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ANALYSIS

Cost-efficient allocation of ship measures and harvest of aquatic invasive species – An application to invasive crabs on the west coast of Sweden

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ABSTRACT

The purpose of this study was to identify cost-efficient combinations of control measures (harvest of established invaders) and prevention measures (ballast water treatment and antifouling to prevent invaders) to achieve targets for the maximum population sizes of two invasive crabs, the Asian shore crab (*Hemigrapsus sanguineus*) and brush-clawed shore crab (*Hemigrapsus takanoi*), in interconnected water basins on the west coast of Sweden. To this end, a spatial bio-economic model was developed using transect methods to quantify population sizes and an ocean circulation high-resolution coastal model constructed to estimate connectivity between the water basins. The results showed that both harvest and vessel treatment measures offer cost-efficient solutions, but their optimal levels and timings depend on the choice of spatial target for acceptable population sizes. The costs can be high if increases in populations are to be avoided, but these costs are doubled when the target is to eradicate the populations. The results were also sensitive to parameter values in the population dynamics and cost functions, and to assumptions involved in policymakers' decisions about the targets to be achieved.

1. Introduction

The management priorities for non-indigenous species (NIS) are well covered in the literature, which includes a plethora of different in situ control measures such as mechanical control by harvest, habitat restoration and biological control (e.g. Giakoumi et al., 2019). However, the effects of in situ control measures for established marine NIS are often counteracted by instantaneous new introductions by vessels due to a lack of effective on-board prevention methods for certain groups, such as mobile live organisms. Shipping is one of the most significant vectors contributing to the spread and establishment of many marine NIS (Saebi et al., 2020; Gren et al., 2022).

Despite the regulation of ballast water treatment (BWT) in force since 2017 (IMO (International Maritime Organisation), 2004) to mitigate NIS spread and disposal by vessels, there are ongoing introductions from other ship areas and structures. One reason is the regulation itself, which allows for the discharge of zooplankton larvae (crab larvae) according to BWMC D2-standard of 10 larvae/m^3. Other reasons are two unregulated shipping-related vectors: biofouling attached to the hull and mobile fauna in structures such as sea chests and anchor boxes. There is currently an imbalance between the regulation relating to transfer with ships, in which ballast water is strictly regulated, and control of biofouling and mobile fauna, which comes in the form of a guideline only (IMO (International Maritime Organisation), 2023).

Unlike the existence of successful cases of eradication of terrestrial NIS, there are very few marine examples. This is probably due to the high environmental connectivity resulting in the high dispersal potential of many marine species at their planktonic larval stages. In addition, the detection of new introductions is more difficult underwater. NIS are introduced to new areas by natural spread from adjacent invaded areas and by shipping (either as larvae in the vessels' ballast water or as adults in niche areas such as sea chests or anchor boxes). With high dispersal potential and a large geographic area, it is more difficult to combat marine NIS, and it is therefore important to consider the size and magnitude of the species' dispersal capacity when planning and implementing prevention and control measures.

The purpose of this study was to calculate the cost-efficient allocation of harvest and vessel measures reducing the disposal of larvae from

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vessels to achieve targets on maximum NIS population sizes in a region featuring several connected marine basins. To this end, a dynamic bio-economic model with a spatial dimension was constructed and applied to the invasive Asian shore crab (*Hemigrapsus sanguineus*) and brush-clawed shore crab (*Hemigrapsus takanoi*) on the west coast of Sweden. Unlike other invasive crabs, such as the Snow Crab in the Barents Sea (Kourantidou and Kaiser, 2024), there are no documented values of the two *Hemigrapsus* crabs. These NIS were first detected in the area in 2018 and have since shown rapid dispersal along the west coast. Ballast water, ship hulls and niche areas have previously been described as common vectors for crabs similar to *Hemigrapsus* (Gollasch, 1999; Carlton and Cohen, 2003).

Bio-economic modelling has a long tradition in the economics of natural resources (see Knowler (2002) and Prelezzo et al. (2012) for reviews). It has been widely applied in the rich literature in economics on the management of NIS with two different approaches to cost-efficiency analysis. The most used approach is the minimization of the costs of damage plus the cost of control and prevention measures, which is applied under different conditions of risk and spatial dispersal (for more details, see Olson, 2006; Gren, 2008; Marbuah et al., 2014; Epanchin-Niell, 2017; Büyüktahtakm and Haight, 2018; Pepin et al., 2022). A key conceptual result in these models is that the efficient management in space and time occurs where the marginal cost of a measure equates the discounted streams of current and future damages avoided from the marginal reduction in the NIS population. Another result is that the optimal allocation of prevention and control measures depends on the shape of the cost function of each type of measure and on damages of an invasion, should it occurr. The cost of prevention may be higher than the avoided damages when the risk of establishment and damage is low. On the other hand, it can be quite costly to control or eradicate an established invasion.

The present study belongs to the relatively small literature using the other approach in cost-efficiency analysis where prevention and control costs are minimized to achieve predetermined NIS population targets in time and space. One argument for this approach is that NIS management in practice is often expressed in terms of eradication or, when this is not possible, containment of established NIS to stop dispersal into non-invaded areas (e.g. IBPES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), 2024). Another argument is the lack of data on the cost of damage from changes in NIS population sizes, which is necessary for minimizing damage plus prevention and control cost (e.g. Epanchin-Niell, 2017). The relatively large body of literature on the damage costs of invasive species does not provide such damage cost functions but instead estimates damage costs for given level of NIS population. Targets to be achieved can then be determined by an assessment of population size with no or limited ecological damage, for example, as suggested by Green and Grosholz (2020). Key results from this cost-efficiency approach point out the role of target setting where minimum control costs increase at large population reductions and that measures are prioritized in time and space according to their costs and impacts on the NIS target during the planning period (e.g. Buhle et al., 2005). A related approach is the minimisation of NIS abundance or damage in time and space under given budget constraints, which highlights the targeting of NIS surveillance and control in time and space (e.g. Hastings et al., 2006; Baker, 2017; Yemshanov et al., 2017; Courtois et al., 2023).

Common to both cost-efficiency approaches is the focus on a single NIS and the assumption that prevention measures avoid NIS establishment in a non-invaded zone. The latter is likely not to be valid for many marine NIS since the establishment and dispersal of NIS occur alongside their new introduction by vessels in the same zone. Control and prevention measures are thus needed to manage established species and prevent new introductions by vessels. A few studies account for the control of established invasive species with instantaneous new introductions, but do not address the prevention of new introductions (e.g. Meadows and Sims, 2023).

In the present study, minimum costs were calculated for attaining targets for the populations of the two *Hemigrapsus* crabs in a fjord system on the west coast of Sweden. Measures include the control of crabs by harvest and the prevention of new introductions by BWT and antifouling measures in vessels. Their effects on the crab populations were estimated using spatial population growth models. Necessary data on initial populations in the different basins were obtained by means of transect methods, and the inter-basins transports were quantified by a particle advection-dispersion model coupled to a high-resolution coastal ocean circulation model (Brunnabend et al., 2020).

The main contribution of this study is threefold: i) it simultaneously considers control of established populations and prevention of new introductions by vessels of the same NIS in a water basin, ii) it includes two invasive crabs with different population growth dynamics and control cost functions, which reveals the economies of scope by vessel measures; and iii) it adds a case study to the relatively limited literature on the cost-efficient allocation of measures in time and space to achieve given NIS population targets,. This paper is organised as follows: Section 2 presents the structure of the bio-economic model and the properties of cost-efficient solutions that provide the basis for the numerical estimates. Data retrieval is described in Section 3, which is followed by the presentation of results in Section 4. The paper ends with a discussion and the main conclusions drawn.

2. The bio-economic model

The decision problem is formulated as minimizing total costs for given future targets on the population sizes of Asian shore crab (*Hemigrapsus sanguineus*) and brush-clawed shore crab (*Hemigrapsus takanoi*), henceforth denoted as HS and HT respectively. The size of the crab population in each time period in a certain marine basin, Q_t^{ik}, where $i = 1,..,o$ basins, k = HS, HT and $t = 1,..,T$ years, is determined by the population at the beginning of the period, the growth of the population, harvest, the supply of larvae from vessels that become crabs in the same period, and the transfer from other basins to basin *i*. The change in the population from a year *t* to the next year $t + 1$ is then described as:

$$Q_{t+1}^{ik} - Q_t^{ik} = g\left(Q_t^{ik}\right) + \sum\nolimits_{j\neq i}\left(a^{ji}Q_t^{jk}\right) + S_t^{ik} - H_t^{ik} \tag{1}$$

where $Q_0^{ik} = Q^{ik}$ and $g\left(Q_t^{ik}\right)$ is the population growth during a year, $\sum_{j\neq i}\left(a^{ji}Q_t^{jk}\right)$ is the transport of crabs from all basins $j \neq i$ to basin *i* where a^{ji} is the constant fraction of crabs in basin *j* that is transported to basin *i*, S_t^{ik} is the disposal of larvae from vessels that become crabs and reproduce in the same year, and H_t^{ik} is the harvest of crabs. A simplification was made by excluding competition between the two crab species, which is justified by differences in their habitat requirements (Section 3.1).

There are no studies featuring the quantified population dynamics for HS and HT in the studied region. With respect to the functional form of population dynamics, a few studies have shown that the rate of change in the population of HS is declining over time (Arim et al., 2006; Bloch et al., 2019). A logistic growth function satisfies this finding and is commonly used in bio-economic modelling (e.g. Knowler, 2002; Prelezzo et al., 2012). This function was also applied in this study, written as:

$$g\left(Q_t^{ik}\right) = rQ_t^{ik}\left(1 - \frac{Q_t^{ik}}{P^{ik}}\right) \tag{2}$$

where *r* is the intrinsic growth rate and P^{ik} is the maximum potential population of the crab species *k* in basin *i*. A simplification was made by assuming the same intrinsic growth rate for both crab species in all basins.

S_t^{ik}, i.e. the disposal of crabs from vessels, occurs from biofouling (including sea chests) and ballast water, which vary for different vessel types depending on their size and transport routes, for example. For each vessel type, such as an oil tanker or cargo vessel, the larvae disposal creating the crabs can be mitigated by different types of BWTs and antifouling measures. BWTs use various methods such as filtration, UV light and chemicals. Each vessel measure is assumed to impact both crab species. The vessels' crab supply in a basin is then written as:

$$S_t^{ik} = \sum_m b^k s^{ik} \left(L^{im} - \sum_n R_t^{inm} \right) \tag{3}$$

where L^{im} is the supply of larval individuals of both species from vessel type m in basin i, b^k is the share of larvae supply of species k from vessels, s^{ik} is the constant fraction of the larvae supply that become crabs, which depends on the temperature and salinity in the basin (see Section 3.1), and R_t^{inm} is the removal of larvae from vessel type m with measure n.

The cost of vessel measures differs between vessel type and measure, which is written as $C^{nm}\left(R_t^{imn}\right)$. The cost of harvesting crabs is assumed to differ between the two crab species due to different habitat needs, $C^k\left(H_t^{ik}\right)$. All cost functions are assumed to be increasing and convex in their arguments. Furthermore, there is a capacity constraint on each vessel measure, which is self-evident, such that the crabs from vessels cannot be reduced by more than the supply.

The targets for the crab species include choices about maximum population sizes and when they are to be achieved. The former can be formulated in different ways. One way is to limit the total population across all basins, $Q_T^{Max,k}$, and another is to target populations in certain basins, $Q_T^{Max,ik}$, for example because of the protection of marine reserves. In this study, both types of targets were considered. The decision problem is then formulated as choosing the allocation of measures in space and time, i.e. H_t^{ik} and R_t^{imn}, which minimises the total cost of achieving a target on the maximum population size of each crab species in period T. This is written as:

$$Min\ C = \sum_t \sum_i \left(\sum_k C^k\left(H_t^{ik}\right) + \sum_n \sum_m C^{nm}\left(R_t^{inm}\right) \right) \rho_t \tag{4}$$

s.t. Eq. (1)–(2), $\sum_n R_t^{inm} \le L^{im}$, $\sum_i Q_t^{ik} \le Q_T^{Max,k}$ or $Q_t^{ik} \le Q_T^{Max,ik}$ for $k = HS,HT$.where L^{im} is the upper limit of larvae removals from vessel type m in basin i, and $\rho_t = \frac{1}{(1+v)^t}$ is the discount factor in time t with v as the discount rate.

The decision problem in eq. (4) is solved by constructing the Hamiltonian and inserting the crab targets as terminal conditions (Section A in the Supplementary Material). A condition for a cost-efficient solution is that the marginal crab removal cost shall be equal for all measures in each time period. For the target relating to maximum total population size, this condition is written as:

$$\frac{\partial C^k}{\partial H_t^{ik}} = \frac{1}{b^k s^{ik}} \left(\frac{\partial C^{mn}}{\partial R_t^{imn}} + \rho \mu_{t+1}^{il\neq k} b^{l\neq k} s^{il\neq k} \right) \tag{5}$$

where $\mu_{t+1}^{il\neq k} \le 0$ is the co-state variable, which reflects the marginal cost of the stock of the 'other' crab l in $t + 1$. The left-hand side (LHS) of Eq. (5) shows the marginal removal cost by harvest of crab k in basin i, and the right-hand side (RHS) shows the marginal removal cost of a vessel measure. The latter includes impacts on both crab species. The denominator on the RHS is the decrease in the crab population k in basin i with a marginal increase in the vessel measure. If this impact is low, the marginal cost of a ship measure is relatively high, and vice versa. However, the marginal cost of the vessel measure is reduced by the simultaneous effects on the other $l \neq k$ crab species (the second term within parentheses on the RHS of Eq. (5)).

Regarding the timing of the measures, the development along the optimal path requires equal marginal costs between time periods, i.e. it should not be possible to reduce the total cost of achieving the population target by reallocating harvest or vessel measures from one period to another. This implies a balance between the benefits and costs of delaying control. The benefit is the lower future cost of a marginal crab removal because of the discount rate. The cost is the increase in the future population from no removal, which implies higher costs of achieving the targets, the magnitude of which is determined by the crab population growth (Section A in the Supplementary Material). Thus, a relatively high discount rate compared with population growth results in a delay in removal, and vice versa.

3. Data retrieval

In order to solve the decision problem in eq. (4), data were needed on the population growth functions, the costs of harvest and vessel measures, and the setting of targets. These data were retrieved for the study region located in the fjord system of Orust-Tjörn on the west coast of Sweden, north of Gothenburg, Sweden's second largest city (Fig. S1 in the Supplementary Material). The region has a water surface area of 108 km^2 and includes three main water basins (Hakefjord, Askeröfjord and Halsefjord) and two main ports (located in Hakefjord and Askeröfjord). The two invasive *Hemigrapsus* crabs were first detected in the southern Hake basin in 2018 and are now found in all the water basins in the study area.

3.1. Population growth functions

There are no data on the initial populations of the crab species, Q_0^{ik} in eq. (1), and they were therefore calculated by multiplying the area of suitable habitats with HS and HT density. Suitable habitats are determined by the area of shallow water, approximately 0–1 m deep, without beaches that drop steeply into the sea and by the characteristics of the coastal zones. The sizes of these areas were obtained from SMHI (The Swedish Meteorological and Hydrological Institute) (2022) and the results showed that the maximum depth of 1 m coastal zones accounts for 19 % of the surface area in the Hakefjord and Askeröfjord and 14.9 % in the Halsefjord (Table S1 in the Supplementary Material).

The two crab species require slightly different habitat characteristics. Areas suitable for HS are exposed beaches with rocks, stones and gravel, while areas suitable for HT consist of more sheltered beaches with sand and mud. However, HT tolerates a wider range of habitats (from rocky to muddy shores), which partly overlaps with the distribution of HS. Suitable habitats were calculated separately for each species using information from aerial photographs and the sea charts of ten randomly selected sites with a diameter of 10 km. The estimates were calibrated with field surveys at three of the sites. The results showed that, on average, 43 % and 80 % of the sea areas with a maximum depth of 1 m offer suitable habitats for HS and HT respectively (Table S2 in the Supplementary Material).

The transect method was applied in field surveys to estimate the density of crabs in the suitable habitats. Experience suggests that it is best to catch crabs at low tide when the water has receded and left the rocks that were previously covered by water a little above the surface of the water. The crabs of both species stay under the rocks rather than follow the low tide out, thus by turning over the rocks, the crabs can be easily spotted, caught and counted. On site on a beach, transects were created by laying a 10-m tape measure along the beach, covering shallow and normal water levels. The number of crabs was calculated in an area 50 cm on either side of the tape. The results of the counts showed slight differences for the two crab species, with an average density for HS and HT of 0.87 and 1.12 crabs/m^2 respectively (Table S2 in the Supplementary Material).

The maximum population sizes in each water basin, P^{ik}, were obtained by multiplying the areas of suitable habitats by potential densities obtained from the literature. Several studies show that the density of the HS can be high, reaching 20 individuals per m^2 in Massachusetts (e.g. Bloch et al., 2019) and at least 250 individuals per m^2 for HT in northwest Europe (Cornelius et al., 2021). However, the estimated initial densities were considerably higher in these studies than the measured densities in the present study region. It was therefore assumed that the relative increase from the initial to the maximum densities was the same, corresponding to an increase in HS and HT by 18 and 13 times, respectively. These relative density increases were used in this study as approximations of maximum population sizes, which were assumed to be the same in all the water basins.

The calculation of the supply of crabs from vessels, S^{ik}, was based on estimates of larvae releases by ballast water, biofouling and niche vessel areas from different vessel types (oil, cargo, LPG, roro, chemical) in the two harbours (Stenungsund and Wallham), and on the survival rate of the larvae. Most of the traffic coming into the Orust-Tjörn fjord system is from areas where crabs are present or established (Gustafsson and Ljungren, 2023), and the duration of the larval stage allows their survival and transportation (Epifano et al., 1998). There were no data on the supply of larvae from vessels in the study region, and results from the literature were therefore transferred and combined with data on gross tonnage per vessel type and ballast water capacity (BWC) obtained from visual inspections at the two ports (Table S3 in the Supplementary Material).

The number of live organisms in vessels depends on several factors such as transport routes, antifouling practices, BWT and type of vessel (e.g. Fernandes et al., 2016). There is a large body of literature calculating the number and risks of NIS introductions by vessels (e.g. Saebi et al., 2020; Gren et al., 2022), but very few studies have quantified live organisms from ballast water, biofouling and niche areas (Bailey et al., 2022; Brinklow et al., 2022). According to Bailey et al. (2022), the zooplankton concentration in the ballast water discharge (BWD) from vessels arriving at ports in Canada ranged from 0 to 3822 per m^3 with an average concentration of 512 organisms/m^3. This concentration clearly exceeds the IMO D2 standard of a maximum of 10 viable organisms/m^3 BWD. The study was carried out shortly after the standard came into force in 2017, and compliance may subsequently have improved.

However, compliance with the IMO D2 standard is regarded as difficult since it is quite detailed and complex. In addition, the functioning of the BWTS is uncertain, and the enforcement and monitoring of compliance with the standard differ between international ports (Wright, 2021). Due to a lack of data and information on compliance with the standard, it was simply assumed in the present study that half of the vessels comply with the standard, which corresponds to the compliance rate found by Bailey et al. (2022). There is no information on the concentration of *Hemigrapsus*, but there is on the taxonomic group *Decopada*, the frequency of which accounted for 5 % of the total NIS detected. This share of the average concentration of NIS per m^3 was assumed for half of the vessels entering the study region, which is an upper limit since this taxonomic group includes several species.

Data on the discharge of NIS organisms from biofouling were obtained from Brinklow et al. (2022), who calculated live organisms and invasive species from different types of commercial ships (oil tankers, cargo, LPG and other vessels) in Canada. There was no information on the size of the vessels, and calculations were therefore made by estimating the disposal of live organisms by vessel type and assuming that the share of *Hemigrapsus* out of the total releases was the same as for discharges by ballast water, i.e. 5 % (Table S3 in the Supplementary Material).

The survival rate of larvae from ballast water and biofouling that reproduce and become crabs depends on several factors, such as salinity and temperature. There are no data on the allocation of larvae releases from vessels between the two crab species, and it was therefore assumed that they account for equal shares, i.e. $b^k = 0.5$ of the total supply. The survival rate of HS at different temperature levels has been estimated by Klassen (2012) and Espinosa-Novo et al. (2023). Both studies found a positive relationship between survival rate and temperature, and the results of Klassen (2012) also showed a positive impact of salinity. The surface salinity level is the same in the water basins in the study region and amounts to approximately 25 kg/m^3 (SMHI (The Swedish Meteorological and Hydrological Institute), 2023). The results of Klassen (2012) were therefore transferred to the present study, where survival rates of HS and HT are expressed as linear functions of long-term average temperature in different months of the year in each of the water basins (Table S4 in the Supplementary Material). The results showed a small difference in survival rates between the basins for both species, but the survival rate of HT was higher than that of HS, amounting to approximately 0.15 and 0.10, respectively (Tables S5-S6 in the Supplementary Material).

Given all these assumptions, the calculated initial and maximum populations and the vessel supply of crabs are as presented in Table 1.

The largest share of total initial crabs is found in the Hake basin because of its relatively large area of suitable habitats compared with the other basins. The relatively large annual vessel supply in the Askerö basin is explained by the discharges from ballast water by vessels at Stenungsund port where ship traffic is high (Table S3 in the Supplementary Material). LPG and oil tankers in Stenungsund harbour account for approximately 75 % of the total crab disposal.

The dispersion of crabs between the basins was studied using a high-resolution ocean coastal model (Brunnabend et al., 2020) that drives a trajectory analysis that gives connectivity matrices in terms of probabilities similar to Jonsson et al. (2020). A high-resolution model was then coupled to a medium-scale ocean circulation model. The trajectory analysis was performed with an open-source Python-based model (Table S7 in the Supplementary Material). In addition, the resulting connectivity matrices depend on assumptions about the biological traits of the dispersals and how to model them. Here, dispersal was assumed to occur throughout the larval stage.

There are no data on the timing of the settling of the larvae on shores during their life of approximately four weeks. Therefore, model experiments were performed with three different settling assumptions at one time occasion of larvae release in an area with a depth of less than 0.5 m: immediately, after three weeks and after four weeks (Table S7 in the Supplementary Material). The major direction of flow was northward in the study area during the lifetime of larvae for this time of release, which varies with wind direction, tides, stratification etc. The results from the second assumption about settling after three weeks were used in the reference case (Table 2).

The final parameter in the population growth functions is the intrinsic growth rate, r. Bloch et al. (2019) estimated an annual population growth rate of invasive HS that varies between −0.5 and 1.6 during the period 2002 and 2012 on Cape Cod in Massachusetts. In the present study, a rate of 0.25 was assumed for both crab species.

3.2. Costs of mitigation measures, discount rate and target formulation

This study comprised three types of measures: harvesting of crabs, antifouling, and cleaning of ballast water. Harvesting of crabs can be done by picking crabs on the shore and by cages in the sea, both of which are labour intensive. Therefore, the cost per hour is assumed to correspond to the average salary for workers of municipalities, including payroll taxes in Sweden, which amounts to 18.8 euros/h (Swedish Statistics, 2022). The cost of the crab harvest then depends on the number of crabs harvested per hour, which is determined by the size of the spot surveyed and the density of crabs. Based on experiences from the measurement of crab species density, a simplification was made in the present study that one hour on average is needed to examine 100 m^2. Time is needed to examine the existence of crabs under stones along the shore, both of which differ between locations. It was assumed that this is reflected in the measured density of crabs per m^2 at different spots (Table S2 in the Supplementary Material). The cost per harvest unit then depends on the densities, with high density implying a relatively low cost and vice versa. At a given labour cost, the highest unit cost is determined at the lowest density, which is 0.1 and 0.4/m^2 for HS and HT respectively.

The cost function for each crab species is assigned a quadratic form

Table 1

Calculated initial population and vessel supply of HS and HT crabs in different basins, million crabs (symbols refer to Eqs. (1)–(2) in Section 2).

	Hake		Askerö		Halse		Total	
	HS	HT	HS	HT	HS	HT	HS	HT
Initial population, Q^{ik} [a]	5.43	13.01	1.27	3.04	0.79	1.88	7.49	17.92
Maximum population, P^{ik} [b]	98	169	23	40	14	24	135	233
Annual vessel supply, S^{ik} [c]	0.09	0.12	1.88	2.77			1.97	2.89

[a] Tables S1-S2 in Supplementary Material; [b]maximum density of 15.7 and 14.6 crabs per m^2 of HS and HT, respectively, multiplied by the area of suitable habitats; [c]supply of crab larvae, L^{im}, (Table S3 in the Supplementary Material), multiplied by the shares of HS and HT larvae $b^k = 0.5$ and the shares of larvae that survive and become crabs, s^{ik}, (Tables S4-S6 in the Supplementary Material).

Table 2

Transport coefficient a^{ji} as share of total larvae from basin j (row) that is transported to basin i (column) of total transport in basin j in the reference case.

From\to	Hake	Askerö	Halse	Outside study area
Hake	0.54	0.21	0.13	0.12
Askerö	0.09	0.43	0.22	0.26
Halse	0.01	0.23	0.45	0.31

Table 3

Estimated cost functions for crab removals by harvest (*H*) and prevention by ship measures *(R)*.

Measure	HS		HT	
Harvest[a]	$0.125*(H)^2$		$0.013*(H)^2$	
Vessels[b]:	BWT	Anti-fouling	BWT	Antifouling
Oil tanker	0.24*R	0.65*R	0.16*R	0.44*R
Cargo	0.73*R	0.61*R	0.50*R	0.42*R
LPG	0.24*R	0.67*R	0.16*R	0.46*R
Roro	0.73*R	0.18*R	0.50*R	0.12*R
Chemical	0.26*R	0.30*R	0.17*R	0.20*R

[a] Table S8 in the Supplementary Material.

[b] $R = b^k s^{ik} R^{inm}$ is the crab prevention by vessels in the Askerö basin (Table S9 in the Supplementary Material).

where the value of parameter is obtained by assuming a linear relation in the marginal harvest cost from zero to the initial population sizes presented in Table 1. The maximum marginal harvest cost at a labour cost of 18.8 euros/h is then 1.88 euros and 0.47 euros per unit HS and HT crab, respectively. A cost function is then obtained by integrating the marginal cost function for each crab species (Table S8 in the Supplementary Material).

Regarding the cost of ship measures, there is a relatively large body of literature on the assessment of the performance of different BWTSs (review in Nwigwe and Kiyokazu, 2023), but only a few studies have performed systematic calculations of the cost of the treatment systems and anti-fouling measures (King et al., 2012; Fernandes et al., 2016; Wang et al., 2021). Costs include investment and operational costs, which are usually annualised with assumptions about the technical life length of the equipment and the discount rate. Such calculations were made by King et al. (2012) and Fernandes et al. (2016), and their results were used in the present study.

King et al. (2012) calculated the cost of BWTS for cargo, roro and tankers. They did not distinguish between different types of tankers, and the cost estimate is therefore assumed to be the same for oil tankers, LPG tankers and chemical tankers. The cost per larvae removal is then calculated by assuming a discharge of 13 larvae/t (Table S3 in the Supplementary Material). Fernandes et al. (2016) calculated costs of antifouling systems as percentage increases in the total annualised operational and investment costs of BWC for similar vessel types to those in King et al. (2012). With data on the costs of BWTS, these relationships were used to calculate the costs of antifouling measures (details in Table S9 in the Supplementary Material).

In order to compare the costs of harvest with those of vessel measures, the cost of larvae reductions by vessel measures is expressed in terms of crab preventions into the water basins. The calculated quadratic cost functions for harvest in all the water basins and the linear cost functions for BWT and antifouling measures in the Askerö water basin are presented in Table 3.

The unit cost of vessel measures in the Hake basin is slightly lower than that in the Askerö basin because of the higher survival rate.

The formulation of targets includes quantification of maximum population sizes in different water basins and the timing of achievement. There are no specific targets relating to any invasive species in Sweden, but only general formulations such as 'managing and eradicating invasive species' (translation from Swedish) (Riksrevisionen, 2022, page 9). In this study, an eradication target was considered, and the 'managing' objective was interpreted as avoiding increases in the total populations presented in Table 1. The vulnerability to the crabs may differ between water basins, but there exist no data or information on the responses in the basins. The Askerö water basin contains areas with the most species-rich and diverse marine waters in Sweden, which are protected under the EU Species and Habitats Directive (Swedish Environmental Protection Agency, 2024). The basin also accounts for the largest supply of crabs from vessels as shown in Table 1. Therefore, targets are introduced at two spatial levels: all basins and only the Askerö basin in order to evaluate effects on the cost-efficient allocation of measures of different spatial targets. The timing of the achievement of the targets is based on the EU directives on biodiversity targets, which Sweden must comply with. One target is the restoration of 20 % of damaged ecosystems in 2030, and another is the restoration of all ecosystems in need in 2050 (EC, 2023). The time perspective chosen in this study in the reference case is a period between these two time specifications, which is approximately 20 years. The formulation of targets is summarized in Table 4.

The final component in the decision problem is the social discount rate, which is much debated in the literature (e.g. Weitzmann, 2001). Without any data or information, the usual assumption is made in this paper that it corresponds to the average long-term growth rate of gross domestic product (e.g. Boardman et al., 2011). The growth rate amounts to 2.7 % per year for the period 1950–2018 (Konjunkturinstitutet, 2019).

The decision problem is solved for each combination of quantified and spatial targets, i.e. four different decision problems, in the reference case and for the sensitivity analyses with the mathematical programming code GAMS using the Conopt solver (Rosenthal, 2008).

Table 4

Summary of target formulations on maximum crab population sizes.

Target	Description
Quantification	Simultaneous 'eradication' and 'no increase' of initial populations of both crab species
Spatial targets	All water basins and Askerö basin only
Timing	20 years

4. Results

4.1. Reference case

The results indicate the differences and similarities in the minimum costs of the four combinations of target formulations (Fig. 1).

The allocation of cost are similar for all targets where the harvest cost of HS is approximately four times higher than the cost of HT harvest. This is explained by the low control cost of HT, which compensates for the large population decrease due to the high initial population. The total costs are similar in all cases except for the eradication of crabs in all water basins. The similar cost for the 'no increase' target for both spatial targets depends on the initial population size in all water basins, which is six times higher than in the Askerö basin alone. These large population sizes also explain the high cost of eradication of the populations because of the need for early harvest in order to achieve the target on time (Fig. 2).

Both the harvest measures and vessel measures are implemented during the entire period under both spatial targets. Except for the 'eradication' target for all water basins, the development over time is similar, with slight annual increases in harvest except for the last few years and the steady and constant implementation of vessel measures. The cost-efficient eradication of crabs in all water basins requires a large early harvest during the first eight years to reduce initial crab populations. Thereafter, all available vessel measures are implemented to inhibit crab establishments.

Similar to the cost-efficient timing of harvest and vessel measures, the cost-efficient spatial allocation shows similarities and differences between target combinations (Table 5).

Common to all target formulations is the need to harvest crabs in all water basins and implement vessel measures in Hake and Askerö basins under all four combinations of target formulations. This is explained by the relatively large sizes of initial populations in the Hake basin, disposal by vessels in the Askerö basin and the inter-basin crab transports. As expected, crab removals by both harvest and vessel measures in the Hake and Halse basins are largest for the targets on maximum populations in all water basins, but focused on the Askerö basin for this basin-specific target due to the direct impact of measures in this basin.

4.2. Sensitivity analyses

The results were affected by changes in the biophysical and economic parameter values and target formulations used in the reference case presented in Tables 1–4 in Section 3. The biophysical parameters include initial and maximum populations, inter-basin transports, the survival rates of larvae from vessel discharges, the allocation of HS and HT in vessel supplies, and intrinsic growth rate. In the present study, experiments were performed only for the transport coefficients of the inter-basin connectivity, with an assumption about the attachments of larvae to the shores in the basin in which they are released, so-called sticky and non-sticky shores (Table S7 in the Supplementary Material). Minimum costs were then calculated for these two transport matrices and for deviations by 50 % from the reference values of all other biophysical parameters values presented in Table 1. The results for the 'eradication' target at both spatial scales are presented in Fig. 3.

The sensitivity of the results to changes in the parameter values can be measured by 'elasticities' in absolute value, i.e. the percentage change in minimum cost divided by the percentage change in the reference value of the respective parameter. At most, this elasticity amounts to 1.8 (increase in maximum population size), followed by the elasticity of changes in initial population sizes (1.3) and vessel supply (1.2).

The elasticities of the other parameter values are relatively low and do not exceed 0.5. The impacts of changes in intrinsic growth rate are explained by the net effect of two counteracting forces: the decrease (increase) in marginal control cost because of the avoided high (low) future population growth and the increase (decrease) in costs due to the high (low) population size in the target year. The latter is limited by the maximum potential population sizes, which implies that the marginal impact on future population growth dominates in the present study. The cost increases when the share of HS increases due to the high harvest cost for this crab species. Costs are slightly lower with the 'no sticky' shores because of the decrease in crab populations in the water basins for both spatial targets. The different impacts on costs with the 'sticky shores' is explained by the larger population sizes in all water basins, but lower population sizes in the Askerö basin because of the reduction in transports from the Hake basin. The pattern of impacts is similar for the 'no increase' target (Fig. S3 in the Supplementary Material).

The economic factors are the costs of harvest measures and ship measures and discount rate, and the calculations of minimum costs made for deviations by 50 % from the reference values of the cost functions presented in Table 3. The target formulations include quantification and timing of achieving the target and separate or simultaneous control of the crab species. Calculations show that minimum costs increase rapidly for eradicating the last 10 % of the population sizes in all water basins, but increase only slightly in the Askerö basin (Fig. S4 in the Supplementary Material). The choice of target year has an impact with a shorter time period for reaching a target increasing costs, and vice

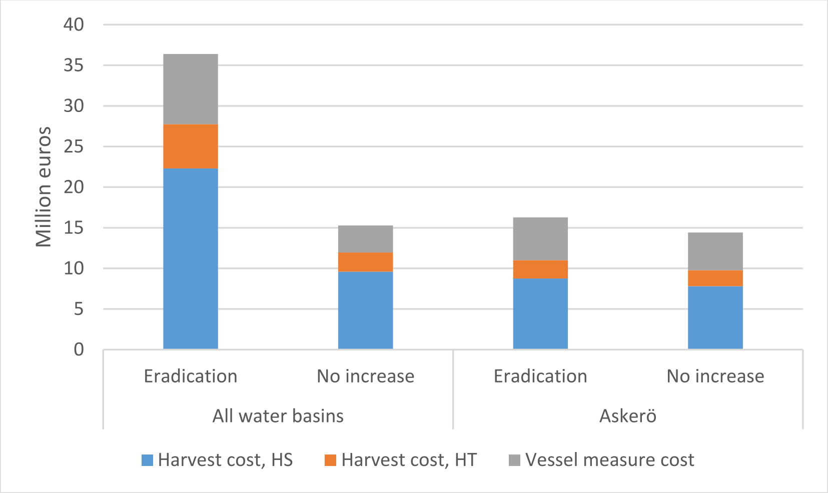

Fig. 1. Minimum discounted total costs and the allocation between harvest of HS and HT, and vessel measures for achieving targets on 'eradication' and 'no increase' of initial populations of HS and HT crabs in all water basins, and in the Askerö basin only, in 20 years (million euros).

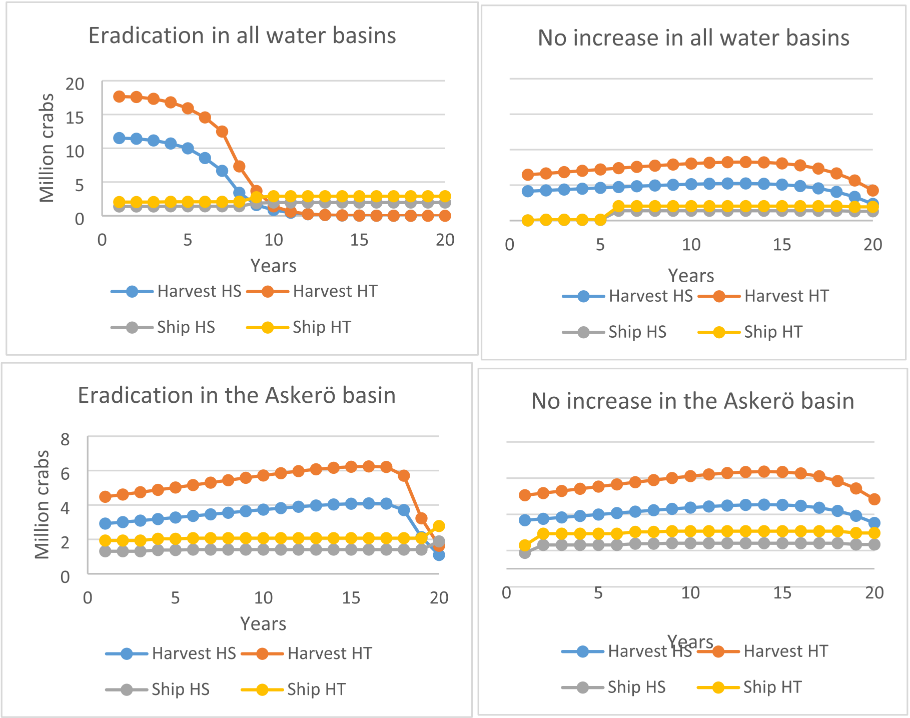

Fig. 2. Cost-efficient annual harvest and ship measures for the 'eradication' and 'no increase' targets for initial populations of HS and HT in all water basins and in the Askerö basin only in 20 years (million crabs).

Table 5
Cost-efficient allocation of removal of crabs by harvest measures and vessel measures in all water basins and in Askerö basin only in 20 years (million crabs).

	Hake		Askerö		Halse	
	HS	HT	HS	HT	HS	HT
All water basins						
Eradication						
Harvest	40	71	30	45	14	22
Vessel	2	2	36	53		
No increase						
Harvest	44	76	35	48	12	20
Vessels	1	2	20	29		
Askerö basin						
Eradication						
Harvest	25	39	39	60	4	6
Vessels	1	2	28	42		
No increase						
Harvest	21	32	38	59	2	4
Vessels	1	1	26	39		

versa. Calculations were made for 50 % changes in the time period, which coincides with the short-term and long-term perspectives adopted by the EU biodiversity directive (EC, 2023) set at 10 years and 30 years, respectively. It was assumed in the reference case that both crab species should be reduced by the same percentage under all target formulations. In general, policies for mitigating invasive species are focused on single species. In order to evaluate the cost impact of separate species targets, calculations were made for this case.

The results indicated that the elasticities for reaching the 'eradication' target are relatively low for changes in the economic parameters, but high for a decrease in the time perspective (Fig. 4).

The largest relative response in minimum costs occurs for a 50 % decrease in the time perspective, for which the elasticity is 2. A shorter time period necessitates early removals in order to achieve the target in time, and reduces the possibility of saving costs by delaying mitigation because of the discount rate, and vice versa with a longer time period. The impact of changes in harvest cost is higher than those of the costs of vessel measures because of the larger crab removals by harvest. As expected, the costs increase with a low discount rate, and vice versa. Separate management of the crab species would increase minimum costs by 15 % and 10 % for eradication in all waters and in the Askerö basin, respectively, because of the complementarity in crab larvae decreases by vessel measures. The impacts are similar for the 'no increase' target (Fig. S5 in the Supplementary Material).

5. Discussion and conclusions

One of the main conclusions of this study is that both control and prevention measures in the same zone should be considered for the cost-efficient attainment of predetermined targets relating to the population of invasive *Hemigrapsus* on Sweden's west coast. Results from other studies on prevention and control show the balance between either prevention or control of a NIS to a specific zone and consider implementation of both measures in a region with dispersal between invaded and non-invaded zones. The results also highlighted the role of target formulation and inclusion of two NIS. The cost of eradication of crabs in all water basins was twice the cost of no increase in the crab populations, but the main increase occurs for eradicating the last 10 % of the population. However, this was not the case for the local basin target because of the availability of low cost measures in surrounding basins with crab dispersals to the target basin. The inclusion of the two *Hemigrapsus* crabs revealed large differences in control cost where the cost for decreasing population of HS was four times the cost of reducing HT. Another result was that the cost of simultaneous control of HS and HT can be 20 % lower than separate management because of economies of scope of vessel measures. The focus on one species at a time, which is common in the literature and in practice in combating invasive species in Sweden, leads to unnecessarily high costs for achieving targets for both species.

Other novel results were that the prevention and control strategies

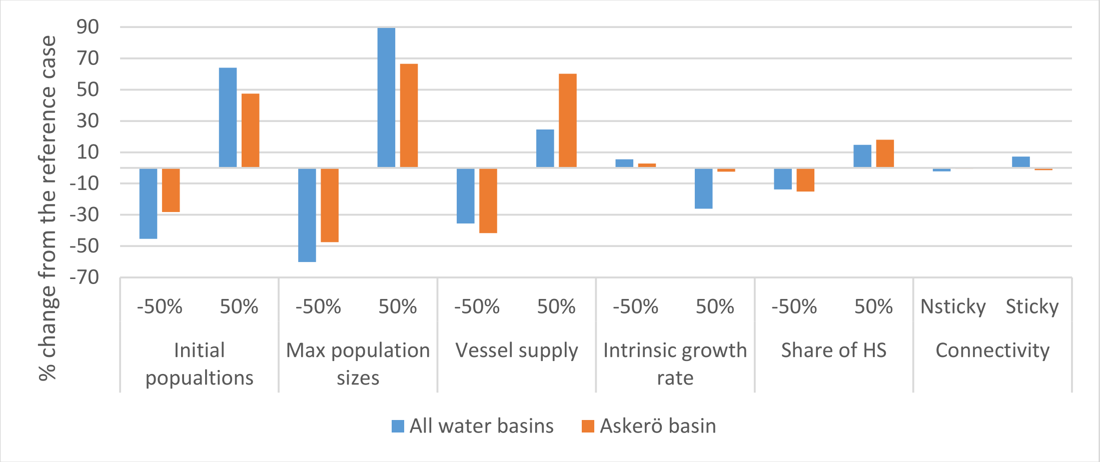

Fig. 3. Change in % in minimum costs from the reference costs of changes in parameter values in the population growth functions for the ‘eradication’ target in all water basins and in the Askerö basin only.

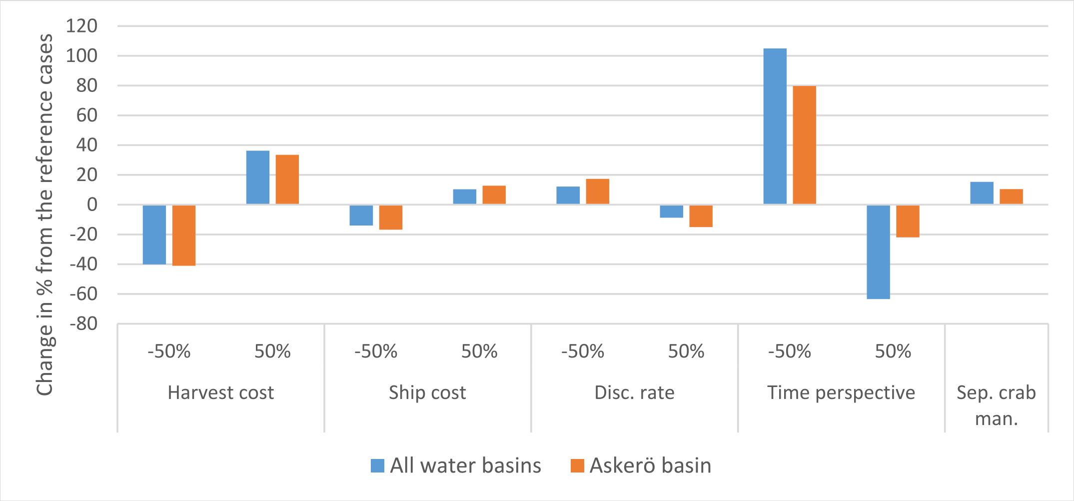

Fig. 4. Change in minimum costs from the reference cases for changes in harvest and ship measure costs, discount rate, time perspective and separate management of each crab species for the eradication of crabs in all basins and in the Askerö basin only.

differ between the targets. While all four target specifications imply a steady reduction in larvae from vessels in all years, the harvest is relatively low in early periods for all targets but eradication of crabs in all water basins. It is then necessary to reduce the existing populations early and then, in addition, continue to mitigate the instantaneous vessel discharges of the crabs. The results also pointed out the role of spatial allocation of established crabs and new introductions, the large parts of which were found in two different water basins implying that control and prevention measures always take place in these basins because of the inter-basin transports irrespective of target formulation.

Despite the focus on cost-efficient achievement of NIS population targets without the need of quantified damage of the NIS, the present study faced large challenges regarding the availability of data needed. The uncertainty in the parameter values was approached with sensitivity analyses using estimates of cost-efficient outcomes for ranges in the values of each parameter. This analysis showed that the cost estimates are robust to changes in the estimates of inter-basin transports for one time occasion of larvae release, which indicates that the matrix can be useful for management of other live organisms than crabs in the study region. On the other hand, the results showed that the minimum costs could be halved or doubled compared with the reference case due to deviations by 50 % from the reference values of initial and maximum crab population sizes. This result supports findings in the literature that highlight the value of information from improved surveillance and monitoring with greater precision in detection and estimation of the magnitude of an invader (review in Epanchin-Niell, 2017). The results also highlighted the role of more politically-oriented decisions in the determination and quantification of the target. For example, a reduction in the time perspective from 20 years in the reference case to 10 years increased the cost of eradicating the crab population in all water basins by 105 %.

The variation in costs of between 0.6 and 7.2 million euros on average per year, depending on the target formulation and parameter values, raises the question of whether the costs of implementing removal programmes are sufficiently low or too high. One response would be that the costs are too great if they exceed the value of the corresponding target achievement. This involves the valuation of crab removals in monetary terms, the difficulties of which are well known in the literature and in practice. Only a few studies have undertaken such valuations for aquatic NIS, but none for the invasive crabs examined in this study (e.g. Marbuah et al., 2014; Cuthbert et al., 2021). One option would then be to compare the costs of removal of crabs with the removal of other invasive species for the prioritisation of targeted species. In Sweden, the cost of mitigating invasive species in 2021 was approximately 12 million euros (Riksrevisionen, 2022). The number of classified invasive species in Sweden was approximately 850 in 2018 (Strand et al., 2018), and in light of that even the calculated low cost of crab removals in this study may seem relatively high. However, the simultaneous effects on several invasive aquatic species of reducing the supply of live organisms from vessels motivate the introduction of ship measures.

A final remark is that this study has shown the importance not only of improved data for assessing parameter values in the crab population and cost functions, which is a common result in the literature applying to data-poor case studies, but also of the need to examine the impacts of more politically-oriented decisions on the formulation and quantification of the targets to be achieved. The suggested bio-economic method can then be applied to several invasive species for the prioritisation of species management. As such, this study may be regarded as a proof-of-concept analysis that does not make direct policy recommendations, but rather indirectly presents the responses of cost-efficient solutions to changes in scientific- based analysis and data and in assumptions about policymakers' target decisions.

CRediT authorship contribution statement

Ing-Marie Gren: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lars Arneborg:** Writing – review & editing, Software, Data curation, Conceptualization. **Sandra-Esther Brunnabend:** Writing – review & editing, Data curation. **Sam Fredriksson:** Writing – review & editing, Validation, Software, Data curation, Conceptualization. **Lena Granhag:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation, Conceptualization. **Björn Källström:** Writing – review & editing, Validation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108612.

Data availability

Data will be made available on request.

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