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No-take marine reserves and illegal fishing under imperfect enforcement*

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No-take marine reserves have been increasingly advocated as an effective means of supporting marine ecosystems and conserving fisheries resources. A major problem that can hinder the effectiveness of no-take reserves is the incidence of illegal fishing, which has created significant ecological and economic losses in global fisheries. We construct a bioeconomic model to explore the connection between the effects of no-take reserves and illegal fishing activities in relation to the level of regulatory control of illegal activities in the reserve and fished areas. Our parameterised model shows that the effects of no-take reserves on both the extent of illegal fishing and the fish biomass critically depend on illegal fishing regulations and the scale and patterns of fish dispersal. In a fishery where illegal fishing can only be partially controlled, increasing the size of the no-take reserve may result in a lose-lose situation in which the level of illegal fishing effort increases and the total biomass decreases. Our results further show that when the pattern of fish dispersal is density dependent, imposing a stricter control on illegal fishing in either reserves or fished areas increases the aggregate level of illegal fishing.

Key words: bioeconomic models, fisheries management, illegal activities, marine reserves.

1. Introduction

Many countries face major challenges in restoring depleted fish stocks and promoting sustainable fishing practices in marine capture fisheries (Worm *et al*. 2009; Sumaila *et al*. 2012). The use of no-take marine reserves has been advocated globally as a conservation and fisheries management strategy to achieve sustainability goals (Roberts *et al*. 2005). There is significant evidence of the conservation benefits of no-take reserves (Lester *et al*. 2009). Previous studies have also shown that the implementation of no-take reserves can generate a range of economic benefits, such as enhancing tourism and recreational activities, generating spillovers of larvae and adults to adjacent

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fished areas and improving the resilience of fisheries to environmental disturbances (Bhat 2003; Grafton *et al*. 2009; Grüss *et al*. 2011).

Although a wide range of benefits has been cited in previous research, the conservation and economic benefits of reserve establishment depend critically on regulation of fishing activities outside the reserve (Little *et al*. 2011; Yamazaki *et al*. 2012). For example, the prohibition on catch within the reserve can cause fishing effort to be displaced to the remaining open areas. In the absence of effective off-reserve management, such spatial displacement of fishing effort may result in the overexploitation of fish stocks (Holland 2000; Smith and Wilen 2003).

One major factor that prevents the effective control of fishing pressure and may inhibit the conservation and economic benefits of no-take reserves is the existence of illegal, unreported and unregulated (IUU) fishing, loosely termed in this paper illegal fishing.[1] Illegal fishing is a major threat to many marine species and ecosystems due to unsustainable fishing practices (MRAG 2005; OECD 2005).[2] These activities have led to significant economic losses, both directly from lost catches and indirectly from the degradation of fish habitats (Sumaila *et al*. 2006), with estimated global economic losses of over \$10 billion per annum or 13–31 percent of reported catches by major fisheries (Agnew *et al*. 2009). In a fishery where the regulation of illegal fishing is absent, the long-run outcome for the fishery is the bionomic equilibrium of the open-access fishery where the net returns from fishing are reduced to zero.

Despite the detrimental effects of illegal fishing, existing studies examining the effectiveness of no-take reserves rarely account for illegal fishing. There are only a few exceptions in which the efficacy of no-take reserves has been studied in the presence of poaching in the reserve (e.g. Kritzer 2004; Byers and Noonburg 2007; Sethi and Hilborn 2008). Yet there remains a lack of knowledge about how reserves affect the aggregate level of illegal fishing and how the regulatory enforcement of illegal fishing and the reserve establishment jointly affect the biological and economic outcomes for the fishery. This paper fills this gap by developing a stylised bioeconomic model of the fishery that captures the connection between the implementation of a no-take reserve and regulatory control of illegal fishing.

Our study builds on the existing literature on the economics of fisheries' noncompliance (Sutinen and Andersen 1985; Milliman 1986; Furlong 1991; Nøstbakken 2008) and bioeconomic models of no-take marine reserves (Hannesson 1998; Grafton *et al*. 2006; Sanchirico *et al*. 2006; Yamazaki *et al*. 2010). The contribution of this paper is to evaluate: (i) the impact of no-take reserves of different sizes on the aggregate level of illegal fishing; (ii) whether

[1] IUU fishing encompasses a range of fisheries catches, including those with no legal right as well as unreported and misreported catches and discards. See OECD (2005) for detailed discussions on different types of IUU fishing.

[2] Poaching is also a significant threat to wildlife conservation in the terrestrial environment. See Milner-Gulland and Leader-Williams (1992).

the establishment of no-take reserves helps to achieve a target level of biomass when both reserve and fished areas are exposed to illegal fishing; and (iii) how the effects of reserve establishment change according to different levels of regulatory control of illegal fishing and to different patterns of fish dispersal between the reserve and fished areas. While we use illegal exploitation of marine resources as our case study to explore the linkage between no-take reserves and enforcement, the issues addressed are important for harvested natural resources in general.

The rest of the paper is organised as follows. In Section 2, we construct a bioeconomic model that explicitly incorporates the establishment of a no-take reserve and illegal exploitation of fish stocks in both the reserve and surrounding fished areas. We set up a dynamic optimisation problem to derive a fishery management target and the optimal effort control rule to maximise the net present value of the fishery. In Section 3, we use the parameter values from the South Georgia Patagonian toothfish fishery to numerically solve the bioeconomic model developed in Section 2. We lastly conduct a sensitivity analysis to examine how our results respond to different patterns of fish dispersal between the reserve and fished areas. The final section provides concluding remarks.

2. A bioeconomic model incorporating no-take reserves and illegal fishing

2.1. Biomass dynamics

Following previous studies, such as Hannesson (1998), Sanchirico *et al.* (2006), and Grafton *et al.* (2009), we incorporate a no-take reserve into a bioeconomic model by using a metapopulation framework in which the harvest and reserve subpopulations x_H, $x_R \geq 0$, are spatially structured into discrete patches. The reserve size is defined as a proportion of the population carrying capacity on which fishing is prohibited.[3]

The biomass dynamics for the harvest and reserve population are, respectively, given as:

$$\dot{x}_H = G_H(x_H) + T(x_H, x_R) - h - h_H^{\mathrm{IUU}} \tag{1}$$

$$\dot{x}_R = G_R(x_R) - T(x_H, x_R) - h_R^{\mathrm{IUU}} \tag{2}$$

where $G_H(.)$ and $G_R(.)$ are the population specific growth function, and $T(.)$ is the fish transfer function that links the two subpopulations. Because fishing of the reserve population is prohibited, the legal harvest, $h \geq 0$, is included in the biomass dynamics of the harvest population only. In contrast, illegal

[3] The effectiveness of a no-take marine reserve depends, among others, on its size, shape and spatial placement. A population-based model incorporates the size of no-take marine reserves, but it does not directly incorporate the shape.

fishing of both the harvest and reserve populations may be occurring, that is $h_R^{\mathrm{IUU}} \geq 0$.

For both fish populations, we use the density-dependent growth function (Grafton *et al.* 2009), that is:

$$G_H(.) = rx_H(1 - x_H/[(1 - s)K])\text{and}G_R(.) = rx_R(1 - x_R/[sK]) \tag{3}$$

where r is the intrinsic growth rate and K is the carrying capacity. The size of the no-take reserve is determined by the parameter s, which takes a value between zero and one, that is 0 percent to 100 percent reserve. We specify the transfer function as:

$$T(.) = m(1 - s)\left[\frac{x_R}{s} - \frac{x_H}{(1 - s)}\right] \tag{4}$$

where $m \geq 0$ is the transfer coefficient that determines the extent of the spillover effect between the harvest and reserve populations. This specification of the transfer function assumes that the spillover effect between the two populations is density dependent (Abesamis and Russ 2005). While the transfer function given in (4) is not a unique form incorporating the density-dependent nature of the spillover effect, we adopt this functional form because earlier bioeconomic studies have used the same or similar functional form (Hannesson 1998; Sanchirico and Wilen 2001; Grafton *et al.* 2006; White and Costello 2011). For the further discussion regarding the density-dependent and independent characteristics of fish migration, see Grüss *et al.* (2011).

Earlier studies of marine reserves find that the economic outcomes of the reserve establishment critically depend on the pattern and scale of fish dispersal between the reserve and adjacent fishery area (Grafton *et al.* 2006; Sanchirico *et al.* 2006), which is determined by, for example, species life history traits, habitat connectivity, interspecies interactions and human interventions (Grüss *et al.* 2011). The sensitivity of our results to the density-dependent assumption of fish dispersal is explored by using alternative specifications for the biomass dynamics equations, given as:

$$\dot{x}_H = G_H(x_H) + m_{\mathrm{HH}}x_H + m_{\mathrm{HR}}x_R - h - h_H^{\mathrm{IUU}} \tag{5}$$

$$\dot{x}_R = G_R(x_R) + m_{\mathrm{RR}}x_R + m_{\mathrm{RH}}x_H - h_R^{\mathrm{IUU}} \tag{6}$$

where $m_{ii} \leq 0$ ($i = H, R$) is the rate of emigration from the population i, and $m_{ij} \geq 0$ ($i, j = H, R, i \neq j$) is the rate of dispersal from the population j to i (Sanchirico and Wilen 2001). The density-dependent nature of fish dispersal disappears with this specification, and the dispersal process is determined by the four parameters, m_{HH}, m_{HR}, m_{RR} and m_{RH}.[4] Sanchirico and Wilen (2001)

[4] One critical difference between the transfer function given in (4) and that given in (5) and (6) is that the direction of fish movement is endogenously determined in (4) depending on the relative size of the harvest and reserve populations, whereas in (5) and (6), the pattern of dispersion is predetermined by the parameters m_{ij} $i, j = H, R, i \neq j$.

use the same specification of the biomass dynamics equation to examine the effects of reserve establishment in an open-access fishery under a sink-source dispersal system. Here, fish dispersal is unidirectional from the source (*reserve*) to the sink (*harvest*) population, such that $m_{HH} = 0$, $m_{RR} < 0$, $m_{HR} > 0$ and $m_{RH} = 0$. The sensitivity analysis results are provided in Section 3.4.

2.2. Biomass management target and harvest control rule

Following Yamazaki *et al.* (2014), we define the biomass level associated with maximum economic yields, or B_{MEY}, as the management target of the fishery. In calculating B_{MEY}, we assume that there are no illegal fishing activities in either the harvest or reserve populations, $h_H^{IUU} = h_R^{IUU} = 0$, such that illegal activity is fully controlled.[5]

We specify the instantaneous profit of the legal harvest as $ph - cE$, where p is the unit price of landed fish, E is fishing effort, and c is the cost per unit of effort. We assume that the harvest follows the standard Schaefer production function given as $h = qEx_H$, where q is the catchability coefficient. Letting ρ be the discount rate, the management problem can be formulated as:

$$\max_{E(t)} \int_0^{\infty} \exp(-t\rho)[pqE(t)x_H(t) - cE(t)]dt \tag{7}$$

Subject to biomass dynamics (1) and (2), given initial conditions $x_j(0) = x_j^0$, $j = H, R$. The current value Hamiltonian for this problem is given as:

$$\begin{aligned} \hat{H}(E, x_H, x_R, \mu_H, \mu_R) = pqEx_H - cE + \mu_H[G_H(x_H) + T(x_H, x_R) - qEx_H] \\ + \mu_R[G_R(x_R) - T(x_H, x_R)] \end{aligned} \tag{8}$$

where μ_H and μ_R are the shadow prices of the harvest and reserve populations, respectively. Because the control variable E is linear in the instantaneous net profit function, the optimal control rule is the most rapid approach path strategy (Clark 1990), such that:

$$E = \begin{cases} E_{\max} \\ \frac{G_H(x_H) + T(x_H, x_R)}{qx_H} \\ 0 \end{cases} \text{if} \begin{cases} \sigma > 0 \\ \sigma = 0 \\ \sigma < 0 \end{cases} \tag{9}$$

where $\sigma = pqx_H - c - \mu_H qx_H$ is the switching function. This control rule sets the level of legal effort, hence harvest, in each period depending on the

[5] An alternative way of calculating a biomass target is to incorporate the expected illegal fishing under different assumptions of illegal fishing regulations.

marginal cost and benefit of additional landings and ensures that the B_{MEY} target is achieved within the shortest period. In other words, the maximum attainable level of the harvest, $h_{max} = qE_{max}x_H$, is taken when the marginal benefit of the harvest is greater than the marginal benefit of delaying the harvest ($\sigma > 0$). In contrast, the fishery is entirely closed ($E = 0$) when the marginal benefit of delaying the harvest is greater than the marginal benefit of the harvest ($\sigma < 0$). The equilibrium condition is satisfied when $\sigma = 0$, for which the level of harvest is equal to the surplus production of the exploited population ($\dot{x}_H = 0$).

Using the first-order conditions, $\partial\hat{H}/\partial E = 0$, $\rho\mu_H - \dot{\mu}_H = \partial\hat{H}/\partial x_H$ and $\rho\mu_R - \dot{\mu}_R = \partial\hat{H}/\partial x_R$, we obtain a modified version of the Clark and Munro (1975) golden rule, such that:

$$\rho = r\left(1 - \frac{2x_H^*}{(1-s)K}\right) + \frac{cqE^*}{pqx_H^* - c} - \frac{\left(\rho - r\left(1 - 2x_R^*/[sK]\right)\right)m}{\rho - r\left(1 - 2x_R^*/[sK]\right) + m(1-s)/s} \tag{10}$$

As for the Clark and Munro golden rule, this modified rule implies that the marginal benefit and cost of delaying the harvest to the next period are equalised at the steady state. We use Equation (10), together with the biomass dynamics Equations (1) and (2) at the steady state, ($\dot{x}_H = 0$ and $\dot{x}_R = 0$) to find the biomass management target associated with B_{MEY}, $x^* = x_H^* + x_R^*$.

2.3. Biomass dynamics in the absence of illegal fishing

Figure 1 illustrates a phase diagram of biomass dynamics of the harvest and reserve populations in the absence of illegal fishing.[6] The two curves shown in the figure are the $\dot{x}_H = 0$ and $\dot{x}_R = 0$ isoclines, along which the sizes of the harvest and reserve populations remain unchanged. The isoclines divide the phase plane into five regions, R1–R5, within each of which $\dot{x}_H$ and $\dot{x}_R$ have a constant sign.

In the absence of illegal fishing, the steady-state level of the harvest and reserve populations is at the biomass management target (x_H^*, x_R^*), denoted as e^* in Figure 1. When the harvest population is at a higher level than the biomass target (R1 and R2, $x_H > x_H^*$), the maximum feasible level of harvest is taken. For the reserve population, on the other hand, a gradual adjustment takes place because the reserve population is not exposed to any fishing pressure when there is no illegal fishing.

When the harvest population is lower than the target level (R3–R5, $x_H < x_H^*$), the fishery is closed until the exploitable biomass is rebuilt to its target level. In this case, the biomass dynamics of the harvest and reserve

[6] The derivation of the $\dot{x}_H = 0$ and $\dot{x}_R = 0$ isoclines and the properties of the phase diagram are available from the authors on request or from the corresponding author's webpage.

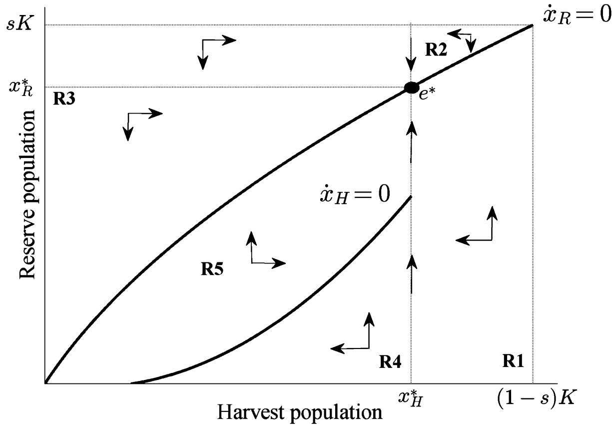

Figure 1 Biomass dynamics of the harvest and reserve populations when there is no illegal fishing.

populations depend on their relative sizes. For instance, spillover of the exploited species occurs from the reserve to the harvest population, when the size of the reserve population is larger relative to the harvest population (R3). Conversely, when the relative size of the reserve population is smaller than the harvest population, spillover occurs from the harvest to the reserve populations (R4). When the relative size of the two populations is similar (R5), the net natural growth is positive for both populations.

2.4. Effects of illegal fishing on biomass dynamics

Figure 2 illustrates a phase diagram of biomass dynamics of the harvest and reserve populations, where both are illegally fished, that is $h_H^{\mathrm{IUU}}, h_R^{\mathrm{IUU}} > 0$. We assume that the level of illegal fishing is determined by the expected economic returns from illegal activities (Sutinen and Andersen 1985). By the nature of illegal activities, there are no entry and exit barriers for illegal vessels to the fishery, and thus, illegal fishing occurs as long as the expected economic gain from illegal fishing is positive (Milliman 1986).

The figure shows that the presence of illegal fishing shifts the $\dot{x}_H = 0$ isocline upward and the $\dot{x}_R = 0$ isocline downward, compared with the isoclines in Figure 1. These shifts in the isoclines are due to the additional fishing pressure caused by illegal catch from *each* of the populations, and the larger the magnitude of illegal fishing, the greater the shifts. As a result of these shifts in the isoclines, the total area in the phase plane, in which either one or both of the harvest and reserve populations are in decline (R2–R4 and R6 in Figure 2), becomes larger than when there is no illegal fishing. Further, because of the additional fishing pressure caused by illegal activity, the steady-state level of total biomass at the new equilibrium, denoted as e^{IUU}, is smaller than the biomass level at the management target, e^*.

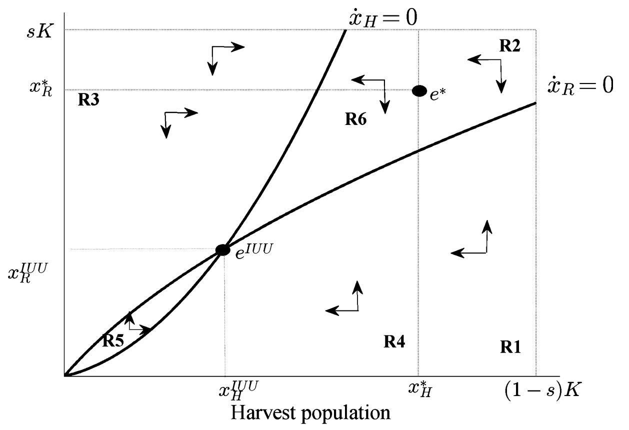

Figure 2 Biomass dynamics of the harvest and reserve populations when both populations are exposed to illegal fishing.

2.5. Effects of illegal fishing control on biomass dynamics

Comparing the two phase diagrams in Figures 1 and 2, it is evident that the aim of regulatory enforcement of illegal fishing is to reduce the level of fishing pressure on each of the populations, so that the $\dot{x}_H = 0$ and $\dot{x}_R = 0$ isoclines in Figure 2 shift towards their positions in Figure 1. In other words, when illegal fishing is fully controlled, the biomass dynamics become as described in Figure 1 and the management target e^* can be achieved with sustainable harvesting of fish stocks. Nevertheless, the biomass management target cannot be achieved when illegal fishing is controlled only in either the reserve or fished area.

Figure 3 illustrates a phase diagram of biomass dynamics when illegal fishing is regulated, but only for the illegal harvest of either the reserve or the harvest population. Figure 3a shows that, if illegal fishing is regulated for the reserve population only and not for the harvest population ($h_R^{\mathrm{IUU}} = 0$ and $h_H^{\mathrm{IUU}} > 0$), the $\dot{x}_R = 0$ isocline shifts upwards, but the $\dot{x}_H = 0$ isocline remains unchanged (Figure 3a). This will result in a steady-state level of biomass at e_a^{IUU}, which is greater than the level in the unregulated case in Figure 2. The steady-state level of biomass is, however, still less than its target level. Likewise, when illegal fishing is regulated for the harvest population only and not for the reserve population ($h_R^{\mathrm{IUU}} > 0$ and $h_H^{\mathrm{IUU}} = 0$), the steady-state level of biomass is greater than the level in the unregulated case but less than its target level (Figure 3b).

The phase diagrams in Figures 1, 2 and 3 do not allow us to further examine what the changes are in the levels of illegal fishing under different scenarios of illegal fishing control, what the effects of no-take reserves are, and the extent to which the effectiveness of illegal fishing control and the no-take reserves are related in terms of combating illegal fishing. To address these issues, in the next section, the model results are generated numerically

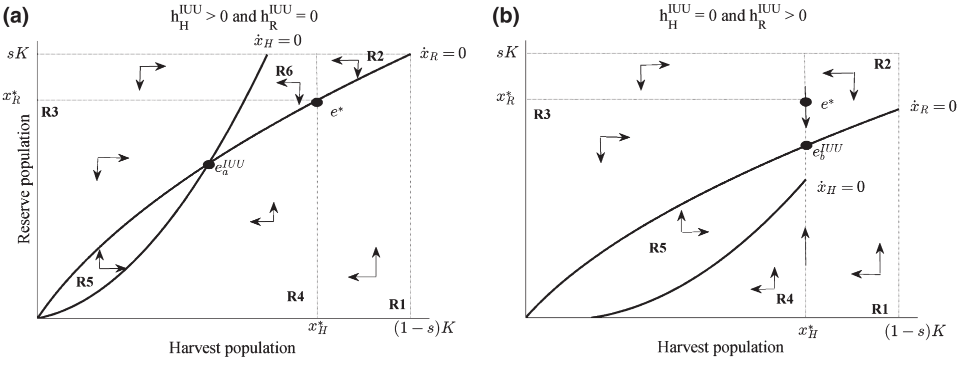

Figure 3 Biomass dynamics of the harvest and reserve populations (a) when illegal fishing on the reserve population is regulated and (b) when illegal fishing on the harvest population is regulated.

using the parameter values from the South Georgia longline fishery for the Patagonian toothfish (*Dissostichus eleginoides*), the specifics of which are described in detail elsewhere (Hoshino *et al.* 2010; Edwards *et al.* 2011).

3. Numerical illustrations

3.1. Production and profit function for illegal vessels

To numerically solve the model developed in Section 2, we must impose some assumptions with regard to the illegal harvest–effort relationship, how the level of illegal fishing is determined, and how the enforcement of illegal fishing control affects the profitability of illegal catches from both the harvest and reserve populations. For the illegal harvest–effort relationship, we use the Schafer production function, that is $h_j^{\mathrm{IUU}} = q_j^{\mathrm{IUU}} E_j^{\mathrm{IUU}} x_j$, ($j = H,\ R$), where E_j^{IUU} is the illegal fishing effort, and q_j^{IUU} is the catchability coefficient.[7]

Because the carrying capacity of the harvest and reserve populations changes with the reserve size, or parameter s, we assume that the catchability coefficient for each of the populations also depends on the reserve size, such that $q_H^{\mathrm{IUU}} = \bar{q}/(1-s)$ and $q_R^{\mathrm{IUU}} = \bar{q}/s$. This implies that, for given sizes of x_H and x_R, the catch per unit of effort (CPUE) for the harvest population increases with the reserve size, that is $dq_H^{\mathrm{IUU}}(.)/ds > 0$ and the CPUE for the reserve population decreases with the reserve size, that is $dq_H^{IUU}(.)/ds < 0$. This specification of the catchability coefficient is compatible with earlier studies

[7] Hoshino *et al.* (2010) empirically tested whether the Cobb-Douglas production function is preferred to the Schaefer production function for the South Grorgia Patagonian toothfish fishery and concluded that the Schaefer production function is preferred for this fishery. Edwards *et al.* (2011) also adopted the Schaefer production function to investigate enforcement of harvest regulations in this fishery.

suggesting that the catchability coefficient is negatively related to the stock area (Winters and Wheeler 1985).[8]

The expected instantaneous profit of illegal fishing is specified as:

$$E\left[\pi^{\mathrm{IUU}}\left(E_j^{\mathrm{IUU}}, x_j, s\right)\right] = p^{\mathrm{IUU}} h_j^{\mathrm{IUU}}(1-\lambda) - c^{\mathrm{IUU}} E_j^{\mathrm{IUU}},\ j = H, R$$

where p^{IUU} is a unit price of the illegal harvest, c^{IUU} is the cost per unit of the illegal fishing effort, and $\lambda_j \in [0, 1]$ is the detection probability of illegal fishing for the j-population. Thus, we consider a control measure in which the illegal harvest is detected and confiscated *ex post* the harvest (e.g. at the port) so that the cost of fishing is not recoverable. Alternative control measures against illegal fishing are discussed by Gallic and Cox (2006).

To determine the level of illegal fishing in our numerical calculations, we adopt the standard rent dissipation process, for which the illegal fishing effort is adjusted depending on the expected profitability of illegal activities where illegal vessels are not subject to any entry and exit barriers (Milliman 1986). Because the illegal harvest is not bound by the legal catch limit, a new entry of illegal fishing activities occurs as long as there is a positive expected profit, and the aggregate level of the illegal fishing effort increases until all expected economic returns from illegal fishing are dissipated. Therefore, in the complete absence of regulatory control on the practice of illegal fishing ($\lambda_H = \lambda_R = 0$), the equilibrium outcome of the fishery is equivalent to the open-access equilibrium.

3.2. Parameters for the South Georgia Patagonian toothfish fishery

The Patagonian toothfish is a large demersal, long-lived fish distributed widely in shelf and shelf-slope waters around subantarctic islands and both the east and west coasts of South America. The Patagonian toothfish is the most valuable fish in Antarctic and subantarctic waters, with its ex-vessel price exceeding US$14 per kg (Hoshino *et al*. 2010). Due to high international demand, the Patagonian toothfish has attracted significant attention from illegal vessels, with an estimated illegal catch of between 30,000 and 40,000 tonnes in Antarctic waters in the mid-1990s, as opposed to a declared legal catch of 40,000 tonnes (Agnew 2000; SC-CAMLR 2008).

We use the estimated biological and economic parameter values related to the South Georgia toothfish fishery reported in Hoshino *et al*. (2010) and Edwards *et al*. (2011).[9] The parameter value of the transfer coefficient (m) is not available, and we initially set $m = 0.1$, which is equivalent to a fish dispersal of about 5–8 percent of the total biomass per annum between the

[8] Alternative forms of the catchability coefficient are discussed in Arreguín-Sánchez (1996).

[9] They also report the 95 percent confidence interval for the parameter estimates of q, r and K. We tested our numerical results with upper and lower bounds of the confidence interval and found that our qualitative results remain unchanged.

Table 1 Parameter values and biomass management target

Parameter	Description	Value
r	Intrinsic growth rate	0.12
K	Carrying capacity (tonnes)	109,225
p	Price of fish (USD per tonne)	9131
c	Cost per unit of effort	1058
q	Catchability coefficient	4.04×10^{-6}
m	Transfer coefficient	0.1
ρ	Discount rate	0.05

reserve and harvest populations. In Section 3.4., we undertake a sensitivity analysis to assess the effects of the fish dispersal. The parameter values used in the numerical analysis are summarised in Table 1.

3.3. Effects of no-take reserves and illegal fishing control

Figure 4 illustrates the aggregate level of illegal fishing and the total biomass for different combinations of detection probabilities of illegal fishing on the harvest and reserve populations (λ_H, $\lambda_R \in [0, 0.8]$) under three different sizes of the no-take reserves ($s = \{0, 0.1, 0.3\}$).

As we would expect, the aggregate level of illegal fishing decreases monotonically when the detection probability of illegal fishing of the both populations collectively increases. For instance, when 30 percent of the total population is placed in a reserve, increasing the detection probability from 0 to 20 percent decreases the illegal catch for the harvest and reserve populations by 199.2 and 85.4 tonnes, respectively (Figure 4). Conversely, the aggregate level of illegal fishing increases when the probability of detecting the illegal harvest of one population increases, while the detection probability for the illegal harvest of the other population remains unchanged ($\Delta\lambda_i > 0$ and $\Delta\lambda_j = 0$, $i, j = H, R, i \neq j$). For instance, when 10 percent of the total population is placed in a no-take reserve, the aggregate level of illegal fishing increases by 2.8 thousand tonnes as a result of increasing the probability of detecting the illegal catch for the reserve population from 0 to 56 percent, while the detection probability for the illegal catch of the harvest population remains constant at 0 percent ($\lambda_H = 0$ and $\Delta\lambda_R = 0.56$).

Implementing different levels of enforcement for the illegal harvest of each population increases the relative abundance of one population compared to the other. Given the density-dependent pattern of fish dispersal, the change in the relative abundance of the two populations causes a spillover of exploitable biomass to the relatively unregulated population. As a result, the illegal fishing effort is reallocated so as to capture the spillover benefits, leading to an increase in the aggregate level of illegal fishing. Figure 4 shows that this destructive displacement of the illegal fishing effort between the two

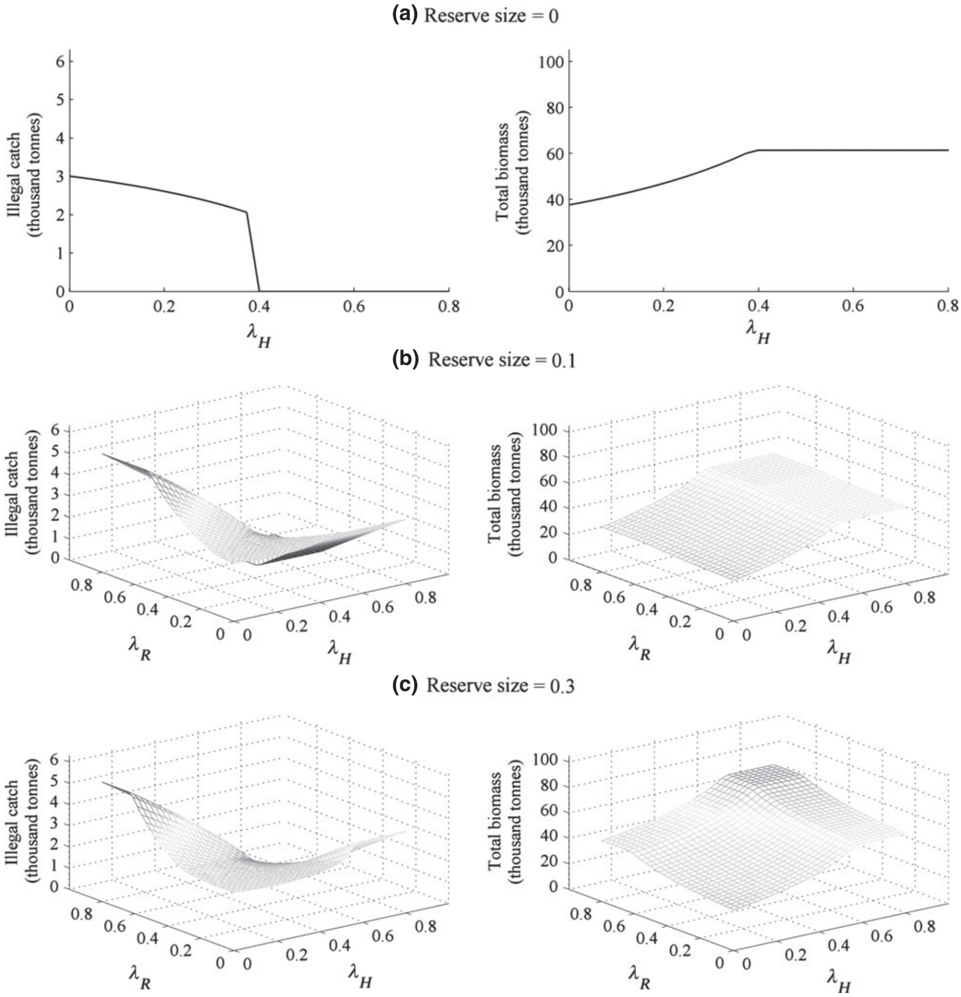

Figure 4 Effects of heterogeneous enforcement of illegal fishing control on the aggregate level of illegal catches and total biomass for three different reserve sizes, (a) s = 0, (b) s = 0.1 and (c) s = 0.3. The target level of total biomass is 61,369, 62,845 and 77,848 tonnes for s = 0, s = 0.1 and s = 0.3, respectively.

populations is most prominent when the reserve size is relatively small and only the illegal catch of the reserve population is regulated (e.g. $s = 0.1$, $\lambda_R = 0.8$ and $\lambda_H = 0$).

The establishment of a no-take reserve may accelerate illegal fishing and reduce the total biomass in the fishery. Figure 5 illustrates the difference in the aggregate level of illegal fishing (Figure 5a) and biomass (Figure 5b) between the 10 or 30 percent reserve (s = 0.1 or 0.3) and the no-reserve case (s = 0) for two regulation scenarios, for which illegal fishing is only partially controlled for either the reserve or harvest population ($\lambda_i = 0.4$ and $\lambda_j = 0$, $i, j = H, R, i \neq j$). The figure shows that the establishment of the 10 percent or 30 percent reserve increases the aggregate level of illegal

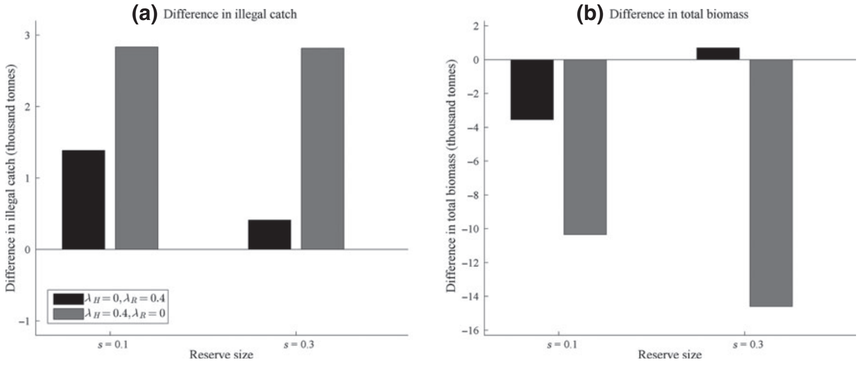

Figure 5 Difference in the (a) illegal catch and (b) total biomass between the 10 or 30 percent reserve and the no-reserve case (s = 0).

fishing, particularly when illegal fishing for the reserve population is unregulated. For instance, when the detection probability of illegal fishing for the harvest and reserve populations is 40 and 0 percent ($\lambda_H = 0.4$ and $\lambda_R = 0$), placing 10 percent of the carrying capacity in a no-take reserve increases the aggregate level of illegal fishing by 2.8 thousand tonnes. When illegal fishing is only partially regulated, placing a greater proportion of the population in a no-take reserve increases the relative profitability of illegal fishing for the reserve population. Consequently, increasing the reserve size leads to more illegal catches in the reserve population, particularly when the detection probability of illegal fishing for the reserve population is low.

Figure 5 further shows that increasing the reserve size may decrease the total biomass, particularly when the illegal fishing for the harvest population is partially regulated, but not at all for the reserve population. When the detection probability of illegal fishing for the harvest and reserve populations is 40 and 0 percent ($\lambda^H = 0.4$ and $\lambda^R = 0$), increasing the reserve size from 0 to 10 percent decreases the total biomass by 10.3 thousand tonnes. These results suggest that when illegal fishing is only partially controlled, increasing the reserve size may result in a lose-lose situation in which the level of illegal fishing is greater and total biomass is less than when the fishery is managed without the reserve. Our results, which show that illegal fishing has detrimental effects on the effectiveness of no-take reserves as conservation tools, are consistent with findings of previous studies, such as Kritzer (2004) and Sethi and Hilborn (2008).

Moreover, even in the case where a reserve establishment increases the total biomass, it might be insufficient by itself to achieve the biomass management target associated with maximum economic yield (Figure 4). For instance, when 56 percent of the illegal harvest is detected for both populations ($\lambda^H = \lambda^R = 0.56$), the establishment of the 30 percent reserve increases the total biomass by 11.1 thousand tonnes. The total biomass, however, is still at

93 percent of its target level. This result is also evidenced by the phase diagram of Figures 2 and 3, which show the total biomass is below the target level when illegal fishing is only partially controlled.

3.4. Sensitivity analysis: fish dispersal

To test the sensitivity of our results in Figures 4 and 5 in which the pattern of fish dispersal between the harvest and reserve populations is density dependent, we consider two alternative forms of fish dispersal: (i) closed system, in which there is no spillover of exploitable biomass, for example sedentary species (Palumbi, 2004) and (ii) sink-source dispersal systems, for example reef fish larvae (Bode *et al.* 2006), in which the spillovers are unidirectional from the reserve (*source*) to the harvest population (*sink*) (Crowder *et al.* 2000). For the former case, we set $m = 0$ in Equation (4) and, for the latter case, we use the specification of the biomass dynamics given in Equations (5) and (6). Figures 6 and 7 show the aggregate level of illegal fishing and total biomass for different combinations of detection probabilities and reserve sizes under each pattern of fish dispersal.

Under the closed system, the aggregate level of illegal fishing decreases monotonically with the increased probability of detection (Figure 7). This result holds for all reserve sizes examined. This implies that, in contrast to the results under the density-dependent dispersal system, there is no destructive displacement of the illegal fishing effort when the detection probability of illegal fishing for one population increases relative to the detection probability of illegal fishing for the other ($\Delta\lambda_i > 0$ and $\Delta\lambda_j = 0$, $i, j = H, R, i \neq j$). In the absence of the spillover of exploitable biomass between the harvest and reserve populations under the closed system, the relative profitability of illegal fishing remains unchanged when different detection probabilities are imposed on each population.

Similarly, for all reserve sizes examined under the sink-source dispersal system, the aggregate level of illegal fishing monotonically decreases with the increased detection probability of illegal fishing for the harvest population, *ceteris paribus* (Figure 6). The fixed spillover from the reserve to harvest population under the sink-source dispersal system makes the exploitation of the source population economically less attractive regardless of the relative size of the detection probability of illegal fishing between the two populations.

Nevertheless, whether increasing the size of the reserve decreases or increases the aggregate level of illegal fishing under the closed and sink-source dispersal system depends on the relative probability of detection between the illegal catch for the harvest and reserve populations (Figures 8,9). When the detection probability of illegal fishing for the reserve population is low, increasing the reserve size displaces the illegal fishing effort from the harvest to the reserve populations and this results in an increase in the aggregate level of illegal fishing.

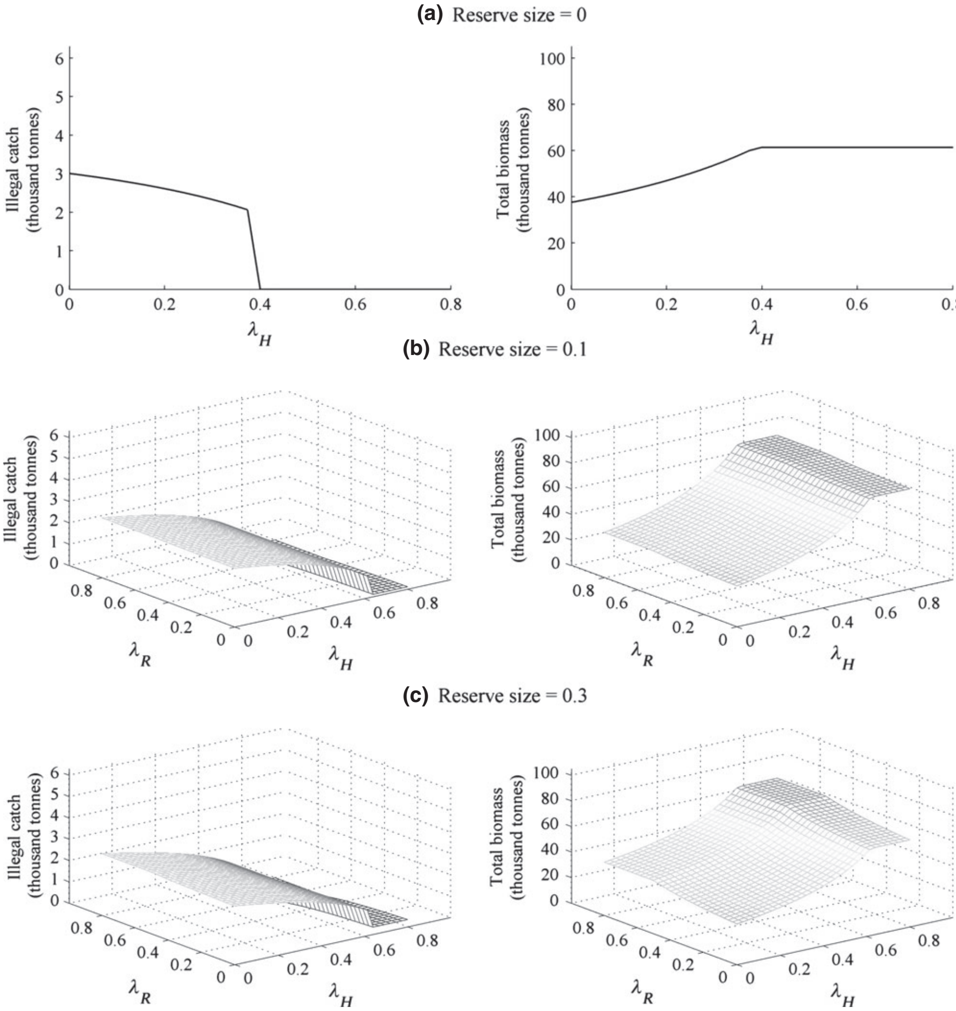

Figure 6 Effects of heterogeneous enforcement of illegal fishing control on the aggregate level of illegal catch and total biomass, under a sink-source dispersal system, for three different reserve sizes, (a) s = 0, (b) s = 0.1 and (c) s = 0.3. The target level of total biomass is 61,369, 81,508 and 77,743 tonnes for s = 0, s = 0.1 and s = 0.3, respectively.

Similar to the case of the density-dependent dispersal system, placing 10 or 30 percent of the carrying capacity in a no-take reserve by itself is generally insufficient to achieve the biomass target, unless the illegal fishing is jointly regulated for both populations (Figures 6,7). In fact, increasing the reserve size may even decrease the total biomass under both the closed and sink-source dispersal systems, particularly when illegal fishing for the reserve population is not controlled (Figures 8,9). More particularly, for a given size of detection probability, increasing the reserve size may result in a lose-lose situation in which the aggregate level of illegal fishing increases and the total biomass decreases. These results are consistent with our earlier results in

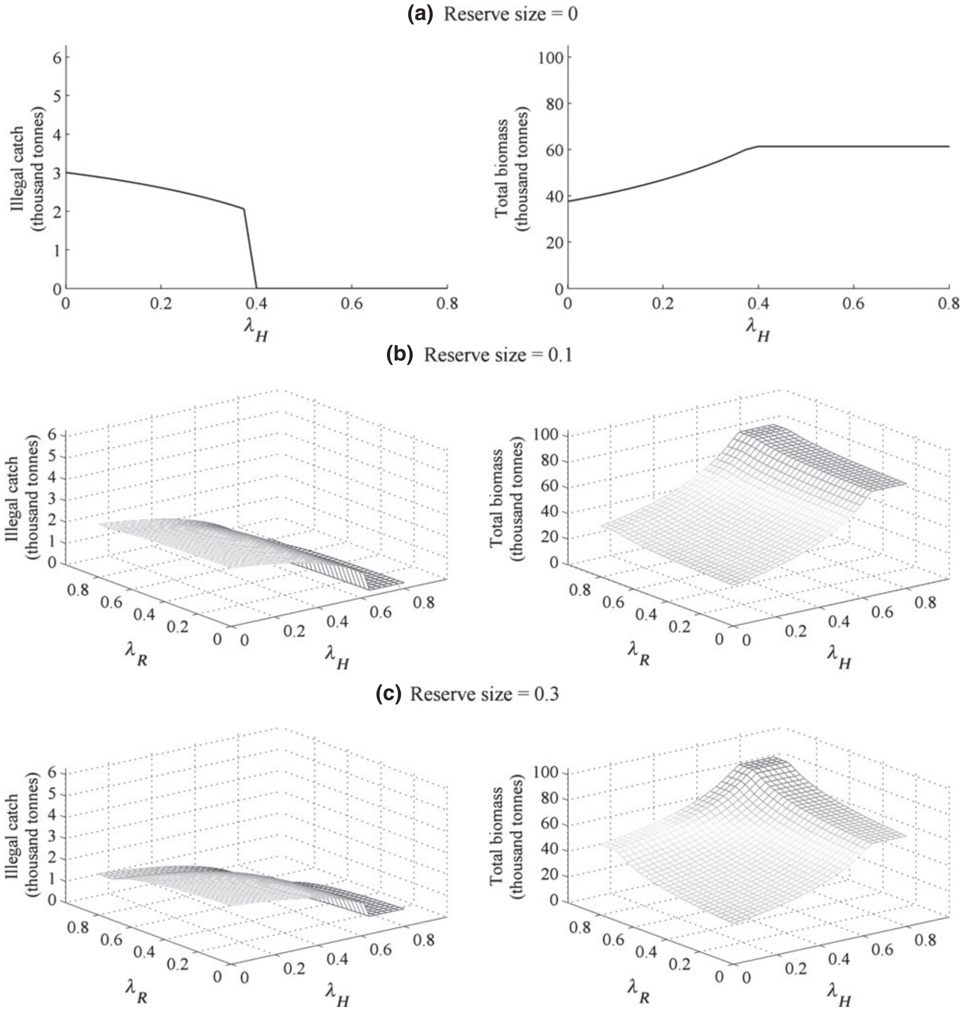

Figure 7 Effects of heterogeneous enforcement of illegal fishing control on the aggregate level of illegal catch and total biomass, under a closed system, for three different reserve sizes, (a) $s = 0$, (b) $s = 0.1$ and (c) $s = 0.3$. The target level of total biomass is 61,369, 89,380 and 93,740 tonnes for $s = 0$, $s = 0.1$ and $s = 0.3$, respectively.

Figures 4 and 5. When illegal fishing is only partially controlled, increasing the size of the no-take reserve displaces the illegal fishing effort to the reserve area in which the expected profit of fishing is relatively high and the risk of detection is relatively low.

4. Concluding remarks

The incidence and detrimental effects of illegal fishing have been reported globally, and the resulting biological and economic losses have become an increasing concern (Sumaila *et al*. 2006; Agnew *et al*. 2009). In response, the

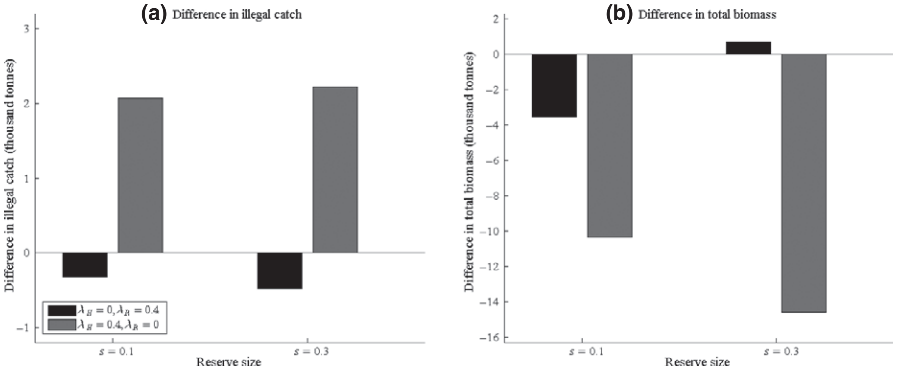

Figure 8 Difference in the (a) illegal catch and (b) total biomass between the 10 or 30 percent reserve and the no-reserve case (s = 0) under a closed system

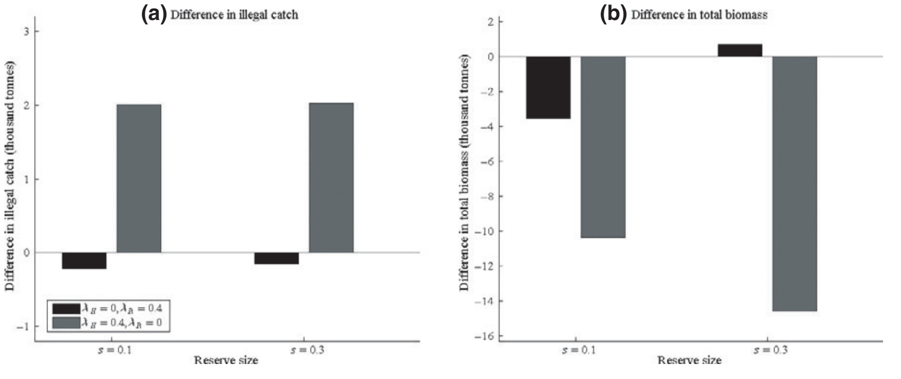

Figure 9 Difference in the (a) illegal catch and (b) total biomass between the 10 or 30 percent reserve and the no-reserve case (s = 0) under a sink-source dispersal system.

efforts to confront illegal fishing have been given high priority in many countries (FAO 2002). No-take marine reserves are both conservation and fishery management tools that have been increasingly advocated and implemented as an effective means of supporting marine ecosystems and promoting the sustainability of fisheries resources. While there is an extensive body of literature examining illegal fishing problems and the effectiveness of no-take marine reserves, only a limited number of studies have considered these two issues jointly. To fill this knowledge gap, we have constructed a bioeconomic model of a no-take reserve that incorporates illegal fishing activities in both reserve and fished areas and regulatory control of these activities. This allows us to examine the effects of no-take reserves of different sizes and regulatory control of illegal fishing inside and outside the reserve on the aggregate level of illegal fishing and total biomass.

Overall, our results demonstrate the importance of a linkage between the reserve size and regulatory enforcement against illegal fishing. While there is a growing body of evidence suggesting that the use of no-take marine reserves as fisheries management tools produces a range of ecological and economic benefits for the fishery, the reserve establishment by itself is not a panacea for all fisheries problems (Allison *et al*. 1998) and not an alternative measure or substitute for conventional fishery management tools (Sanchirico *et al*. 2006; Grafton *et al*. 2009; Rassweiler *et al*. 2012). Our bioeconomic model shows that the success of no-take reserves depends on the regulation governing illegal activities in *both* reserve and fished areas. For instance, the establishment of a no-take reserve may accelerate illegal fishing and reduce the total biomass under the circumstance where the regulatory control of illegal fishing is imperfect (Figures 5,8,9).

The incidence of illegal fishing can hinder both the ecological and economic benefits of no-take reserves significantly. In the absence of effective control of illegal fishing, no-take reserves potentially provide an unintended economic incentive for fishers to engage in illegal fishing and adversely place fish stocks under increasing pressure. Nevertheless, our study is limited to assessing the aggregate level of illegal fishing, and our model does not incorporate the behavioural response of individual fishers to different sized reserves under imperfect enforcement. It is imperative to further explore how the establishment of no-take reserves of different designs (e.g. size, shape and spatial placement) and alternative control measures against illegal fishing affect the behaviour of illegal fishers as well as the ecological and economic performance of the fishery.

To make the model tractable and to confine our analysis to the research questions in this paper, we impose some assumptions that need to be carefully considered when our model results are interpreted and applied elsewhere. First, we assume that the *ex post* detection of illegal fishing is the sole control measure of illegal activity. In practice, however, a number of different measures have been implemented jointly to combat illegal fishing, including penalties or fines imposed on the illegal fishing effort and confiscation of illegal vessels (Gallic and Cox 2006). Second, we assume that the level of the illegal fishing effort is solely determined by economic incentives and the level of deterrence, which seem to be the predominant factors affecting the compliance behaviour of fishers in practice (Hatcher and Gordon 2005). However, previous studies also find that the level of regulatory compliance depends on other nonmonetary factors, such as normative belief and social influence (Hatcher *et al*. 2000). An alternative approach characterising the spatial behaviour of illegal fishing is to integrate the bioeconomic model with an empirical model of individual choice (Holland 2000; Smith and Wilen 2003). Lastly, our bioeconomic model does not incorporate the establishment and operational costs of no-take reserves and the enforcement costs of the regulation of illegal fishing, which are significant components of the financial costs in fisheries management (Arnason *et al*. 2000; Balmford *et al*. 2004). Future research could extend our bioeconomic model to include these costs explicitly. This would allow researchers to evaluate trade-offs between the costs and benefits of alternative regulatory measures of illegal fishing under different assumptions of the size of no-take reserves and to characterise the optimal management of no-take reserves and illegal fishing.

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