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INVASIVE SPECIES - ORIGINAL PAPER

Spatially explicit risk assessment for coastal invaders under different management scenarios

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Abstract Biological invasions are particularly challenging in marine environments, where control strategies are scarce and efforts to reduce the abundance of the invader are costly and difficult, often representing insurmountable challenges. However, the magnitude of the impact of the invasion depends not only on the characteristics of the invading species, but also on the inherent features of the receiving environment; managing the environmental matrix could therefore be the best option for preventing or reducing undesired effects. The objective of the present work was to develop a spatially explicit risk-based approach to evaluate the effectiveness of different management practices designed to mitigate the potential impacts of the Pacific oyster (*Crassostrea gigas*) in the Bahía Blanca estuary (38°50′S, 62°20′W). A Risk Index (RI) was constructed to assess the potential negative impact of oyster bed expansion on environmental values and human health. RI maps were built to compare the potential effects of different management options in terms of risk reduction. An integral sanitation program within the coastal zone produced the largest reduction in the areas previously ranked as under very low, low, medium, high, and very high risk. Treatment of domestic sewage produced a major reduction in the areas under high and medium risk, mainly in the inner zone of the estuary, but changes in the area under very high risk were negligible. Removal of oysters at specific locations had a modest effect on risk reduction in terms of the whole area, but produced significant improvements at a local scale.

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Introduction

Invasive species are increasingly considered by scientists and policy makers to be a major threat to biodiversity, economy, and human health (Ricciardi 2007; Pimentel 2011; Simberloff et al. 2013), with particularly serious and persistent effects on marine and coastal environments (Carlton 1999; Bax et al. 2003; Molnar et al. 2008). The spread of non-native marine species has been associated with declines in populations of indigenous species (Kappel 2005) and food web alterations (Nichols et al. 1990; Oguz et al. 2008). The introduction and spread of marine invaders affect the structure and functions of natural communities (Neira et al. 2006; Sousa et al. 2009) and represent a growing threat both to marine life and human health (Ruiz et al. 2000; Pysek and Richardson 2010). Cases of biological invasions in marine environments continue to increase worldwide (Cohen and Carlton 1998; Molnar et al. 2008), and their associated harmful effects are a major concern to coastal managers looking for feasible control options, which are under increasing investigation by scientists (Bax et al. 2001).

A generalized consensus points to prevention through the management of vectors and pathways as the most

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effective line of defense against marine invasive species (Molnar et al. 2008). However, alternative management approaches are required once a species is established, especially in the case of widespread species. In a classical paper, MacDougall and Turkington (2005) proposed that invasive species are usually passengers (more than drivers) of ecological change, with their chances of invasion depending on human-driven habitat modification. Environmental stressors such as water eutrophication, metal pollutant of anti-fouling paints, over-harvesting, and the introduction of other non-native species could be responsible not only for an increase in ecosystem invasibility, but also for the magnitude of the invader impact (Seas et al. 2000; Byers 2002; Piola and Johnston 2008; Crooks et al. 2011). In these cases, modifying the receiving environment to be less suitable for establishment of exotic species could be a suitable option for mitigating the harmful effects associated with a biological invasion.

The Pacific oyster (*Crassostrea gigas*) has been introduced for aquaculture worldwide, and invasive populations have frequently become established and spread outside cultivation farms, where they cause significant changes to coastal ecosystems (Chew 1990; Ruesink et al. 2005). Invasive habitat-forming bivalves can have disproportionately large ecological impacts in mudflats and marsh environments, where hard surfaces are naturally limited (Commito et al. 2008). Bivalve shells increase attachment substrate, as well as the habitat complexity of an environment, changing the abundance and diversity of associated organisms (Crooks 2002). Besides changing the benthic environment, oysters are filter feeders that consume suspended plankton and organic matter. *C. gigas* has an especially high filtration rate, so dense reefs of oysters can reduce food availability for native filter feeding species such as fishes or others invertebrates (Ruesink et al. 2005). Clusters of feeding bivalves produce currents that modify plankton dispersal and survival and may lead to population changes in benthic species with planktonic stages in their life history (Tamburri et al. 2007; Troost et al. 2009; Woodford and McIntosh 2010; Wilkie et al. 2013). In addition to harmful ecological effects on native ecosystems, invasive populations of *C. gigas* are associated with a potential risk to public health, due to human consumption of oysters harvested from areas contaminated by domestic sewage discharge and industrial effluents. Bivalves can concentrate and retain human pathogenic contaminants present in seawater and have been related to several outbreaks of foodborne diseases worldwide, when eaten without appropriate treatment (Iwamoto et al. 2010). Field studies have demonstrated a clear relationship between fecal contamination in seawater, produced by domestic sewage discharges, and the presence of pathogens like *Escherichia coli* and *Salmonella* sp in *C. gigas* (Albarnaz et al. 2007; Vega Corrales and Marín-Vindas 2014). Sediment-associated heavy metals and polycyclic aromatic hydrocarbons (PAHs) are bioavailable and concentrate in *C. gigas* (Geffard et al. 2003), raising concern about their possible harmful effects on human health through the consumption of contaminated oysters (Han et al. 1998).

The Pacific oyster was introduced in Argentina in 1982 (40°S), and its first spontaneous population was recorded in 1987 (Orensanz et al. 2002; Escapa et al. 2004; Borges 2006). Since then, it has spread both northward (Bahia Blanca estuary 38°S; Dos Santos and Fiori 2010) and southward (El Condor 41°S; Roche et al. 2010), indicating its sustained expansion. The aim of the present study was to develop a spatially explicit risk-based approach to evaluate the effectiveness of different management interventions to mitigate the potential impacts of *C. gigas* in the Bahía Blanca estuary (Argentina). A Risk Index (RI) was constructed considering a hazard component, which is the probability of oysters expanding beyond known locations, and the impacts of oyster establishment. Main impacts of oyster bed expansion were assumed to be a lowering of environmental quality (lower pelagic primary productivity and reduced benthic and pelagic feeding resources for fish and shorebird species) and increased risk of human health (through consumption of oysters harvested from contaminated areas). Based on the previous knowledge of the study area, simplifying assumptions and variable values were proposed to create a RI map reflecting the present situation (baseline map). Additional RI maps were built to compare the baseline situation with the predicted risk under different management options, including integral sanitation of the coastal zone, treatment of domestic sewage, and manual removal of oyster beds at specific locations. A sensitivity analysis was also conducted to test the relative impacts of modifying the assumptions underlying each variable, on the overall RI value.

Study area

The Bahia Blanca estuary (38°S 62°W) is a mesotidal system of northwest to southeast channels separated by islands and wide tidal flats (Fig. 1). The northern portion of the estuary is dominated by Canal Principal, the main navigational channel, which has a total length of 61 km (Piccolo et al. 2008). Tidal amplitude increases steadily from 2.2 m at the mouth of Canal Principal to 3.5 m through the head. Within the intertidal fringe, non-vegetated tidal flats are the dominant land cover type (836 km^2). Salt marshes of *Spartina alterniflora* (196 km^2) are commonly restricted to lower marshes in the middle reach of the estuary. Intertidal marshes of *Sarcocornia perennis* are less represented (72 km^2), and the dominant species commonly forms

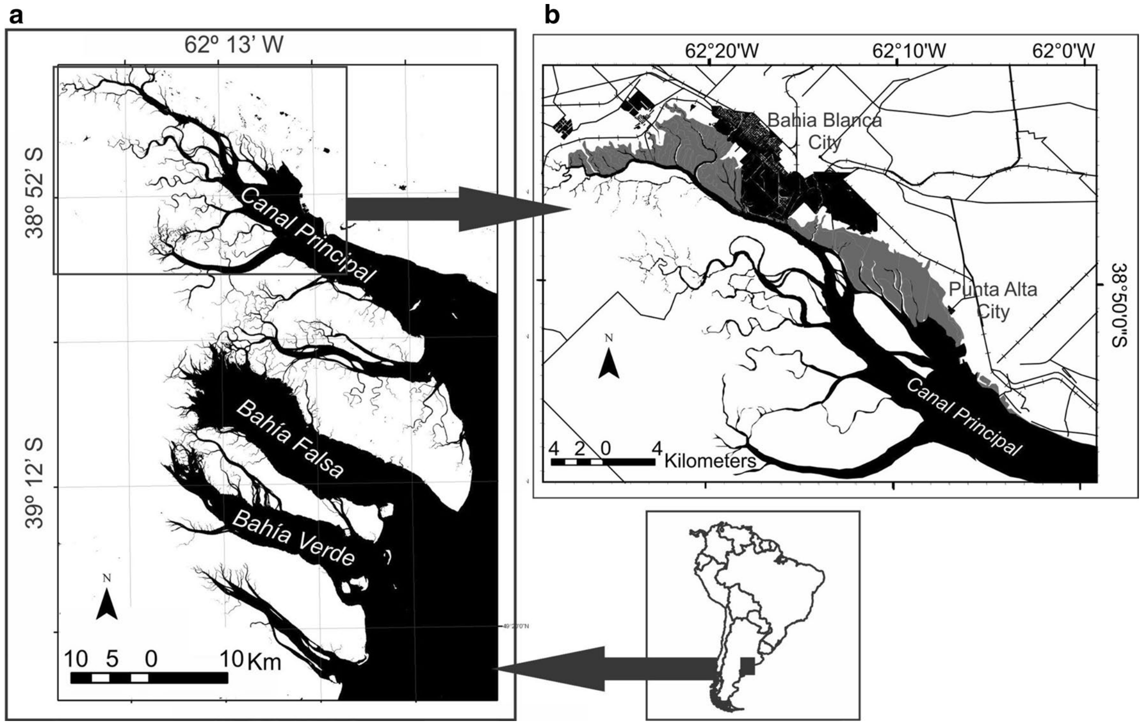


Fig. 1 **a** Location of the Bahía Blanca Estuary and its major inlets, **b** study area (*dark gray*) in the northern shore of Canal Principal

circular mounds, sometimes in association with *Heterostachys ritteriana* or *Spartina densiflora* (Pratolongo et al. 2013).

Coastal wetlands of the Bahía Blanca estuary have high conservation value due to the concentration of marine and coastal biological diversity (Nebbia and Zalba 2006). In the inner zone of Canal Principal, the shallow waters and commonly elevated nutrient levels give place to a highly productive pelagic system (López Cazorla 2004; Hoffmeyer and Barría de Cao 2007; Spetter et al. 2015). In addition, mudflats and marshes are known to provide high-quality conditions for benthic fauna (Bremec et al. 2004; Elias et al. 2004; Isacch et al. 2006), supporting a great diversity of both resident and migratory species, including endemic, threatened, and endangered fishes and shorebird species (Delhey and Petracci 2004). Several nature reserves covering ca. 260,000 ha were established in the area, with the general purpose of safeguarding the integrity of the marine ecosystem, and also to protect and preserve major resting and reproductive habitats for different terrestrial and marine species.

The estuary is under constant and increasing anthropogenic pressure because several urban settlements (350,000 habitants), including industrial developments (petrochemical complex, industrial park, oil refinery) and harbors, produce an impact on the environment through the discharge of sewages to the estuary without sufficient pretreatment and purification (Ferrer et al. 2000; Tombesi et al. 2000; Marcovecchio et al. 2008). Agricultural activities also have an impact on the environment (Perillo et al. 2001; Botte et al. 2007).

Methods

The spatial analysis was concentrated on the northern shore of Canal Principal, covering the intertidal fringe (ca. 50 km in length). A Risk Index (RI) was constructed combining the probability of oyster beds expanding beyond known locations with its potential impact. The RI was defined as:

$$\mathrm{RI} = (\mathrm{OE} \times \mathrm{OR}) \times \frac{(\mathrm{EV} + \mathrm{HH})}{2}$$

The likelihood of oyster bed expansion is represented by (OE × OR), combining habitat suitability for oyster establishment (OE) and distance to known oyster beds (OR). The impact component is given by (EV + HH)/2, which considers the ecological value of the receiving environment (EV), and the potential impacts on human health (HH), associated with the consumption of contaminated oysters. A value from 0 to 1 can be assigned to each individual variable; thus, RI ranges from 0 (no risk) to a theoretical maximum value of 1.

OE was built based on bibliographic information on the ecology of *C. gigas* and its invasive behavior in a similar ecosystem (Borges 2006; Carrasco 2012). It depends on two habitat variables related to the chance of successful establishment: substrate type (S) and vertical position along the intertidal range (T). Four land cover classes were considered for S: natural or artificial hard bottoms, *S. alterniflora* marshes, *S. perennis* marshes, and mudflats. Scores from 1 to 0 can be assigned to the different habitats based on their suitability for oyster colonization (Table 1). In the case of T, *C. gigas* is an intertidal species, very tolerant to varying abiotic conditions. Successful establishment and survival at different elevations within the intertidal range may depend on site specific conditions like tidal range and atmospheric temperatures (Carrasco and Baron 2010). To account for these local conditions, a score from 0 to 1 can be assigned to different elevations within the intertidal fringe. Both S and T were considered equally essential for oyster establishment and were then combined by their geometrical mean. In this way, a null value was assigned to OE if either S or T was 0:

$$\mathrm{OE} = \sqrt{(\mathrm{S} \times \mathrm{T})}$$

Populations of *C. gigas* establish reefs of hard structure above an estuarine seafloor. The mature reefs are well-anchored, solid structures, and oysters themselves recruit onto and grow on the shells of other oysters, thereby extending the reef (Reise and Van Beusekom 2008). In case bed expansion rates are available, distances to the edge can be further associated to the probability of oyster establishment in a given time. OR ranging from 1 to 0 was assumed to be associated to the radial expansion of known oyster beds, with higher likelihood of oyster establishment close to bed edges and decreasing over space based on in situ measurements in the last five years. Bravo et al. (2016) conducted an annual monitoring of seven oyster beds, in Bahia Blanca estuary, during the first five years of species establishment (2010–2015). Authors showed that beds are almost radially expanded, at a rate average 100 m/year, until they cover the available substrate.

The ecological value (EV) considers two major ecological functions identified for the area: the high pelagic primary productivity (P) and the presence of feeding grounds for especially important biodiversity components (C). *C. gigas* may exert a top-down control of phytoplankton biomass (Ren et al. 2000) and food depletion in the water column (Diederich 2005). Additionally, dense aggregations of *C. gigas* are known to result in the limitation of food and space available for other intertidal benthic species (Martin and Cooper 2002). In accordance, high oyster densities can cause a severe decline in the pelagic primary productivity, zooplankton, and also benthic macrofauna (Leguerrier et al. 2004), affecting both pelagic and benthic consumers. For evaluating EV, P may assume a value between 1 and 0, according to the pelagic primary productivity of a given area. In the case of C, different habitat types can be assigned a score from 1 to 0 according to their relevance as feeding grounds for fish and bird species of economic and ecological importance (Table 1). P and C were combined by their arithmetic mean, provided their equally important and additive contribution to the global ecological value:

$$\mathrm{EV} = (\mathrm{P} + \mathrm{C})/2$$

The human health component (HH) reflects the impacts associated with human consumption of oysters growing in polluted environments. It combines two variables: the access to the coast (A) and the distance to point sources of pollution (DP). In the case of A, a value from 1 to 0 can be assigned according to the distance to access points (public roads, piers, fishing areas, beaches, and recreational spots). Similarly, DP values from 1 to 0 can be assigned according to the distance to point sources of pollution (Table 1). The term HH was constructed by the geometric mean of A and DP, since it was considered that either unpolluted or non-accessible areas represent a null risk of human health:

$$\mathrm{HH} = \sqrt{(\mathrm{A} \times \mathrm{DP})}$$

Based on the literature and previous work on the study area, different simplifying assumptions and variable scores were proposed to construct a RI map reflecting the present situation (Fig. 2). Baseline values and their corresponding rationale are provided in Table 1. Once the baseline RI map was obtained, the effects of different management actions on the frequency and spatial distribution of risk values were evaluated. Management scenarios included:

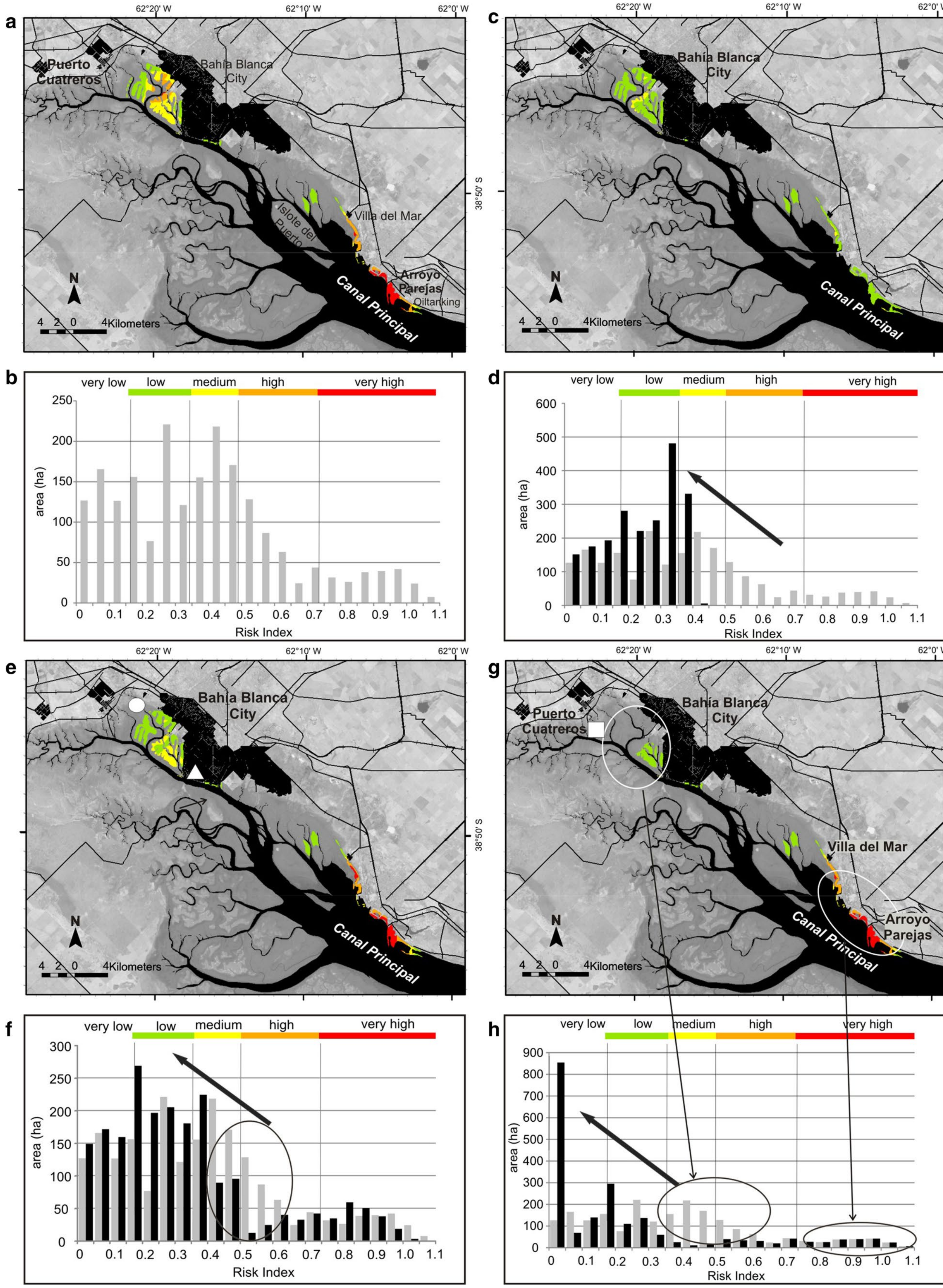
1. Completely effective treatment and proper disposal of domestic sewage: In DP calculations, a score of 0 was assigned within 3 km of sewage discharge points, instead of the linear decrease described in Table 1. Values associated to point sources of industrial effluents remained as described in Table 1.
2. Integral sanitation of the coastal zone, including completely effective treatment of both domestic sewage and industrial effluents: DP values were set to 0 over the entire area.
3. Completely effective oyster removal by manual extraction of all the individuals present at specific locations: For a given oyster bed, a score of 0 was assigned to OR within 5 km of its edge, instead of the linear decrease described in Table 1.

Based on the no-intervention scenario (baseline RI map), low, medium, high, and very high RI values were estimated as the 25, 50, 75, and 90 percentiles, respectively.

Table 1 Variable scores proposed to construct a Risk Index map reflecting the present situation (baseline scenario) and their corresponding rationale for the risk assessment of the Pacific oyster in Bahia Blanca estuary (Argentina)

Baseline values		Rationale
S		
Hard bottoms	1	Oysters preferably attach to hard substrates such as rocks, dike foots, stone walls, and harbor facilities (highest score). In marshes, oysters can also attach to living plants, small stones, shell fragments, or other dwebris. Intermediate scores were assigned to both salt marshes, considering that those dominated by *S. alterniflora* have higher stem densities and lower hydrodynamic energy, allowing debris deposition (Negrin et al. 2016). Bare mudflats (lowest score) are highly dynamic environments, dominated by heavy erosion and sediment deposition rates, which may impede oyster establishment (Pratolongo et al. 2010)
Spartina alterniflora Marshes	0.7	
Sarcocornia perennis Marshes	0.5	
Mudflats	0	
T		
Linear decrease from 1 (low tide) to 0 (highest astronomical tide)		The mesotidal regime in the study area imposes large periods of aerial exposure in the upper intertidal zone. Under a combination of high summer temperatures and strong winds blowing all year round, desiccation is the dominant stressor for benthic species (Zapperi et al. 2016). Oyster survival was assumed to decrease as aerial exposure increases
OR		
Linear decrease from 1 to 0 within 5 km from the edge of known oyster beds		In those areas where the influence of different oyster beds overlaps, the highest value was chosen. A 5 km distance was chosen to represent the long term likelihood of oyster establishment. Field observations in the study area suggest that radial expansion of oyster beds is about 100 m/year (Dos Santos and Fiori 2010; Bravo et al. 2016)
P		
Linear decrease from 1 to 0 from head to mouth		It has been largely documented that pelagic primary productivity decreases from the inner through external zone of Canal Principal. Differences are given by a typically strong winter phytoplankton bloom that takes place in shallow waters close to the head of the estuary (Popovich and Marcovecchio 2008; Popovich et al. 2008)
C		
Salt marshes	0.8–1	A value linearly decreasing from 1 to 0.8 was assigned to feeding areas within a radius of 10 km from natural reserve Islote del Puerto, nesting site of the endemic Olrog Gull (*Larus atlanticus*). The radius was chosen based on the average flying distance for feeding (Suárez et al. 2012). A value of 0.8 was assigned to salt marshes considered feeding habitat for other migratory and resident birds, and a value of 0.5 was assigned to soft bottoms with known high benthic biomass, providing feeding resources for fish species (Yorio et al. 1997, 1998; Bremec et al. 2004; Delhey and Petracci 2004; Elias et al. 2004; Isacch et al. 2006)
Soft bottoms	0.5	
A		
Linear decrease from 1–0 within 3 km to access points		The distance was chosen based on the average walking distance observed in oyster collectors (personal observation)
DP		
Industrial effluents: linear decrease from 1 to 0 within 3 km Sewage discharge: linear decrease from 1 to 0 within 5 km		Distances to major sources of pollution were chosen based on the average concentrations of fecal coliforms and industrial contaminants reported by Marcovecchio et al. (2001), Cabezali et al. (2004), Freije et al. (2008), Arias et al. (2010) and Baldini and Cubito (2014). In those areas where different A and DP radius overlap, the highest value was chosen

References: S (substrate type); T (intertidal range); OR (distance to known oyster beds); P (primary productivity); C (especially important biodiversity components); A (access points: public roads, piers, sport and recreational fishing areas, beaches, and recreational spots); DP (distance to point sources of pollution)


a
62°20' W
62°10' W
62°0' W
38°50' S
Puerto Cuatreros
Bahía Blanca City
Islote del Puerto
Villa del Mar
Arroyo Parejas
Oiltanking
Canal Principal
N
4 2 0 4Kilometers
b
very low
low
medium
high
very high
area (ha)
Risk Index
c
Bahía Blanca City
Canal Principal
d
e
f
g
h

◂**Fig. 2** Maps showing areas under low (*green*), medium (*yellow*), high (*orange*), and very high risk (*red*), according to Risk Index (RI) values estimated in: **a** the present condition (no-management scenario), **b** frequency histogram of RI values in the present condition, **c** a scenario of integral sanitation of the coastal zone, including domestic sewage and industrial effluents, **e** a scenario that included treatment of domestic sewage. *White circle* domestic sewage discharge. *White Triangle* industrial pole, **g** a scenario of manual removal of oyster near Puerto Cuatreros, **d**, **f**, **h** frequency histograms of RI values comparing the present condition with each management scenarios

The different management scenarios were compared to the actual RI map by means of the areas under low, mean, high, and very high risk, as well as the spatial distribution of RI values. Finally, a sensitivity analysis was conducted to test how sensitive the model is to changes in the simplifying assumptions and values chosen. To perform the analysis, each single variable (S, T, OR, P, C, A, and DP) was modified, assigning the lowest and highest possible scores, within ecologically reasonable limits. In the case of T, P, OR, A and DP, linear increases or decreases were considered for the baseline estimations. Exponential trends for these variables were additionally considered in the sensitivity analysis. Variables were modified one at a time, with the rest of the variables held at their baseline values. RI values for each modified variable were estimated over the entire study area and average RI values were reported.

The different layers of information required to build the spatial expression of RI (habitat types, point sources of pollution, access points, oyster beds) were obtained through on-screen digitizing of satellite images Landsat 5, 7, and Spot (available from the U.S. Geological Survey, USA, and Comisión Nacional de Actividades Espaciales, Argentina), and polygons transformed to raster (30 × 30 m pixel size) for further calculations. Low- and high-elevation contours were digitized from Landsat 5 images acquired during the lowest and highest tides registered during sensor lifetime. Distances from lines, points, and polygons were automatically calculated in ArcGis.

Results

A total area of 2092 ha was considered in this analysis, with 345 and 218 ha falling within the high and very high risk categories (Fig. 2). The highest RI value estimated was 0.64, more than half of the theoretical maximum of 1.00. The baseline RI map allows a clear differentiation of two zones: a low-to-high RI zone close to Bahia Blanca City, in the inner zone of Canal Principal, and a predominantly high and very high risk area in the coastal zone from Villa del Mar to the Oil Tanking transfer buoy, in the middle reach of the Estuary. Close to Bahia Blanca, the impact component is dominated by HH, the potential impacts on human health given by several domestic sewage discharge points, as the major source of pollution, and the multiple access points for fishing and recreation. However, the likelihood of oyster expansion (OE × OR) is relatively low, given the presence of one single oyster bed in the area. Through the middle reach of Canal Principal, pollutants derive from multiple sources and the area concentrates most of the oyster beds already established, resulting in 152 ha of salt marshes and natural hard bottoms under very high risk. In an intermediate position between the head and the middle reach of Canal Principal, two small areas of low and medium risk can be observed. They correspond to *S. alterniflora* marshes that fall within the radius of 10 km from natural reserve Islote del Puerto and are also affected by a potential expansion of the oyster bed at Villa del Mar.

Comparisons between the baseline RI map and the management scenario involving an integral sanitation of the coastal zone, including domestic sewage and industrial effluents, are shown in Fig. 2. As a global result, most of the area previously ranked as under medium, high and very high risk turned into low and very low risk zones after management (Table 2), and risk reduction was homogeneous throughout the landscape. This management option eliminates the risk to human health (HH term becomes zero). Under this scenario, the remaining 1035 and 33.48 ha of low and medium RI represent potential impacts on environmental values (EV term).

The effect of treatment and proper disposal of domestic sewage alone was evaluated (Fig. 2; Table 2). Consequences associated with this intervention occurred at the high-risk area, which was reduced from 344.61 to 143.28 ha, and at the medium risk area, changing from 515.34 to 370.71 ha. However, 176.13 ha still remained in the very high risk category (81% of the original area, under a no-intervention scenario).

A similar impact, in terms of reduction in RI, is obtained through manual removal of oysters from the bed established near Puerto Cuatreros (Fig. 2). Assuming a 100% effective treatment impeding oyster bed expansion, the area under high risk would be reduced from 344.61 to 141.84 ha, and the area under medium risk would be reduced from 515.34 to 148.23 ha, mostly changing to a very low risk status (Table 2).

Two of the most populated recreational sites (Villa del Mar and Arroyo Parejas beaches) are located in the outer section of the study area, where treatment of domestic sewage, as an isolated measure may not be sufficient to diminish the area under high and very high risk. Results obtained through oyster removal at each one of the three oyster beds established in the middle reach of Canal Principal are shown in Fig. 3 and Table 2. Oyster removal at Puerto Rosales resulted in 104 ha changing from a very high risk status to low- and high-risk condition. However, there were still 112.59 ha remaining under very high risk, which were

Table 2 Areas (in hectares) under very low, low, medium, high and very high risk, in relation to different management scenarios for the risk assessment of the Pacific oyster in Bahia Blanca estuary (Argentina)

Management scenarios	Very low risk	Low risk	Medium risk	High risk	Very high risk
Baseline	496.44	480.96	515.34	344.61	217.62
Integral sanitation	986.49	1035.00	33.48	0.00	0.00
Treatment of domestic sewage discharges	660.51	704.34	370.71	143.28	176.13
Eradication of oyster beds at					
Puerto Cuatreros	1212.75	374.94	148.23	141.84	177.21
Puerto Rosales	559.44	459.81	523.71	399.42	112.59
Transfer buoy	513.63	492.21	489.69	341.82	217.62
Villa del mar	700.56	390.06	485.82	292.77	185.76

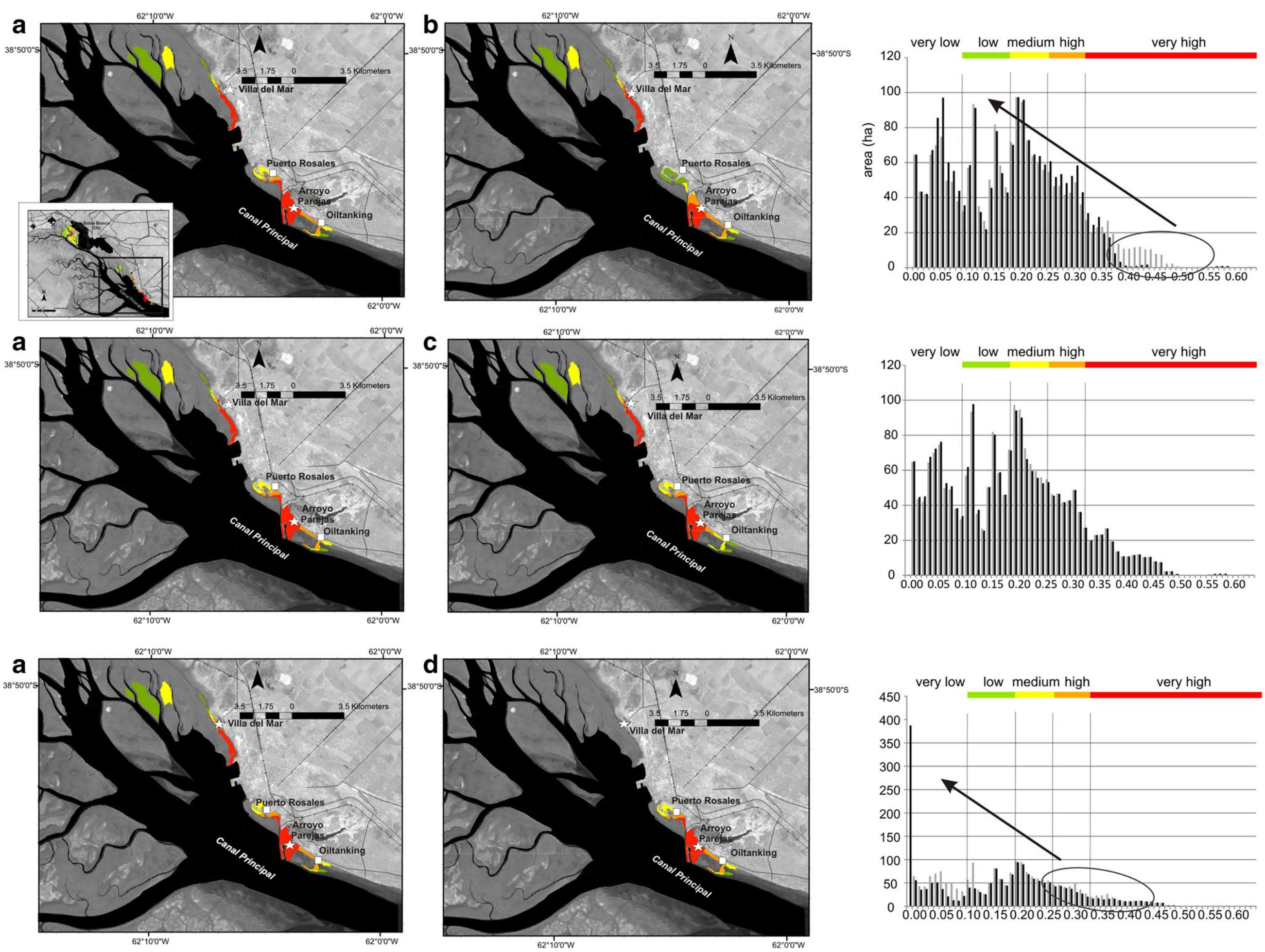


Fig. 3 Comparisons between Risk Index (RI) values estimated in **a** the present condition (no-management scenario), and RI values estimated in a scenario of manual removal of oyster to impede bed expansion near, **b** Puerto Rosales, **c** Oiltanking, and **d** Villa del Mar. Maps show areas under low (*green*), medium (*yellow*), high (*orange*), and very high risk (*red*), according to RI values estimated in each scenario. *White square* actual oyster beds. *White star* public beach. Frequency histograms comparing no-management and management scenarios are shown in the *right column*

located, along with a large high risk area, close to Arroyo Parejas beach. Eradication of oysters in the transfer buoy Oiltanking resulted in very subtle changes, focused in the medium risk area that reduced from 515.34 to 489.69 ha, but the access at Arroyo Parejas Beach would remain under high risk condition. Finally, oyster removal at Villa del Mar

Table 3 Sensitivity analysis to test how sensitive is the Risk Index to changes in the assumptions and values chosen for each variable

RI component	Assigned values			Mean RI	Total variation
	Hard bottoms	*Spartina perennis* marshes	*Spartina alterniflora* marshes		
S1	1	0.1	0.1	0.09	
S2	1	1	1	0.25	
S3	1	1	0.1	0.19	0.16
S4	1	0.1	1	0.14	
$S_{baseline}$	1	0.5	0.7	0.19	
T1	1 across the entire intertidal range			0.22	
T2	Exponential decrease from 1 (low tide) to 0 (high tide)			0.12	0.10
$T_{baseline}$	Linear decrease from 1 (low tide) to 0 (high tide)			0.19	
OR1	Exponential decrease from 1 to 0 within 5 km			0.09	
OR2	Linear decrease from 1 to 0 within 1 km			0.05	0.14
$OR_{baseline}$	Linear decrease from 1 to 0 within 5 km			0.19	
P1	Exponential decrease from 1 (head) to 0 (mouth)			0.17	0.02
$P_{baseline}$	Linear decrease from 1 (head) to 0 (mouth)			0.19	
	Salt marshes	Soft bottoms			
C1	0.1	0.1		0.15	
C2	1	1		0.23	
C3	0.1	1		0.19	0.08
C4	1	0.1		0.18	
$C_{baseline}$	0.8–1	0.5		0.19	
A1	Exponential decrease within 3 km			0.14	
A2	Linear decrease within 1 km			0.12	0.07
A3	Linear decrease within 5 km			0.20	
$A_{baseline}$	Linear decrease within 3 km			0.19	
	Industrial effluents	Sewage discharge			
DP1	Exponential decrease within 3 km	Exponential decrease within 5 km		0.15	
DP2	Linear decrease within 1 km	Linear decrease within 1 km		0.12	0.08
DP3	Linear decrease within 5 km	Linear decrease within 5 km		0.20	
$DP_{baseline}$	Linear decrease within 3 km	Linear decrease within 5 km		0.19	

References: S (substrate type); T (intertidal range); OR (distance to known oyster beds); P (primary productivity); C (especially important biodiversity components); A (access to the coast); DP (distance to point sources of pollution)

Beach produced a modest effect in terms of the area changing to a lower risk status (only 32 and 52 ha of very high and high risk, respectively, changed to low and very low risk).

Results from the sensitivity analysis (Table 3) showed that RI is particularly sensitive to variations in S, the score assigned to different land cover types, regarding suitability for oyster colonization. Changes in S may account for variations up to 16% in the overall RI value. Changes in the spatial range and linear versus nonlinear scaling in OR may also have a similar impact on RI, but these variations have to be further related to actual rates of oyster bed expansion to be interpreted. Changes in T accounted for variations up to 10% of RI, with the largest effect observed when considering the highest score through the entire intertidal range. Variations in C, A, and DP have a smaller impact (lower than 10%), with P being the least sensitive variable.

Discussion

Invasive species include organisms that generate both public health and environmental concerns, and so, risk assessments provide opportunities to integrate human health and ecological risk issues (Andersen et al. 2004a). Assessing the potential impact posed by organisms of interest is a critical initial stage in a systematic response to emerging invasive alien species threats. Risk analysis is a precursor to the development of policies and tactical strategies to deal with emerging problems. Such analysis should bring together data and expertise to synthesize possible impacts (Andersen et al. 2004b).

Risk maps, as the spatially explicit realizations of risk assessments, have become increasingly popular among decision makers and regulators as support tools to allocate resources for quarantine, monitoring, and control of invasive alien species (Pysek and Richardson 2010). Some models further combine the predicted distribution of the invader with habitat components that are particularly susceptible to its impact, resulting in maps of potential impact (Allen et al. 2006; Foxcroft et al. 2007; Whittier et al. 2008). Through an integrated, spatially explicit, assessment of the risk posed by *C. gigas* on human health and environmental values, this work provides a valuable tool to forecast the change in risk imposed by different management options. Such an approach could greatly improve the chances of effectively reducing the severity of biological invasions in particularly challenging scenarios. The current and potential values of each term in the RI clearly indicate a number of potential alterations that could lead to a significant worsening of the present situation (e.g., development of additional sources of pollution, establishment of new oyster beds, creation of artificial hard-bottom substrates, proliferation of unregulated access points, and illegal harvesting.). Although the modeled scenarios relate to control actions directed at diminishing the impacts of the invasive oyster, the RI approach could also be used to evaluate the negative impacts of unrelated management practices, such as site selection for dredged spoil deposition or coastal planning and design of recreation facilities.

Strayer (2010) suggests that interactions between alien species and other anthropogenic stressors are common, strong, and bi-directional, so that management of alien species is inextricably linked to management other environmental stressors. In many cases, it probably will make sense to manage alien species and other stressors as a group of closely linked problems, rather than as separate problems. In this regard, projections under different management scenarios show that the negative impact of the expansion of the Pacific oyster could be significantly reduced by managing the environmental matrix, even with reduced or non-direct control operations. The best results in terms of a reduction in the severity and extension of the oyster impact are associated with the integral sanitation treatment for city dwellings and the control of industrial and port effluents, leading to the virtual disappearance of areas under high and very high risk, and also a severe reduction of the area under medium risk. This management option eliminates the risk to human health, but the remaining areas of low and medium RI still represent potential impacts on environmental values (EV term), where oyster bed expansion would threaten pelagic primary productivity and feeding grounds for marine and coastal biodiversity. In this management scenario, risk reduction was evenly distributed through the estuary, a situation that could not be attained with the treatment of domestic sewage alone.

Although an integral sanitation would be the optimal strategy in terms of its consequences for human health, treatment and proper disposal of domestic sewage alone are more realistic management option in the short term. The effects of this management action concentrate in the inner zone, close to Bahia Blanca City, but are negligible in the middle reach, where pollution from industrial and port activities is superimposed on domestic sewage contamination. For the inner zone, several fishing areas, piers, and recreational sites are located within the radius of influence of a major domestic sewage discharge point, and the appropriate wastewater treatment would greatly reduce the impacts of oyster beds expansion on human health. However, a relatively large area under medium and high risk would still persist, under the influence of effluents from the industrial zone at Ingeniero White, and potential impacts on environmental values (EV term) would also remain. Zedler and Kercher (2004) have suggested that nutrient enrichment facilitate invasions of alien plants, because they free up resources that can be used by new invaders. Therefore, effective control of urban effluents may involve other benefits not evaluated in this study, but relevant to a port area as Bahia Blanca estuary exposed to constant introduction of exotic species carried in ballast water.

Manual removal of oysters is a management action that can be decided locally, with a minimal financial investment if undertaken by volunteer labor. Although it is an option that cannot be considered for large areas, oyster removal can effectively eliminate both the environmental and human health components of the RI, at a local scale. Two of the most populated recreational sites (Villa del Mar and Arroyo Parejas beaches) are located in the outer section of the study area, where treatment of domestic sewage as an isolated measure may not be sufficient to diminish the area under high and very high risk. Results obtained through oyster removal at each one of the three oyster beds established in the middle reach of Canal Principal would be an effective option to locally diminish risk around this recreational area. Moreover, oyster removal eliminates the impact component (both the environmental and human health terms in RI), and thus, it would be a preferred choice for the ecological conservation of salt marshes within a radius of 10 km from natural reserve Islote del Puerto.

Projections of direct control operations as eradication of adult oysters at specific locations may yield different results in terms of risk reduction, depending of the invaded locality considered. Guy and Roberts (2010) show that small scale hand removal of *C. gigas* is an effective means of controlling populations of this particularly invasive species at early stages of its spread. They proposed that this strategy should be considered as a realistic option for limiting the spread of *C. gigas* in small areas, such as natural reserve, where conservation issues are important. In the present study, a complete eradication was assumed, but the approach is sufficiently flexible to allow exploring the effects of an incomplete removal of adult oysters. This type of comparisons is a major strength of spatially explicit approaches, which provide a clear visualization of the geographical scope of a given action and contribute to a more efficient allocation of resources.

Complete eradication of invasive aquatic species, especially in marine environments, is difficult or almost impossible to achieve (e.g., *Rapana venosa*, *Undaria pinnatifida*, *Didemnum vexillum*, *Sabella spallanzanii*, *Mytilopsis sallei*, *Terebrasabella heterouncinata*, and *Caulerpa taxifolia*; Schaffelke et al. 2006). Particularly, the implementation of direct management practices to control *C. gigas* is further complicated by the economic importance of the species; measures in this context are usually aimed at containing it within aquaculture facilities and minimizing the impact on native biodiversity by controlling the possible expansion of diseases (Harris 2008). The current proposal of reducing the impact of an invasive species by managing the receiving environmental matrix may augment the technical and socioeconomic viability for intervening in these cases.

This framework guides the assessment of management priorities in a logical and structured way and provides insights into the problems and solutions of managing invasive species in a large landscape in a clear, meaningful manner. This procedure provide managers an efficient and flexible tool for identifying and calculating risk related to different management measures that could be implemented to control or to eradicate an alien species or mitigate the oyster impact. This procedure also allows incorporating other variables, providing that they can be modeled spatially.

Spatially explicit tools are essential for environmental research, resource management, and conservation planning. Activities that may benefit from spatially explicit approaches include biodiversity assessment, reserve design, habitat management and restoration, and species conservation. Moreover, including the spatial dimension helps to improve predictions of the effects of environmental change on species and ecosystems. The methodology proposed in this study can be easily transferred to other marine and non-marine species for which some information on occurrence and socioenvironmental matrix data are available. The model is efficient and flexible in its application and is suitable for a broad variety of stressors and management interventions; it is also equally applicable over a wide range of spatial scales.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interest.

Human and animal rights This article does not contain any studies with animals performed by any of the authors.

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