

# Capital Investment for Optimal Exploitation of Renewable Resource Stocks in the Age of Global Change Biology

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## Abstract

The world is rapidly changing, and people must adapt to changes in the amount and spatial distribution of natural capital. One option is to change the way people interact with natural capital, for example changing harvest levels of fisheries. Alternatively, people can invest in reproducible or human capital, which may be a substitute or complement for natural capital stocks. The economic and ecological details of the system jointly determine the optimal investment in human or reproducible capital as well as investment decisions in natural capital. We focus on the spatial case of capital that enables targeted ecological management. In the case where capital investment is necessary to enable targeting, it is not clear that such investments will always be made. Such investments are most valuable when there are economic differences and ecological interactions among natural capital stocks. Ecological interactions alone may not be sufficient to lead to targeting. This is particularly relevant to fisheries facing climate change and the spread of invasive species. In fisheries impacted by climate change, the market substitutability of many fish products may work against investment in species specific targeting. In the case of invasive species, economic interest may lead to capital investments to avoid invasive species damages while permitting the pest to spread causing an environmental damage that is not capitalized by decision makers.

**JEL Codes:** O13, Q22, Q54; Q57

**Keywords:** fisheries, climate change, invasive species, optimal control, bioeconomics

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## INTRODUCTION

Ecosystem services are generated when people combine know-how (human capital), built capital, and natural capital to take advantage of biophysical production from ecosystems. The quasi-fixed nature of the human and built capital used to capture ecological production is well known to impose adjustment costs (Clark et al., 1979), but changing ecosystems also impose adjustment costs. Such adjustment costs are important to consider in the context of adaptation and mitigation strategies to changes in the biophysical state of the world (Mendelsohn, 2012; Perrings, 2005). Indeed, these investment strategies are critical to adaptation, but they are also important for considering mitigative strategy, because how society reacts if mitigation fails is important for choosing the optimal mitigation strategy (Homans and Horie, 2011; Mehta et al., 2007; Polasky, 2010).

Changing environmental conditions, studied in the field of “global change biology,” include habitat alteration from land-uses such as agriculture, mining, etc. as well from climatic change. Such changes impact ecological community composition and how organisms affect each other’s growth rates (Ordonez et al., 2016). Already, species’ distributions have been observed to follow, for example, their thermal niche (e.g., Molinos et al., 2015; Parmesan and Yohe, 2003; Pinsky et al., 2013a). The magnitude of change and the organismal response in the ocean has been particularly pronounced (Burrows et al., 2011; Doney et al., 2009; Dulvy et al., 2008), with many species tracking their thermal niches albeit at different rates. Shifts of species uniformly in a single direction appear to be the exception rather than the rule (Breshears et al., 2008; Hampe and Petit, 2005; Pinsky et al., 2013a), leading to expectations of potentially novel combinations of species. In addition to species movements in response to changed habitat, human activity can also directly facilitate the introduction of species into new areas (Mack et al., 2000) through a variety of vectors, including stowaways in international shipping, or as unwanted pet

release. These invasive species are numerous and cause great economic and ecological damage (Pimentel et al., 2005). Whether a new entrant to an area arrives as a climate refugee or as an alien species, the movement of species into new areas and interacting with the resident species is both currently and projected to be a common occurrence (Sorte et al., 2010).

Changing composition of ecological communities can also impact how people interact with the environment. Adapting to the rebalancing of the portfolio of natural capital requires rebalancing investments in human and built capital stocks (Horan et al., in press). An important special case is when a new species enters a socio-ecological system. The new species can impact ecological relationships and production decisions, especially in the case of provision services such as fisheries. The arrival of a new species can lead to joint production (Baumgartner et al., 2001; Hutniczak, 2015) because prior to the arrival of the species there would have been little incentive to develop human or technical capital to target the species differentially. But, an ability to target after the arrival of the new species is often necessary for optimal management (Fenichel and Horan, 2007; Fenichel and Horan, 2016; Horan et al., 2011). We contribute the literature by extending Clark, Clarke, and Munro's (1979) classic model to analyze the how investment in a capital stock adjust to the introduction of a new species under a variety of ecological and economic scenarios. We show that targeting is most important when there are economic difference and ecological interactions between the resident and introduced populations. If there are no economic differences or ecological interactions, then it will not be optimal to invest in targeting capital. In case with ecological interactions, but limited economic differences, then there must be strong asymmetry in the ecological interactions for it to be optimal to invest in targeting capital. However, substantial economic difference may be sufficient to lead to investment in targeting capital.

## **MOTIVATING LITERATURE**

The motivation for this work comes from the importance of increasing the ecological (Tschirhart, 2009) and economic (Fenichel and Abbott, 2014a) realism of bioeconomic models. Specifically, we fill a gap in the literature by exploring how changes in the ecological system feedback lead to changes in investment decisions in reproducible and human capital. Despite a growing body of work on the management of novel species, whether invasive or due to climate change, the majority of that work neglects the condition of the invaded ecosystems and focuses on managing the invader (e.g., Epanchin-Niell and Wilen, 2012).

The impacts of shifting species on harvesting behavior have been well studied in a single species context. Joshi et al. (2009) modelled a logistically growing population that follows a moving habitat patch and show that a moving no-take zone ahead of the center of the moving population, surrounded by maximal effort, maximizes yield. Researchers find that for a stock that is moving between two harvesters, the harvester losing the stock has little conservation incentive and tends to heavily harvest the stock once they have lost the majority share (Diekert and Nieminen, 2016; Hannesson, 2007; Liu and Heino, 2013). Over short time periods, insight from stationary harvest models can provide insight. For example, if a valuable species moves into an area, the profit (or yield) maximizing harvest strategy is to hold-off harvest until it reaches a threshold level if the net benefits function is linear in the control (Conrad and Clark, 1987).

Species shifts do not exist in isolation. A species moving into a new area enters the context set by resident species, harvesters, and institutional arrangements. Prior work in ecology and in economics suggests that predator-harvester behavior when two prey-stocks are available can be quite different from single stock results (Bravo and Tamburino, 2011; Fenichel and Horan, 2016; Flaaten, 1991; Horan et al., 2011; Mesterton-Gibbons, 1988, 1996). In the ecology literature, predators switching among two prey species can induce coexistence among all three species (Tansky, 1978) and can reduce the risk of stock collapse when harvesters target the species with a higher expected income (Katsukawa and

Matsuda, 2003). The incidental catch of a non-target species has been implicated in the extinction of early human mega-faunal extinctions (Bulte et al., 2006). The previous literature fixes the harvesting technology fixing the degree of joint production in the system. Our analysis differs from the prior literature in two important ways. First, we develop a model from first principles that captures the opportunity costs of non-targeted joint production. Second, we allow harvests, guided by a social planner, to optimally invest in capital that enables targeting. We focus on the case when a population is entering a new area, optimally managed for a single species, in order to study the optimal adjustment path.

## MODEL

Consider the case of an optimally managed fishery, where fish stock  $x$  with biomass  $X(t)$  grows logistically and is harvested according to the Schaefer harvest function  $h = qXE$ .<sup>1</sup> The  $q$  represents catchability, which can be thought of as a technology parameter in the Cobb-Douglas framework. The  $E(t)$  is the effort exerted by fishers. Furthermore, we assume that  $E$  is chosen to maximize  $\int_0^\infty \pi(X, E)e^{-\rho t} dt$ , where  $\rho$  is a discount rate and  $\pi = ph - cE$  is a net revenue function, with a constant price,  $p$ , per unit harvest and cost,  $c$ , per unit effort. The bang-bang solution to this problem is well understood (Conrad and Clark, 1987), and we will take the solution to this problem as our starting point. We assume this is the state of the world prior to establishment of a species  $y$ .

### *Ecological model*

Consider the case when a new species,  $y$ , with biomass  $Y(t) > 0$ , enters the system. The new species enters as a one-off introduction, and we assume that species  $y$  establishes. The invasive species

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<sup>1</sup> We use upper case letters to indicate the biomass quantities, the state variables, in the model and lower case letters to indicate their indices. Time,  $t$ , is suppressed when doing so does not cause confusion.

literature emphasizes the importance of the leading-edge and long distance dispersers in establishing an invasion (Fagan et al., 2002; Shigesada and Kawasaki, 2002) and a singular invasion event is often considered in the bioeconomic literature (Epanchin-Niell and Wilen, 2012; Fresard and Ropars-Collet, 2014). Species  $x$  and  $y$  may interact directly as competitors or as predator and prey. These species may also interact through their interaction with humans, especially if technology  $q$  is non-targeted, i.e., a joint-production fishery. It is also possible that the introduction of species  $y$  leads people to alter their behavior. Using superscripts as indices, the dynamics of the system ecosystem are modeled

$$(1) \quad \dot{X} = F(X, Y) - h^x$$

$$(2) \quad \dot{Y} = G(X, Y) - h^y$$

The ecological production functions  $F$  and  $G$  could represent a Lotka-Volterra competition system, a Holling-style predator-prey system (Fenichel et al., 2015; Fenichel and Horan, 2016; Gotelli, 2008), or  $F_Y = 0$  and  $G_X = 0$  (where subscripts are partial derivatives) suggesting no ecological interaction at all. In our analysis below we consider two cases: no ecological interactions and Lotka-Volterra style competition. The Lotka-Volterra competition provides sufficient intuition to conjecture what would happen in the predator-prey case, which we discuss at the end of the paper, but ultimately leave for future investigation.

### ***Economic model***

The introduction of species  $y$  requires us to reconsider the canonical economic setup of this harvesting problem. Importantly, prior to the introduction of species  $y$ , harvesters would have had little incentive to develop harvesting technologies that uniquely targeted stocks  $x$  and  $y$ . More likely, the harvest would develop the least cost technology for harvesting species  $x$ , which we assume is equally good at catching species  $y$ . Once species  $y$  is in the system, then in principle harvests can target effort at stock  $x$ ,  $E^x$ , and stock  $y$ ,  $E^y$ . However, this is only reasonable if the harvesting technology

differentiates stocks  $x$  and  $y$ . Otherwise,  $E^x + E^y = E$ , and the harvesters would simply choose an aggregate effort level,  $E$ . In the case where effort at  $x$  and  $y$  is completely untargeted, then it must be the case that  $q^x = q^y = Z(t)$ , where  $Z(t)$  is a cross-catchability term represents state of technology and its (in)ability to uniquely target between  $x$  and  $y$ . We discuss this investment in capital to reduce  $Z$  momentarily, but first we develop a model that captures the opportunity cost of joint production.

If the harvester's goal is to catch  $x$  only, which might be the case if  $p^y = 0$ , then the harvester must budget some effort for the inevitable by-catch of  $y$  as the "cost of doing business." This means that the harvester must consider  $E^x$  as the sum of effort directed towards the stock of interest,  $E^a$ , and effort directed towards handling by-catch,  $E^b$ ; so that  $E^x = E^a + E^b$ . This form provides structure as suggested by Reimer et al. (2017), who argue harvesting is about deploying fixed inputs in time and space. The effort that targets  $x$  will yield  $q^x E^a X$  of  $x$  and  $Z E^a Y$  of  $y$ . Assume that the effort exerted towards handling by-catch is proportional to the amount of by-catch caught;  $E^b = Z E^a Y \tau$ , where  $\tau$  is a parameter governing the 'handling time' for by-catch. Re-arranging, we get  $E^a = \frac{E^x}{1 + ZY\tau}$ . Thus, when  $x$  is targeted, effort  $E^x$  yields a total catch rate of  $\frac{q^x x E^x}{1 + ZY\tau}$  of  $x$  and  $\frac{ZY E^x}{1 + ZY\tau}$  of  $y$ .<sup>2</sup> Therefore,

$$(3) \quad h^x = \frac{q^x E^x X}{1 + ZY\tau} + \frac{ZE^y X}{1 + ZX\tau}$$

A symmetric process applies for when  $y$  is targeted. The classic Schaefer harvest function is recovered when  $Z = 0$  or the non-target stock is zero. Fig (1) illustrates the harvests of species  $x$  as a function of stocks  $X$  and  $Y$ .

This nature of the harvest function suggests that harvesters have limited capacity to harvest targeted and non-targeted species. Therefore, this setup implies an opportunity cost to using non-targeted harvesting capital, and potentially there are benefits from technological change that enables

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<sup>2</sup> Fenichel et al. (2010) provide this economic interpretation for the Holling type II predator-prey function.

more specialized harvesting. We assume that harvesters can invest in capital  $K(t)$  to reduce  $Z(t)$  to enable targeting at a cost. We follow Clark et al. (1979) and assume

$$(4) \quad \dot{K} = I - \delta K$$

where  $I$  is the cost of investing in capital and  $\delta$  is a depreciation rate. Clark et al. (1979) assume capital investment is necessary for harvesting. They show that the adjustment cost problem leads to over-investment and cycles.<sup>3</sup> In contrast, we think of capital investment innovation and maintenance of either skills or technology that enables a degree of targeting. Specifically, we assume that capital,  $K$ , maps into  $Z$  according to

$$(5) \quad Z(K) = \bar{z} - \frac{\phi K}{K + \epsilon},$$

where  $\bar{z}$  is the maximum value of  $Z$  e.g.,  $\bar{z} = q^x$ , and  $\phi \geq \bar{z} + \frac{\bar{z}\epsilon}{K}$ . If  $Z$  may be driven to zero, then this expression holds as an equality, and the parameter  $\hat{K}$  is the value of  $K$  so that  $Z = 0$ . If the expression is an inequality, then perfect targeting is not possible. This functional form implies diminishing returns as  $Z$  is driven closer to zero (Fig 2).

Once  $y$  has entered the system, the social planner's new problem is

$$(6) \quad V(X, Y, K) = \max_{\{E^x, E^y, I\}} \int_0^\infty \left( (\sum_i p^i h^i - c^i E^i) - wI \right) e^{-\rho t} dt \quad \text{for } i = [x, y] \text{ Subject to Eq (1)-(4),}$$

$$X(0) = X^\#, Y(0), K(0) = 0$$

where  $w$  is the cost of a unit of capital,  $X^\#$  is the optimal steady state stock size for the single species problem,  $Y(0)$  is the initial stock size of stock  $y$ , and in accordance with Eq (5)  $K(0) = 0$  implies  $Z(0) = q^x = q^y$ . The current value Hamiltonian (CVH) for the social planner's problem is

$$(7) \quad H = (\sum_i p^i h^i(t) - c^i E^i(t)) - wI(t) + \lambda(t)\dot{X}(t) + \mu(t)\dot{Y}(t) + \gamma(t)\dot{K}(t) \quad \text{where } i = [x, y]$$

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<sup>3</sup> Liski et al. (2001) and Wirl (1995) extend the model for cases when there are convex investment costs. However, this has little qualitative impact on the intuition from Clark, Clarke, and Munro.



where  $\lambda, \mu$ , and  $\gamma$  are co-state variables associated with the three state variables. The problem is linear in the three control variables, therefore the solution is a sequence of bang-bang and feedback controls (Conrad and Clark, 1987; Fenichel et al., 2015; Horan et al., 2011). The marginal impact of effort on the CVH is

$$(8) \quad H_{E^i} = p^i \frac{q^i S^i}{1+ZS^j\tau} + p^j \frac{ZS^j}{1+ZS^j\tau} - c^i + \lambda \frac{q^i i}{1+ZS^j\tau} + \mu \frac{ZS^j}{1+ZS^j\tau}$$

with  $S^i = [X, Y]$  corresponding to the index,  $i = [x, y]$  and  $i \neq j$ . When  $H_{E^i} > 0$ , the effort on species  $i$  should be set to the maximum available amount. When  $H_{E^i} < 0$  effort directed at species  $i$  should be set to the minimum amount, which we assume is zero. A single feedback rule is implied when Eq (8) vanishes. Moreover, setting Eq (8) exactly equal to zero implies a switching curve  $\sigma^i$  in state space that determines when to switch between the maximum and minimum effort levels.

The marginal impact of  $I$  on the CVH is

$$(9) \quad H_I = -w + \gamma.$$

Eq (9) also leads to a feedback control rule: if  $H_I > 0$ , invest at the maximum allowable level. This may be an arbitrary amount in the presence of well-functioning capital markets or  $\sum_i (p^i h^i - c^i E^i)$  if capital markets are missing.<sup>4</sup> If  $H_I < 0$ , then it will be optimal not to invest. The singular solution provides a feedback rule when Eq (9) vanishes. The singular value for capital investment is straightforward – invest so that the marginal value of a unit of capital stock is equal to its marginal cost. The initial conditions also suggest that  $\gamma(0) \leq w$  so that there was not a prior incentive to invest in differentiating capital. Horan et al. (2008) find it optimal to invest in biosecurity, which is similar to targeting capital, right away using a bang-bang control or not at all. However, the nonlinear nature of the harvesting function may lead to a singular arc for capital investment.

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<sup>4</sup> We assume well-functioning capital market, but plan to consider capital constraints in future work.

When Eq (8) is zero for  $x$  and  $y$  and Eq (9) is zero this is a triple-singular solution.<sup>5</sup> But, this will only occur at most at a finite number of points in state space, which may be only a single point. It is also possible that the triple singular solution is never optimal. Away from these points it will be optimal to pursue partial singular solutions or bang-bang controls. There are 27 potential control rule combinations. These must be pieced together to produce feedback control diagrams that illustrate the state space dynamics and investment paths through time (Fenichel et al., 2010; Horan et al., 2011).

In order to determine the any of the singular feedback rules, we also must consider the co-state equations

$$(10) \quad \dot{\lambda} = \rho\lambda - H_X = \rho\lambda - [p^x h_X^x + p^y h_X^y + \lambda F_X + \mu G_X]$$

$$(11) \quad \dot{\mu} = \rho\lambda - H_Y = \rho\mu - [p^x h_Y^x + p^y h_Y^y + \lambda F_Y + \mu G_Y]$$

$$(12) \quad \dot{\gamma} = \rho\gamma - H_K = \rho\gamma - p^x h_K^x - p^y h_K^y + \lambda h_K^x + \mu h_K^y + \gamma\delta = \\ (\rho + \delta)\gamma - (p^x - \lambda)h_K^x - (p^y - \mu)h_K^y$$

Eq (10) and (11) can be rearranged into two modified golden-rule equation

$$(13) \quad \rho = \frac{\dot{\lambda}}{\lambda} + \frac{1}{\lambda} (p^x h_X^x + p^y h_X^y) + F_X + \frac{\mu}{\lambda} G_X$$

$$(14) \quad \rho = \frac{\dot{\mu}}{\mu} + \frac{1}{\mu} (p^x h_Y^x + p^y h_Y^y) + G_Y + \frac{\lambda}{\mu} F_Y$$

The left-hand side (LHS) of these equations is the discount rate, which represents the opportunity cost of forgone harvests in terms of the rate of return that could have been earned elsewhere in the economy. The right-hand side (RHS) is the required rate of return from holding more of the stock. The first term is a capital gains or loss term, the second term is the marginal value greater stocks in terms of current period harvests, the final two terms are stock effects terms, which reflect stocks own and cross effects on growth rate. The terms  $F_X$  and  $F_Y$  are the own appreciation or depreciation rate of the natural

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<sup>5</sup> Triple singular solution also require that Kelley's condition or the generalized Legendre-Clebsch condition is satisfied (Bryson and Ho, 1975; Robbins, 1967).

capital. When these are positive, they effectively lower the discount rate. In the case of renewable resource assets such terms are often endogenous (Fenichel and Abbott, 2014b). Finally, if there is competition between species we expect  $G_X$  and  $F_Y$  to be negative. So, competition acts like an additional source depreciation, and hence a greater rate of return is required. This greater rate of depreciation lowers the value of capital stock, which is likely to lead to lower investment in targeting capital, all else equal.

Eq (12) can also be rearranged into a modified golden-rule equation,

$$(15) \quad \rho = \frac{\dot{Y}}{Y} + \frac{1}{\gamma} [(p^x - \lambda)h_k^x + (p^y - \mu)h_k^y] - \delta$$

and has a similar interpretation. The LHS is the opportunity cost of investing fishing capital that enables differentiation in terms of what such an investment could have earned elsewhere in the market. The RHS is a capital gains or loss term plus the rate of return associated with greater ability to target fishing effort less the depreciation rate. The depreciation rate acts to increase the effective discount rate. Therefore, the fishing capital investment must provide a premium, which covers depreciation, in addition to returns from the stock in terms of differentiation.

### **Parameterization**

Generalized analytical results are intractable. Therefore, we use an illustrative parameterization to investigate how difference in market value and ecological relationships drive investment in capital  $K$ .

We let  $F(x, y), G(x, y)$  be Lotka-Volterra competition models:  $F = r^x x \left(1 - \frac{\beta^{xy} y}{k^x}\right)$  and  $G = r^y y \left(1 - \frac{x + \beta^{yx} x}{k^y}\right)$ . We assume competition is symmetric  $\beta_{xy} = \beta_{yx} = \beta$ . We contrast a case with no interaction ( $\beta = 0$ ) with a competitive case ( $\beta > 0$ ); species invasions are often antagonistic to the resident community, so this relationship is ecologically relevant (Sorte et al., 2010).

Economic parameters are chosen to be illustrative of scenarios where the concerns discussed in this paper are non-trivial. We chose symmetric catchability and harvest costs between the species. The discount rate is set at 3%, using the US Office of Management and Budget's lower social discount rate and depreciation of capital were set at 4% such that effective discount rate on capital is OMB's upper rate (OMB, 2003). We used  $\phi = \frac{\bar{Z}\epsilon}{\kappa}$  in Eq. 5, which guarantees  $Z$  cannot be negative as long as  $\kappa > \epsilon$ . We chose values of  $\kappa$  and  $\epsilon$ , which govern how investment influences the cross-catchability, such that  $Z$  declines meaningfully with increase in  $K$ . We set handling time,  $\tau$ , so that the impact of by-catch was non-negligible. We chose the cost of investment as half that of effort, as early simulations indicated that investment in capital can easily be prohibitive. Parameter values are listed in Table 1.

## RESULTS

The case studies that we consider are generally nested inside a model where  $p^y \geq 0$  and the two species compete,  $\beta = 0$  as a special case. Solutions where species  $y$  is valueless or the species do not interact are special cases of this scenario. In principle we need to consider each of the 27 possible solution strategy combinations and piece them together Horan et al. (2011). We begin by considering the long-run equilibria (Table 2, Fig 3), then we investigate investment trajectories. We find that long-run equilibria do exist rather than a series of overshoot cycles as in Clark et al. (1979). However, we also find that fully (triple) singular solution does not provide the long-run equilibrium in contrast with Horan et al. (2011).

### *Long-run equilibria*

It is useful to consider the initial condition as a benchmark. Given the parameterization, the social welfare provided by the system is 40.69 ( $H = 1.22$ ). The state, co-state, and control take the value 0.48, 9.8, and 26.22 respectively.

*Case 1: equivalent prices and no competition*

Case 1 is a potential outcome of climate change. If climate velocities (Pinsky et al.) lead new valuable species to arrive to an area, but residents also stay, and the new species have limited ecological impacts, then in the extreme case this ecological change boosts the endowment of natural capital. This simply doubles the natural capital stock in equilibrium, doubling the value of the CVH and effort used (Table 2). Indeed, the introduction of the new stock has no impact on the harvesting of stock  $x$  in the long-run and there is no reason to target. This is because by-catch is symmetrical and species are equally valued, making harvests indifferent.

*Case 2. Equivalent prices and Lotka-Volterra competition*

Case 2 also seemingly treats the introduction of species  $y$  as a new endowment of natural capital. Furthermore, so long as competition is symmetric (and other ecological parameters are similar) harvesters are indifferent between, which species is caught in equilibrium. This means in equilibrium there is no reason to hold capital,  $K$ , which requires effort to be non-targeted. However, unlike case one the competition between species increases the natural capital assets' depreciation rates. This reduces the shadow values of the stock and leads the harvests to hold smaller stocks of natural capital relative to Case 1. However, so long as competition between species is not so fierce, the social welfare provide by the function can still increase as illustrated by the increase in the value of the CVH relative to the initial conditions. However, the value of the CVH will necessarily be less than the case with no competition.

*Case 3.  $p^y = 0$  and no competition*

Case 3 satisfies Clinton's (1999) definition of the invasive species because it provides no harvesting value but generates an opportunity cost to harvests, even though it has no ecological impact. The opportunity

cost is sufficient to induce harvester to invest in targeting technology sufficient to nearly eliminate by-catch of species  $y$ , given a sufficiently large  $\tau$ . This is similar to Horan et al.'s (2008) result related to biosecurity – the goal is to separate the nuisance species,  $y$ , from the valuable one,  $x$ . Even with this adaptation, species  $y$  causes harm. The value of the CVH is less than for the initial condition. The reason is that large investments in capital must be maintained to more or less stay at the level of the initial conditions. This despite the fact that species  $y$  has no ecological impact.

In practice fishers are unlikely to invest to such a large level in targeting capital for four reasons. First, the marginal cost of available capital may have lower marginal benefits. Second, in practice  $\tau$  maybe relatively small. Third, harvests may not be able to privately capitalize the value of fishing innovation, especially in cases where fisheries suffer from management inefficiencies *ex ante*. Finally, harvests may face imperfect capital market. It is possible that this long-run equilibrium is not approachable if harvests must finance capital investment from current period revenue.<sup>6</sup>

#### Case 4. $p^y = 0$ and Lotka-Volterra competition

In Case 4 species  $y$  increases the depreciation rate of species  $x$  in addition to being a nuisance in the harvesting process. In this case it is optimal to harvest the “weedy” species  $y$ . However, it helpful to harvest it at differential level than species  $x$ . This requires targeting capital. Harvesting species  $y$  is necessary to reduce competition with species  $x$ . But, harvesting species  $y$ , i.e., lower stocks of species  $y$ , is also as substitute for capital  $K$  in reducing opportunity cost associate with catching stock  $y$ . However, catching stock  $y$  as by-catch also helps reduce stock  $y$ . Therefore, it is optimal to hold less capital than in Case 3. Nevertheless, the losses in this case are even greater than in Case 3. However, the correct counter-factual scenario is the case with no capital and no ability to target harvest. If we constrain

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<sup>6</sup> We plan to investigate this in future work.

harvests to employ  $K = 0$  always the ecological outcome is similar to Case 2, but the social welfare is 26 (CVH = 0.78).

### **Optimal investment paths**

Solving for the optimal investment paths requires piecing together a sequence of singular arcs and bang-bang controls. We know that it can never be optimal to set  $E^y > 0$  if  $K = 0$ . Since  $\gamma$  changes a function of the state of the world (Eq 12), it is investment in capital, if it exists, will generally follow a singular arc condition on  $E^y = 0$  and  $E^x$  defined by Eq (8). We first explore the solution to Case 4. We derive partial singular solutions following (Horan et al., 2011).

### **Discussion**

Targeting is generally necessary for the optimal management of interacting stocks of natural capital (Fenichel and Horan, 2007; Fenichel and Horan, 2016). We develop a case where this condition does not hold – symmetric interactions, and show that asymmetry in the marginal value of harvest is sufficient to induce targeting. This is important because targeting will not emerge costlessly, rather the ability to target is likely to require an investment in some human or reproducible capital stock. Optimal management requires balancing the marginal returns from all investments whether these are forgone harvests, control of a weedy species, or targeting capital, and the need to balance these investment decisions can lead to counter-intuitive results.

Most surprising, antagonistic ecological interactions can lead to lower levels of capital holdings when species are differentially valued for harvest. The reason for this is that spillovers or harvesting by-catch help off-set the costs of controlling the weedy species.

Asymmetry in ecological relationships is also necessary for targeting to be optimal. As far as simple ecological models, only competition can provide the symmetry we use in this analysis. Predator-

prey relationships are fundamentally asymmetric. Indeed, prey generally reduce the depreciation rate of predators, while predators generally increase the depreciation rate of prey. This has implications for investment in targeting capital.

Bioeconomics has mostly focused on how changes in the state of natural capital impacts conservation and exploitation decisions conditional on a fixed production process. But, investments in new technology are important for sustainability and adaptation to a changing world. Indeed, the processes of global change imply a transition path along which resource rents are extracted. Some of these rents will be reinvested in natural capital stocks, but others will necessarily be invested in human or reproducible capital. Optimal management requires the reinvestment of these rents (Hartwick, 1977). Yet, unlike in Harwick's (1977) classic model, some investments in capital shape the nature of resource rents going forward. It is imperative that we better understand the connections between natural and other forms of capital to best understand investment decisions. At a minimum this is required for a sustainable future, but it would be nice the future were also one that maximized social welfare.

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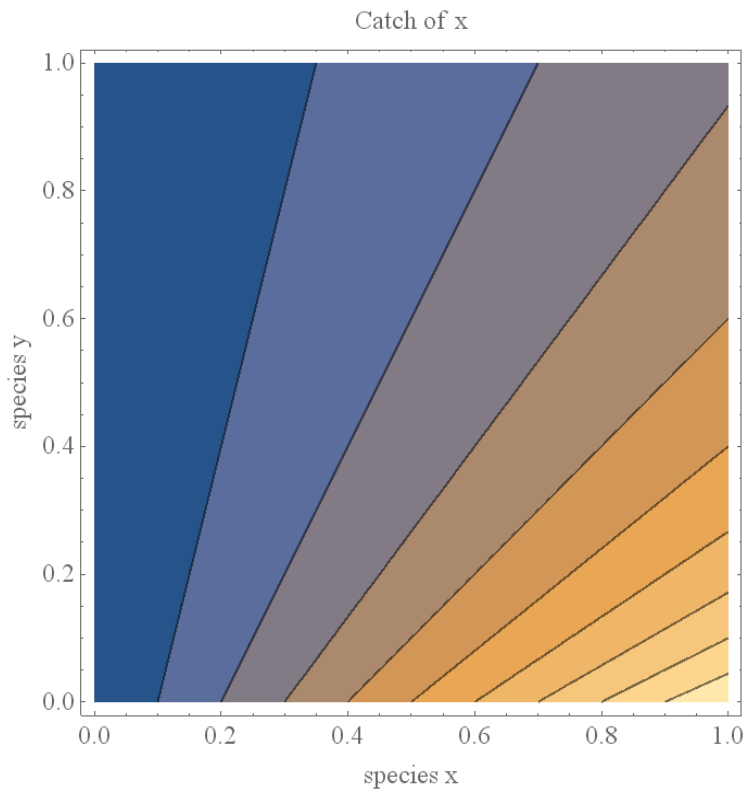
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## Figures and Tables

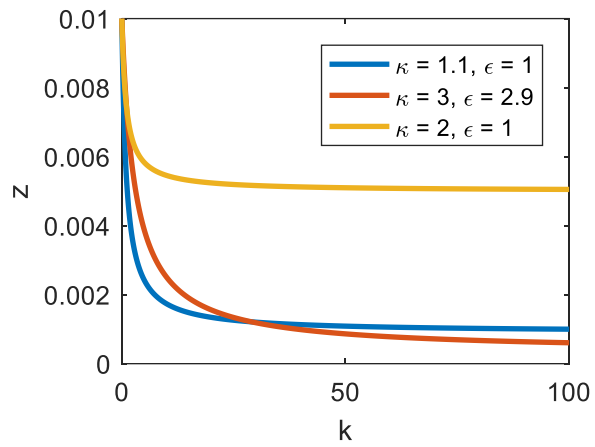
$r^x = r^y$	.5
$k^x = k^y$	1
$\beta$	0 or 0.5
$\kappa$	1.1
$\epsilon$	1
$\tau$	250
$q^x = q^y = \bar{z}$	0.01
$p^x$	10
$p^y$	10 or 0
$c^x$	0.001
$c^y$	0.001
$\delta$	0.04
$w$	0.0005
$\rho$	0.03

Table 2. Characteristic of long-run optimal equilibria.

Case	Optimal solution in equilibrium	$X$	$Y$	$K$	$\lambda$	$\mu$	$\gamma$	$E^x$	$E^y$	$I$	CVH
1. $p^x = p^y$ , $\beta = 0$	Singular in $E^x$ only	0.48	0.48	0	9.8	9.8		52.44	0	0	<b>2.44</b>
2. $p^x = p^y$ , $\beta > 0$	Singular in $E^x$ only	0.32	0.32	0	9.7	9.7		47.0	0	0	<b>1.61</b>
3. $p^y = 0$ , $\beta = 0$	Singular in $E^x$ and $I$	0.48	0.94	40.0	9.7		0.0005	33.1	0	1.56	<b>1.21</b>
4. $p^y = 0$ , $\beta > 0$	Triple singular	0.47	0.003	2.82	9.9	-37.3	0.0005	15.5	45.7	0.113	<b>1.18</b>

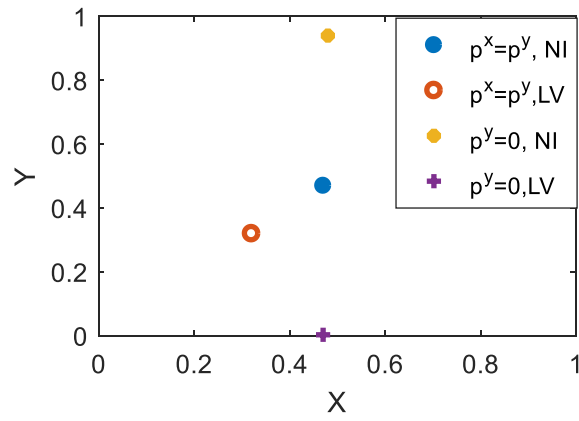


**Fig. 1:** Illustration of the harvest function, for a fixed amount of effort directed at  $x$ . Cool colors indicate low harvest; light tan colors are high harvests. As the abundance of  $x$  increases, so does the catch. The catch declines as  $y$  increases, since for the same exerted effort, more time is spent handling the bycaught  $y$ .



**Fig. 2:** Plot showing  $z$  as a function of  $k$ , for the functional form used for different values of  $\kappa$  and  $\epsilon$ .

Let  $\phi = \frac{\bar{z}\epsilon}{\kappa}$ . When  $k = 0$ , the catchability is at its maximum. As long as  $\epsilon < \kappa$ ,  $Z$  cannot decline below 0.



**Fig. 3:** Equilibrium optimal stock sizes for the four cases developed here. Investment was optimal in both  $p^y = 0$  cases.