale-watching: Sustainable Tourism and Ecological Management, eds J. Higham, L. Bejder and R. Williams.
Published by Cambridge University Press.

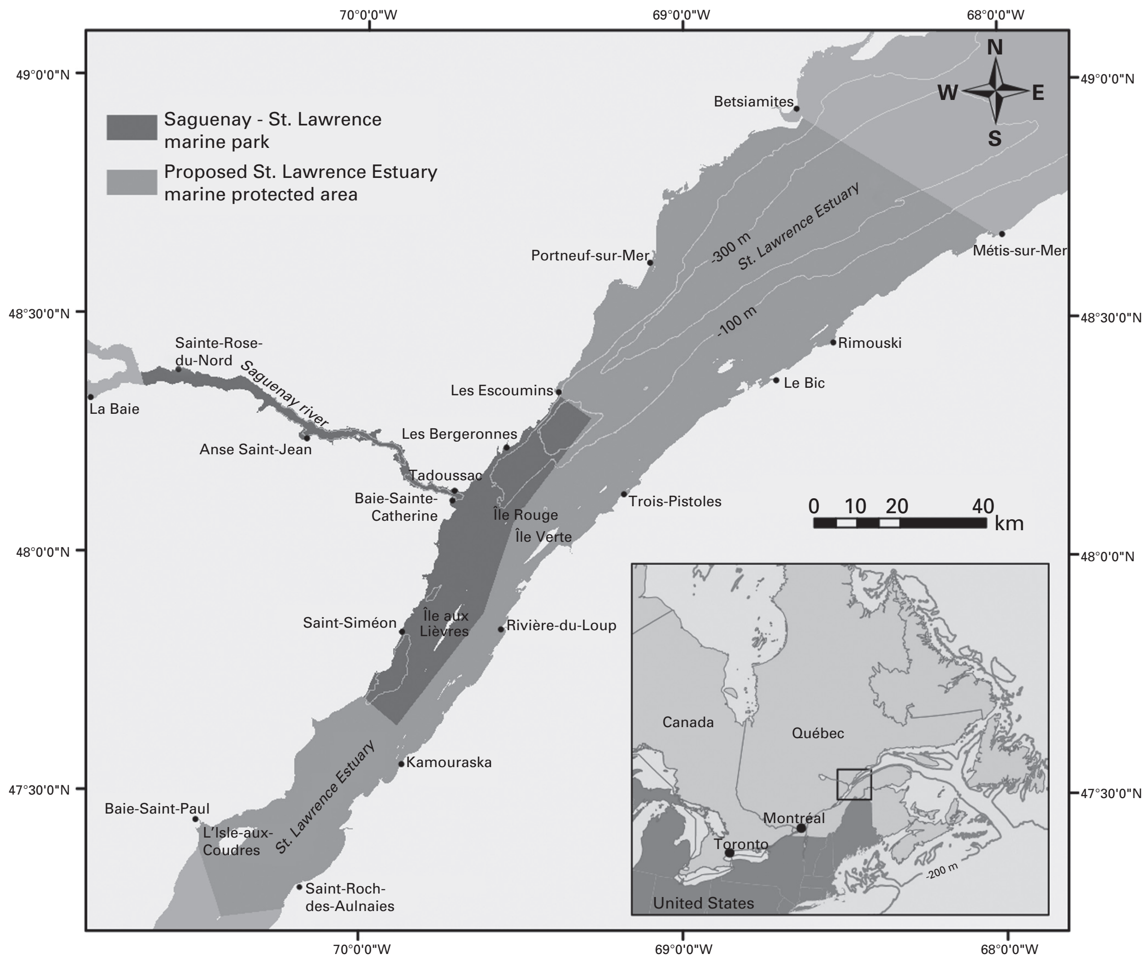

Figure 20.1 The study area encompassing the Saguenay–Saint-Lawrence Marine Park and the projected Saint-Lawrence Estuary marine protected area.

Figure 20.1. The implementation of regulations on marine activities followed in 2002 (Parks Canada, 2002), with law enforcement ensured by Parks Canada wardens. In addition to a series of rules regulating observation activities (e.g. maximum observation duration), the regulations also fixed a cap of 59 commercial permits for regular boats operating in the marine park (53 dedicated to whale-watching) (Parks Canada, 2002). Whale-watching activities in the marine park area rely on the relatively predictable presence of several whale species, five of which represent 98.5% of the total number of observations (Michaud *et al.*, 2008). In 2007, we estimated that approximately 13,000 commercial excursions went to sea, 80% of which were dedicated to whale-watching within the marine park (Chion *et al.*, 2009). The projected Saint Lawrence Estuary Marine Protected Area (MPA), proposed by Fisheries and Oceans Canada, is expected to extend the protection of marine ecosystems beyond the marine park limits (Figure 20.1). As whale-watching activities are significantly less dense and abundant

in the MPA than in the marine park, we decided to focus our study on excursions taking place in the marine park only.

3MTSim combines an ABM of navigation activities with an IBM of whale movements into a GIS-based representation of the geographic area. An asset of 3MTSim is that it allows the collection of exhaustive data of phenomena difficult or expensive to sample in the real system, such as the total amount of time each individual whale is exposed to observation boats. Major components of local marine activities are considered in 3MTSim with a special focus on whale-watching excursions. A great deal of effort was made to understand whale-watching captains' decision-making in order to reproduce realistically their behaviour in 3MTSim. Whale-watching excursions' data analysis and investigation of captains' decision-making processes through cognitive interviews revealed that they often favour *sure observations* of *potentially dramatic species* (Chion, 2011, chapters 3 and 4). Captains achieve *sure observations* mainly by exploiting the knowledge of current observations made by other whale-watching boats; a high level of cooperation at sea being the fundamental behavioural mechanism allowing the flow of information via the radio VHF communication channel. *Potentially dramatic species* are those well known for their spectacular displays (e.g. humpback whales' breaches or tail-slapping, fin whales hunting in large groups) or having notable characteristics (e.g. the blue whale is the largest animal ever on Earth; adult belugas are all white). Similarly, a vast collection of multi-platform observation data (enumerated later) was used to simulate the movements and distribution of whale species.

In this chapter, we investigate the effect of different captains' decision-making strategies on the exposure of targeted whales to observation vessels. Our investigation is aimed at demonstrating the feasibility of using an ABM for advisory purposes. After an overview of 3MTSim, we use the model to explore how alternative decision-making strategies, which could be suggested to whale-watching captains via a code of conduct or training sessions, might decrease whales' exposure to boats. We then discuss some lessons and insights that can be learned about the dynamics of whale-watching excursions using multi-agent modelling.

Overview of 3MTSim

3MTSim was developed as a decision-support tool for MPA managers. It integrates features dedicated to test the potential effects of alternative zoning and regulation plans (e.g. introducing speed limits, altering shipping routes, adding restricted access zones) on the patterns of traffic in and around the marine park and thus on the characteristics of whale–vessel encounters (e.g. rate, location). A description of the model and its functionalities is provided in Parrott *et al.* (2011).

The model combines a grid-based spatial environment (GIS) with an individual-based model of whale movements and an agent-based model of boats. During simulation runs, the movement of each individual whale and each boat is determined by algorithms and rules calibrated to reproduce observed patterns of behaviours (Grimm *et al.*, 2005). Simulations are run for short periods of time, based on realistic environmental conditions and known scenarios of whale abundances and patterns of habitat selection. The model time step currently used for simulations is one minute.

Spatial environment

The spatial environment of 3MTSim is represented by grid data (i.e. rasters) stored in an embedded GIS. The bathymetry is considered in the displacement and diving routines of whales, as well as for navigation. The state of the tide is modelled according to a simple daily cycle that selects the tide condition (flood, high, ebb and low tide) according to the date and time of day. While weather conditions are not explicitly modelled, visibility extent is represented by a single parameter for the whole area. This value remains constant for the duration of a simulation, mainly affecting whale-watching captains' ability to locate whales in their vicinity.

Whale individuals

The IBM of whale movements is described in detail in Lamontagne (2009). It includes the five most common species in the estuary: beluga (*Delphinapterus leucas*), minke (*Balaenoptera acutorostrata*), fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*) and blue whales (*Balaenoptera musculus*). Insufficient data were available on whales' food sources and on individuals' activity budgets, preventing any attempt to devise a behavioural model. Instead, whale movement patterns were extracted from:

- tracking VHF data: 80 tracks for more than 380 hours, for beluga (Lemieux Lefebvre, 2009), fin and blue whales (Giard & Michaud, 1997; Michaud & Giard, 1997, 1998); and
- land-based theodolite tracks of the four rorqual species: 140 focal follows with ~100 hours of tracking of individuals followed for more than 30 min (C.C.A. Martins, unpublished data).

Spatial distribution and aggregation patterns were derived from:

- sightings made from research vessels: ~550 baleen whales sightings from transect surveys (Group for Research and Education on Marine Mammals (GREMM), 2007); and
- sightings made from whale-watching vessels: 32,000 marine mammal sightings from more than 2100 sampled whale-watching excursions (Michaud *et al.*, 1997, 2008).

The model combines a simple diving routine with a displacement algorithm to determine each individual whale's depth, direction and speed at each model time step (i.e. 1 min). Diving and surface sequence durations are randomly selected from an empirically derived Weibull distribution computed for each species from land-based tracking data (Lamontagne, 2009). The diving routine uses a simple deterministic function to calculate the amount of remaining oxygen as a function of the whale's depth and diving time, thus forcing the whale to surface regularly for breathing. Several displacement algorithms were implemented and tested, starting from a simple random walk and increasing in complexity to include residence indexes (Turchin, 1998) and social interaction between whales (Couzin *et al.*, 2005). The ability of each algorithm to successfully match the (often conflicting) patterns for each species was assessed. The MMNB algorithm (minimization of the mean normalized bias), a modification of the correlated random walk (Turchin, 1998), proved the most successful at reproducing the desired patterns, and is currently implemented in the model. For each species, MMNB randomly selects an individual's speed and move duration from the empirical distribution and then adjusts the turning angle to reduce the normalized mean difference between the real and simulated group size (animal density within a 2 km radius), turning angle and spatial distribution patterns (Lamontagne, 2009).

Whale-watching boat captain agents

Whale-watching excursions are challenging to model. Their dynamics, driven by captains' decisions, is highly dependent on several factors, such as whales' spatiotemporal distribution, species' abundance, and contextual factors (e.g. regulations, current observations made by concurrent companies, companies' guidelines and directions). These boat captains are goal-oriented and have to find a way to achieve their goal in a dynamic environment. Interviews with boat captains and marine park wardens conducted after excursions at sea, as well as VHF radio monitoring, revealed a number of attributes of their decision-making, that were included in the model. In particular, whale-watching boat captains: (1) take advantage of information on the most recent observations to explore space when no other information is available; (2) share information about whale locations; (3)

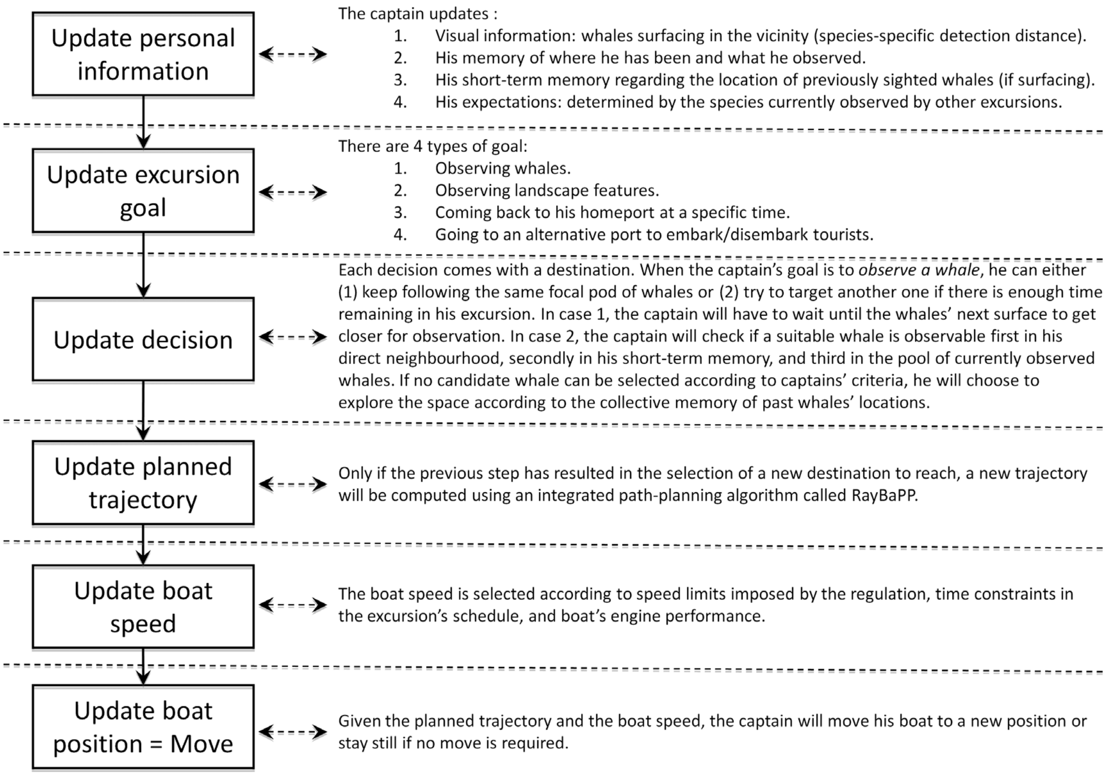

Figure 20.2 Sequence of actions (from top to bottom) that each captain agent goes through at each time step during the simulation.

give priority to more dramatic species such as the humpback whale; (4) try to adjust the content of their excursion according to that of their direct competitors; and (5) must respect navigational limits related to currents and bathymetry. In the model, at each time step the virtual captain agents follow a series of steps from information acquisition to movement execution (Figure 20.2).

A whale-watching captain's main objective is to observe whales during an excursion (although some also have subobjectives related to sightseeing, for example). In the model, excursions leave port according to planned schedules. Captains navigate using a path-planning algorithm to select the shortest path to their destination. Captains choose which whale to observe using a cognitive heuristic decision-making module (Chion *et al.*, 2011) according to their preferences and constraints. The captains must make use of existing information (either from current data on whale locations if available, or retrieving from the memory of previous excursions' observations) to select where to navigate their excursion to observe whales. This type of decision is quick, based on limited information, with no optimal universal solution, and is repeated several times during an excursion. We assume, therefore, that the captains are operating in a context of bounded rationality, where they will select what appears to be the best choice given currently available information and the contextual setting both in time (e.g. what species they have already observed during the excursion will affect their choice of the next pod to target) and in space. The validation of the whale-watching vessel captain model is described in further detail in Chion *et al.* (2011).

Other whale-watching captains' cognitive and sensory capabilities are implemented within the model. Past observations are aggregated in a collective spatial memory according to a simple clustering algorithm that groups those past observations in clusters where the maximum pairwise distance does not exceed the visibility extent. This approach was chosen to represent the way captains aggregate past unique observations in broader regions where the action took place, rather than in precise locations where each given observation occurred. The distance of whale detection by a captain's visual module is species-dependent. For each species, the detection distance was calibrated using the knowledge of observers working at counting whales on the Saint-Lawrence during sea-based transects.

Methods

Rules considered by whale-watching captains to choose a whale to observe

Our investigation of whale-watching captains' decision-making revealed several notable characteristics and mechanisms which were subsequently implemented within the model (Figure 20.2). The following decision rules were elicited from field work mainly consisting of (1) seven semi-structured interviews (~10 hours) conducted with whale-watching captains after an excursion, (2) 15 hours of VHF radio monitoring, and (3) observations made during 30 excursions onboard all boats and ports in the marine park area. Extracted decision rules serve as the reference model for whale-watching captains' decision-making about which pod to target for observation. Within the sequence of actions detailed in Figure 20.2, these rules intervene at the step 'update decision', when the goal is 'observing whales' and a new pod of whales has to be targeted among a set of candidate animals. Given a set of candidate whales, the captain agent jumps to the next rule until only one whale remains in the list. Rules are ranked as follows.

1. Captains try to find species that are not currently observed by any captain at sea. If such a species appears opportunistically in their surroundings, the captain will target it. This will give him/her an edge over the competition.
2. Captains favour species not already observed in their own excursion that have been observed in other excursions.
3. Captains prioritize the whales belonging to the overall top-ranking species in their decision (i.e. humpback, fin and blue whales). In fact, species' attractiveness is not the same for all species. When present in the area, data from sampled excursions show that humpback whales are responsible for the largest aggregations of boats followed by the fin, blue, minke and beluga whales (all pairwise differences statistically significant). Several characteristics have an impact on species' attractiveness, such as their potential spectacular displays, ease of observation (no fleeing behaviour), predictability of individual distribution, core habitat areas (e.g. proximity from departure ports), abundance, and species-specific regulations.
4. Captains prefer whales that are about to be lost from the pool of discovered ones (i.e. no boat observing them anymore). This is all the more true for individuals from species standing high in the preference ranking such as humpback whales.
5. The next criterion is the preference for whales with the lowest number of boats in their surroundings. Some captains, often those with more experience, give a higher priority to non-crowded sites.
6. Captains favour observations allowing subsequent observations in the area. This ability to anticipate and build an excursion in advance and adjust it as a function of upcoming information is expected to be more prevalent with experienced captains.

7. In case of a tie between candidate whales, captains will break the tie by choosing the closest whale.

We followed a naturalistic decision-making approach to investigate captains' decisions in action (Klein *et al.*, 1989; Klein, 2008) and modelled it following the bounded rationality framework (Simon, 1957; Gigerenzer & Selten, 2001). Being aware that all captains neither have the same experience nor the same values, using a single model to represent all captains' decision processes is a current limitation of the model. However, the validation process proved that this approach allowed the faithful reproduction of some key individual (total length, activity budget and contribution of species in observations) and collective (core areas of activity and boat aggregations) patterns of excursions (Chion *et al.*, 2011). This suggests that from the collective perspective, which is of particular interest, individual differences have a less critical influence on the global dynamics than individual similarities (e.g. overall preference ranking for given species) and shared collective mechanisms (e.g. cooperation via communication, prevalence of knowledge exploitation over space exploration).

The rules described above were implemented as cues within the *take-the-best* heuristic structure (Gigerenzer & Goldstein, 1996) that has proved to best reproduce excursion patterns (Chion *et al.*, 2011) among several cognitive heuristics taken from the bounded rationality literature (Gigerenzer & Selten, 2001). The prevalence of a non-compensatory heuristic such as *take-the-best* over compensatory ones (e.g. tallying) supports the fact that whales' characteristics do not have the same importance in captains' decisions.

Alternative decision-making strategies

To study how the decision-making process of captains can influence the dynamics of whale-watching excursions and ultimately affect the global dynamics of the system, we implemented two alternative decision-making strategies in 3MTSim that virtual captains follow when deciding which whale to observe. Our objective was to foresee how such alternative behaviours could affect both whales' exposure and excursions' dynamics and content. This type of application could lead to a series of recommendations passed on to captains during seasonal training sessions. The simulations run with each alternative decision-making model (DMM) aimed at demonstrating the feasibility of such a utilization of ABM for advisory purposes.

We present hereafter the two simple alternative DMMs that were implemented and tested within 3MTSim. Rules contained within these two alternative models were implemented within the *take-the-best* heuristic structure. The alternatives were expected to mitigate whales' exposure without significantly affecting observation activities (e.g. time spent in observation).

Preference for less-crowded observation sites (DMM-1)

The idea of this DMM is to favour whales with fewer boats in observation. Taking into account this criterion in the process of selecting whales to observe is expected to decrease the aggregation of boats on observation sites, which is a goal pursued by the marine park managers regarding the management of whale-watching activities. Captains using this decision strategy will apply decision rules in the following order.

1. Captains try to find species that are not currently observed by any captain at sea. If such a species is visible in their surroundings, it will be targeted.
2. Captains favour species not already observed in their own excursion.
3. Captains will pick the observation site with the fewest boats on it, with a coordination mechanism allowing captains to account for others' intentions (i.e. captains heading to observe a whale but not currently observing it).
4. In case of a tie, captains will choose the closest site regardless of species.

No preference ranking of whale species (DMM-2)

This DMM gives the same weight (i.e. importance) to all species in captains' selection process of which pod of whales to target. The idea to test this DMM comes from an issue noticed repeatedly in the past, when some whales belonging to scarce species attract numerous boats in their vicinity, via a domino effect. Captains using this decision-making module will apply the following rules.

1. Captains try to find species that are not currently observed by any captain at sea. If such a species appears in their surroundings, it will be targeted.
2. Captains favour species not already observed in their own excursion.
3. Captains will not ground their decision based on a species preference ranking.
4. In case of a tie, captains will pick the closest whale between remaining candidates.

Design of experiment and simulation parameters

For the reference model and both alternative DMMs described above, we ran 10 replications of a one-week simulation. We fixed the number of runs to 10 by monitoring the inter-run variability.

The data from the first day of each simulation (transient state) were systematically discarded to keep only the model's steady state. The visibility parameter was set to 4 km for all simulations. The period of the year simulated is the peak tourist season (between mid-July and mid-August); this is the most critical time of the year in terms of the number of boats at sea. Excursion schedules and zodiac departures reach a peak at this time of the year in response to the maximum tourism demand.

All simulations were run with the same whale species' abundance and spatial distribution settings (Table 20.1). Except for belugas, abundances were selected to reflect the approximate proportion of each species compared to the others, as observed during recent seasons. For belugas, because they are often excluded from observation activities due to the minimum observation distance restriction (400 m), we lowered their number (from ~1000 in the real system to 100) to speed up simulations.

Table 20.1 Whale species' setting used for simulations.

Species	Abundance	Years of spatial distribution data used
Minke	40	2007
Fin	20	2007
Blue	3	2007
Humpback	3	2007
Beluga	100	1994–2007

Output variables observed

In order to assess the impact of a given DMM strategy on the system, we observed several variables returned by the model. We distinguish variables characterizing the impact on whales' exposure from those impacting excursions' dynamics.

Variables characterizing whales' exposure to whale-watching boats

We chose four variables to characterize whale exposure to observation boats. We made the distinction between individuals, species and overall exposure.

- Exposure of individual whales.
- *Percentage of individual whales observed.* This variable provides insight on the proportion of individual whales that have been exposed to observation activities.
- *Duration of continuous sequences of observation.* This variable allows monitoring the duration of the continuous sequences of observation that animals are subject to. For instance, if two boats observe the same whale during 30 min successively (the first boat leaving when the

second arrives), the duration of the continuous observation sequence will be 60 min.

- Exposure of species.
- *Species' contribution to observation activities.* This variable tells us the contribution of each species to the budget of all whale-watching activities.
- Overall exposure of whales present in the area.
- *Time spent in observation activity.* This variable allows computing the total time whale-watching boats have been observing whales.

We are aware that some of these variables should be regarded cautiously as the level of knowledge introduced in the model may affect their accuracy. For instance, the percentage of individuals observed partially depends on the spatial location of individual whales; however, in reality some specific individuals may display some site fidelity, which is not fully known or modelled within 3MTSim.

Variables characterizing excursions' dynamics

Modifying a captain's strategy affects excursions' dynamics. We monitor changes by recording and analysing the following variables.

- *Success of the excursions.* This variable informs us about the percentage of excursions that made at least one observation during the outing.
- *Time spent in observation activity* (cf. description above).
- *Proportion of time boats are alone with the targeted pod.* This variable is an indicator of the quality of observations. Because the large number of boats at sea is one of the top-most sources of concern about whales' protection and the most negative element experienced by whale-watching tourists during their excursion (see Giroul *et al.*, 2000: 53–54), it can be reasonably inferred that decreasing boat concentrations would contribute to the enhancement of the visitors' experience.
- *Boat aggregations around observed pods of whales.* This is a critical variable for managers who wish to decrease boat aggregations at sea, known to modify whale behaviour (Michaud & Giard, 1997, 1998).

Table 20.2 Increase in the total number of individual whales observed each simulated day for both alternative DMM in comparison to the reference model.

DMM-1 (compared to reference)	DMM-2 (compared to reference)
+15%	+1.5%

More variables could be added to this analysis framework. However, the set of variables presented above are intended to give an insight into 3MTSim's capability to monitor effects induced by captains' changes of behaviour.

Results and discussion

We now present and discuss the simulation results for both alternative models (DMM-1 and DMM-2) and compare them to the reference model's outputs characterizing the current situation at sea.

Whale exposure

Simulations revealed that DMM-1 and DMM-2 both increase the total number of individual whales observed during a day compared to the current situation (modelled by the reference DMM). The strategy where captains favour observation sites with fewer boats leads to a 15% increase in the number of individuals observed, whereas the strategy where no preference ranking of species exists leads to a 1.5% increase in the number of observed individuals (Table 20.2). These relative increases are significant with both p-values < 0.01 (Wilcoxon rank sum test).

We compared the distributions of the duration of observation sequences produced by DMM-1 and DMM-2 (cf. Figure 20.3). Neither DMM-1 nor DMM-2 affected this metric significantly compared to the reference model (Wilcoxon rank sum test). This is a consistent result because the rule that controls the decision to leave the observation site remained the same for all tested models (a

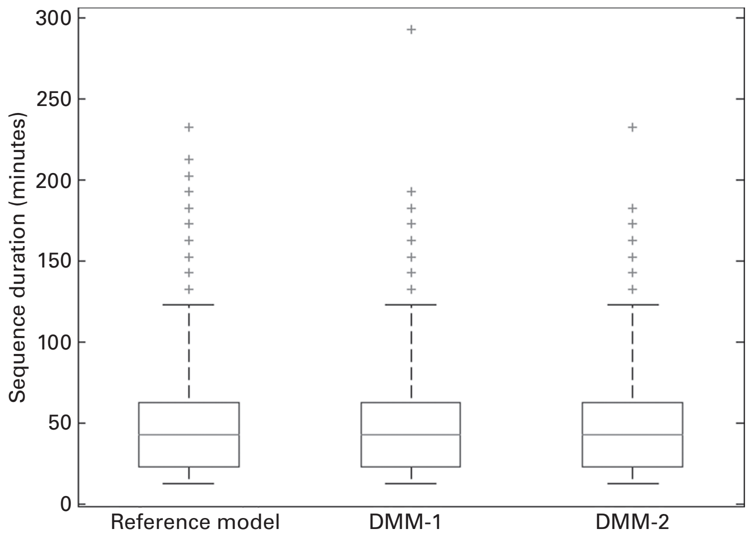

Figure 20.3 Boxplots of observation sequence durations for the three tested DMMs. No statistical difference was noticed between the distributions.

function of the number of the targeted whale's surfaces observed, the maximum time allowed by the marine park regulations for observing the same pod, the presence of other whales observable in the vicinity, and the remaining time in the excursion).

Several ways could be envisioned to reduce the duration of observation sequences in the real system: giving incentives to explore space to search for new whales instead of taking advantage of discovered whales; reducing the maximum authorized time in observation of the same pod (currently 60 min); or giving incentives to diversify activities at sea leading to more time spent discovering landscape features (e.g. lighthouses, sand dunes). Such strategies could be tested in the model to predict the effects on the duration of observation sequences.

Table 20.3 shows the repartition of observation effort on the four rorqual species. Both DMM-1 and DMM-2 led to a significant reduction of the proportion of time devoted to humpback whales observation. Attractiveness of this species is particularly high in the area for several reasons including its occasional spectacular behaviours, stability of individual locations, and core habitat located in the vicinity of the busiest ports of excursion departure. In contrast, despite having the same abundance across simulation runs (3), blue whales always account for a smaller part of observations, especially because their home-range is located more downstream, farther from the most active homeports.

Table 20.3 Contribution of each species to overall observation activities (%).

	Minke whale	Fin whale	Blue whale	Humpback whale
Reference model	32.8	31.1	4.0	32.1
DMM-1	44.3	35.9	3.9	15.9
DMM-2	34.4	37.7	8.2	19.7

Excursion dynamics

The percentage of unsuccessful excursions (i.e. no whale observation) is similar for all tested models at approximately 3%. Again, this is consistent because

Table 20.4 Average and standard deviation of proportion of time spent in observation during excursions (%).

Reference model	DMM-1	DMM-2
49.4 ± 1.6	54.1 ± 0.8	53.0 ± 2.1

Table 20.5 Proportion of the total observation time an excursion is alone (1) or with another boat (2) observing a pod (%).

	Reference model	DMM-1	DMM-2
1. Alone with the pod	26.3	32.2	25.7
2. Two boats observing the same pod	22.8	27.7	23.6
Sum (1+2)	49.1	59.9	49.3

for all simulations captains favour (when possible) the exploitation of discovered whales rather than the more risky exploration of space. Consequently the success rate is not affected. Conversely, we found a slight change in the total amount of observation activities. Both DMM-1 and DMM-2 strategies lead to more observations than the reference model (Table 20.4).

The increase in time spent in observation is due to the fact that captains promote opportunistic observations for both DMM-1 and DMM-2. In the case of DMM-1, this is due to the fact that a whale surfacing opportunistically in the vicinity can be the best choice because there is no boat observing it. In the case of DMM-2, as the species is no longer a criterion for whale selection, whales surfacing in the vicinity of a boat will have more chance to be selected for observation. Observing close whales opportunistically reduces the travel time needed to reach a more distant site, thus explaining the increase in observation activities.

Reducing boat aggregations around pods of whales is positive both for whales and visitors' experience. Table 20.5 shows the proportion of time one or two boats are simultaneously observing the same pod. As expected, using the DMM-1 strategy, captains significantly increase by ~11% the proportion of time they spend alone or with only another boat observing a pod when compared to the reference model. In contrast, DMM-2 does not significantly affect those variables. Let us point out that these figures take into account all excursions in a day, including early and late excursions where most observations occur alone as few boats are at sea at these times (compared to busier midday schedules).

Figure 20.4 shows the boxplots of the boat number distributions on observation sites. Only DMM-1 significantly reduces boat densities around whales, including median and maxima (Wilcoxon rank sum test).

Conclusion

Our goal was to provide insights on the use of multi-agent modelling to better understand the nature of interactions between whale-watching excursions and whales. 3MTSim is a spatially explicit multi-agent model representing whale movements and navigation activities within the Saint-Lawrence Estuary, Québec, Canada. This model was primarily developed to test alternative navigation-related management scenarios, including whale-watching activities. Because the whale-watching captains' decision process was modelled in detail, 3MTSim can also be used to predict outcomes from changes in captains' strategies to locate and observe whales, which was presented here.

Currently, whale-watching captains mostly ground their decisions of which whale to observe based on species, proximity, and competitor excursions' content. We demonstrated that prioritizing other criteria such as low aggregations of boats could help to decrease the overall density of boats in the vicinity of whales, without affecting important excursions' performance (e.g. time spent in observation). Additional decision strategies, not simulated, could also improve the situation at sea. For instance, captains could engage in more space *exploration* (as opposed to the currently widespread

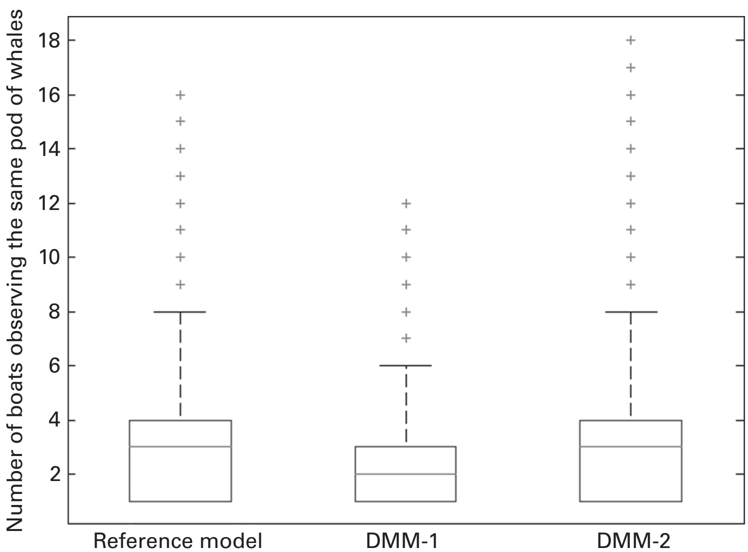

Figure 20.4 Boxplots representing the number of boats on observation sites for each tested DMM.

exploitation of discovered whales) or could systematically present some landscape or historical features (e.g. lighthouses, sand dunes) as part of their excursion instead of focusing exclusively on whale observation.

By simulating alternative decision strategies that could be followed by whale-watching captains, it is possible to devise a set of recommendations that marine park managers could communicate to captains during training sessions. As a decision-support tool, 3MTSim has the advantage of being able to illustrate the whole picture of the collective impact of navigation, including whale-watching activities, on whales. An appreciation of their collective impact on targeted whales was particularly absent from captains' discourses during interviews, 3MTSim could therefore help in raising further awareness about this issue. As new knowledge about the system's dynamics will become available, it will be possible to integrate it in 3MTSim. Expected model improvements include the implementation of noise emission by boats along with 3D propagation in the area, whales' reaction to the presence of boats, and captains' individual differences (e.g. values, preferences). This way, additional model output variables could be accounted for to achieve a more complete impact analysis (e.g. spatial variations of boat–whale co-occurrences, whales' cumulative exposure to noise sources).

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REFERENCES

Beauchamp, J., Bouchard, H., de Margerie, P., Otis, N. & Savaria, J.-Y. (2009). Recovery strategy for the blue whale

(Balaenoptera musculus), Northwest Atlantic population, in Canada [FINAL]. Ottawa: Fisheries and Oceans Canada, 62 pp.

Bennett, D.A. & McGinnis, D. (2008). Coupled and complex: Human–environment interaction in the Greater Yellowstone Ecosystem, USA. *Geoforum* 39, 833–845.

Chion, C. (2011). An agent-based model for the sustainable management of navigation activities in the Saint Lawrence estuary. PhD Thesis, École de technologie supérieure.

Chion, C., Turgeon, S., Michaud, R., Landry, J.-A. & Parrott, L. (2009). Portrait de la Navigation dans le Parc Marin du Saguenay–Saint-Laurent. Caractérisation des activités sans prélèvement de ressources entre le 1er mai et le 31 octobre 2007. Report presented to Parks Canada. Montréal: École de technologie supérieure and Université de Montréal, 86 pp.

Chion, C., Lamontagne, P., Turgeon, S., *et al.* (2011). Eliciting cognitive processes underlying patterns of human–wildlife interactions for agent-based modelling. *Ecological Modelling* 222(14), 2213–2226.

COSEWIC (2005). COSEWIC assessment and update status report on the fin whale *Balaenoptera physalus* in Canada. Ottawa: Committee on the Status of Endangered Wildlife in Canada, ix + 37 pp.

Couzin, I.D., Krause, J., Franks, N.R. & Levin, S.A. (2005). Effective leadership and decision-making in animal groups on the move. *Nature* 433(7025), 513–516.

Demers, A., Bouchard, H. & Beauchamp, J. (2011). Recovery strategy for the beluga (*Delphinapterus leucas*), St. Lawrence Estuary population, in Canada [PROPOSED]. Ottawa: Fisheries and Oceans Canada, 88 + X pp.

Dionne, S. (2001). Saguenay–St. Lawrence Marine Park Ecosystem Conservation Plan Summary. Quebec: Parks Canada.

Giard, J. & Michaud, R. (1997). L'observation des rorquals sous surveillance par la telemetrie VHF. *Le Naturaliste Canadien* 121, 25–29.

Gigerenzer, G. & Goldstein, D.G. (1996). Reasoning the fast and frugal way: Models of bounded rationality. *Psychological Review* 103(4), 650–669.

Gigerenzer, G. & Selten, R. (2001). *Bounded Rationality: The adaptive toolbox*. Cambridge, MA: The MIT Press.

Gimblett, H.R. (2002). *Integrating Geographic Information Systems and Agent-Based Modeling Techniques for Simulating Social and Ecological Processes*. Santa Fe, NM: Oxford University Press.

Gimblett, H.R., Richards, M.T. & Itami, B. (2002). Simulating wildland recreation use and conflicting spatial interactions using rule-driven intelligent agents. In *Integrating Geographic Information Systems and Agent-based Modeling Techniques for Simulating Social Ecological Processes*. Santa Fe, NM: Oxford University Press, pp. 211–243.

Giroul, C., Ouellet, G. & Soubrier, R. (2000). Étude des attentes de la clientèle des croisières aux baleines dans le secteur du parc marin du Saguenay–Saint-Laurent: Faits saillants. Presented to Parks Canada. Université du Québec à Trois-Rivières, 56 pp.

Grimm, V., Revilla, E., Berger, U., *et al.* (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science* 310, 987–991.

Gross, J., McAllister, R., Abel, N., Smith, D. & Maru, Y. (2006). Australian rangelands as complex adaptive systems: A conceptual model and preliminary results. *Environmental Modelling & Software* 21, 1264–1272.

Groupe de recherche et d'éducation sur les mammifères marins (GREMM) (2007). Recensement visuel et photographique systématique des grands rorquals dans le parc marin du Saguenay–Saint-Laurent – Projet pilote 2006. Final report presented to Parks Canada. Tadoussac (Qc), Canada.

Guénette, S. & Alder, J. (2007). Lessons from marine protected areas and integrated ocean management initiatives in Canada. *Coastal Management* 35, 51–78.

Itami, R., Raulings, R., MacLaren, G., *et al.* (2003). RBSim 2: Simulating the complex interactions between human movement and outdoor recreation environment. *Journal for Nature Conservation* 11, 278–286.

Janssen, M.A. & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society* 11(2), 37.

Klein, G.A. (2008). Naturalistic decision making. *Human Factors* 50(3), 456–460.

Klein, G.A., Calderwood, R. & MacGregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions of Systems, Man and Cybernetics* 19(3), 462–472.

Lamontagne, P. (2009). Modélisation spatio-temporelle orientée par patrons avec une approche basée sur individus. Master in Engineering, École de technologie supérieure.

Lemieux Lefebvre, S. (2009). Déplacements et patrons de résidence chez la population de bélugas (*Delphinapterus leucas*) de l'estuaire du St-Laurent. Master, Université du Québec à Rimouski.

Manson, S.M. (2005). Agent-based modeling and genetic programming for modeling land change in the Southern Yucatan Peninsular Region of Mexico. *Agriculture Ecosystems & Environment* 111, 47–62.

Michaud, R. & Giard, J. (1997). Les rorquals communs et les activités d'observation en mer dans l'estuaire du Saint-Laurent entre 1994 et 1996: 1) Étude de l'utilisation du territoire et évaluation de l'exposition aux activités d'observation à l'aide de la télémétrie VHF. Joint project from the GREMM, ministère de l'Environnement et Faune du Québec, Fisheries and Oceans Canada, Heritage Canada, and Parks Canada. Group for Research and Education on Marine Mammals (GREMM), Tadoussac (Qc), Canada. 30 pp.

Michaud, R. and Giard, J. (1998). Les rorquals communs et les activités d'observation en mer dans l'estuaire maritime du Saint-Laurent entre 1994 et 1996: 2) Évaluation de l'impact des activités d'observation en mer sur le comportement des rorquals communs. Joint project from the GREMM, ministère de l'Environnement et Faune du Québec, Fisheries and Oceans Canada, Heritage Canada, and Parks Canada. Group for Research and Education on Marine Mammals (GREMM), Tadoussac (Qc), Canada. 22 pp.

Michaud, R., Bédard, C., Mingelbier, M. & Gilbert, M.-C. (1997). Whale watching activities at sea in the St. Lawrence marine estuary, 1985–1996: A study of spatial distribution of activities and factors favouring boat aggregation at whale watching sites. Final report submitted to Parks Canada. Le Groupe de Recherche et d'Éducation sur les Mammifères Marins, GREMM, Tadoussac, Québec, Canada.

Michaud, R., D'Arcy, M.-H., de la Chenelière, V. & Moisan, M. (2008). Les activités d'observation en mer (AOM) dans l'estuaire du Saint-Laurent: Zone de Protection Marine Estuaire du Saint-Laurent et Parc Marin du Saguenay–Saint-Laurent – Suivi annuel 2007. Final report submitted to Parks Canada. Tadoussac: GREMM, 71 pp.

Monticino, M., Acevedo, M., Callicott, B., Cogdill, T. & Lindquist, C. (2007). Coupled human and natural systems: A multi-agent-based approach. *Environmental Modelling & Software* 22, 656–663.

Moreno, N., Quintero, R., Ablan, M., *et al.* (2007). Biocomplexity of deforestation in the Caparo tropical forest reserve in Venezuela: An integrated multi-agent and cellular automata model. *Environmental Modelling & Software* 22, 664–673.

Parks Canada (2002). *Marine Activities in the Saguenay–St. Lawrence Marine Park Regulations: Saguenay–St. Lawrence Marine Park Act.* Canada: Parks Canada.

Parrott, L., Chion, C., Martins, C.C.A., *et al.* (2011). A decision support system to assist the sustainable management of navigation activities in the St. Lawrence River Estuary, Canada. *Environmental Modelling & Software* 26(12), 1403–1418.

Railsback, S.F., Lytinen, S.L. & Jackson, S.K. (2006). Agent-based simulation platforms: Review and development recommendations. *Simulation* 89(9), 609–623.

Roberts, C.A., Stallman, D. & Bieri, J.A. (2002). Modeling complex human–environment interactions: The Grand Canyon river trip simulator. *Ecological Modelling* 153, 181–196.

Schlüter, M. & Pahl-Wostl, C. (2007). Mechanisms of resilience in common-pool resource management systems: An agent-based model of water use in a river basin. *Ecology and Society* 12(2), art. 4.

Simon, H.A. (1957). *Models of Man: Social and rational.* New York, NY: Wiley.

Turchin, P. (1998). *Quantitative Analysis of Movement: Measuring and modeling population redistribution in animals and plants.* Sunderland, MA: Sinauer.

van Oel, P.R., Krol, M.S., Hoekstra, A.Y. & Taddei, R.R. (2010). Feedback mechanisms between water availability and water use in a semi-arid river basin: A spatially explicit multi-agent simulation approach. *Environmental Modelling & Software* 25, 433–443.