

On Marine Reserves: Rents, Resilience and ‘Rules of Thumb’

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Abstract

Using a bioeconomic model with two separate forms of uncertainty (a diffusion process and a jump process) a perturbation method is used to determine optimal reserve size for a harvested population with density-dependent growth. The results show that the benefits of reserves are understated in deterministic models and that, even with optimal harvesting, risk neutrality, a persistent population and without initial overexploitation, reserves have a positive economic value. Concavity of the value function with respect to optimal reserve size under uncertainty implies that, for many harvested populations, a positive economic return will arise from initially establishing small reserves, even when harvesting is optimal. The results also lead to general ‘rules of thumb’ when establishing reserves. Namely, that optimal reserve size rises with (1) the greater the rate of transfer from the reserve, (2) the greater the magnitude or the likelihood of negative shocks, (3) the more the actual harvest exceeds the optimal harvest, (4) the lower the intrinsic growth rate, (5) an increase in price or demand provided the population is between zero and its maximum yield, (6) an increase in marginal harvesting costs provided the population is between its maximum yield and carrying capacity and (7) the lower the discount rate.

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1. Introduction

Reserves, which we define as spatially well-defined areas where no harvesting takes place, have been used for thousands of years as a conservation tool for harvested populations. Traditionally their location has often coincided with particular landscapes (such as forests), physical features (such as a bay) and identified breeding, spawning and nursery areas. Today, reserves are touted as a management tool to help address a range of issues including population persistence, biodiversity, overharvesting and habitat destruction.

A decade ago there were over 1300 marine reserves worldwide, with a median size of almost 1600 hectares (Kelleher *et al.* 1995), but many more reserves are planned ostensibly to prevent further overfishing (Botsford *et al.* 1997, Malakoff 1997) and misuse of marine resources (Pauly *et al.* 1998). The proposed expansion of reserves and protected areas (where some harvesting may be permitted) goes far beyond traditional protection for spawning or nursery grounds, and includes the agreement by national governments at the 2002 World Summit on Sustainable Development (WSSD) to develop representative networks of marine protected areas by 2012.¹ If this commitment is achieved it will represent the largest ever transformation in the use (or rather non-use) of the earth's surface. In particular, marine protected areas could increase from just 0.4% of the area in the coastal US (Lindholm and Barr 2001) and less than 1% of the earth's oceans (Boersma and Parrish 1999) to upwards of 20% or more of marine coastal areas.²

Marine protected areas still remain a controversial management tool. This is despite the endorsement of reserves at the WSSD, an Executive Order 13158 by President Clinton in 2000 to investigate the establishment of a network of reserves and marine protected areas (Schrope 2001) and overwhelming empirical evidence that reserves can raise the spawning biomass and mean size of exploited populations within protected areas (Gell and Roberts 2002).³ The concerns of fishers are that establishment of reserves will reduce (at least initially) their harvests and increase costs, restrict when and where they can go fishing and, depending upon their location, unduly penalize individuals who may be prohibited from operating in traditional fishing grounds. In addition, placing reserves in inappropriate locations or creating reserves of an inappropriate size may generate lower payoffs than other management alternatives.

In this paper we address the important question regarding reserves: what is their optimal economic size, taking into account both the sustainability of the resource and net returns from harvesting? To answer this question we use a stochastic bioeconomic model that includes two forms of uncertainty (a continuous diffusion process and a jump process) with optimal harvesting.⁴ A stochastic approach to determining optimal economic reserve size is required because deterministic models that are common in the existing economics literature cannot show the effect of reserves on two prominent variables, namely, the variability of the exploited population, and its resilience, or the speed it takes a population to return to a former (possibly varying) state following a shock.⁵

By explicitly accounting for uncertainty and solving for the optimal harvest levels and reserve size using a perturbation method, we find that the economic benefits of reserves are understated in deterministic models. We also show that the value function is concave with respect to optimal reserve size under uncertainty. This result has an important policy implication, namely, that a reserve less than its optimal size can generate higher economic benefits than no reserve even with optimal harvesting, risk neutrality and a persistent population. Our results also provide a number of general ‘rules of thumb’ when establishing or enlarging reserves. Such rules are important and of immediate value given the data challenges required to determine optimal reserve size.

The remainder of the paper is structured as follows. Section two reviews the existing literature and insights of both biological and economic models of reserves. Section three outlines the bioeconomic model and method we use to solve for an optimal reserve size. Section four uses specific parameters for a growth function and cost function estimated from a given resource to analyze the effects of biological and economic parameters on reserve size given optimal harvesting. Section five explores the insights of the stochastic model in terms of the establishment of reserves, and derives the general ‘rules of thumb’ for optimal reserve size. Our concluding remarks are presented in section six.

2. The Bioeconomics of Reserves

Provided there exists a well-defined spatial area where rules that prevent harvesting are both perfectly monitored and enforced, which we define as a reserve, then species that remain within the “no take” area are afforded a measure of protection or conservation. If the protected species within the reserve frequently leave the no-take area then the reserve may have little or no direct effect on their mortality rate and provide little or no added value in terms of conservation, apart from any indirect benefits that may accrue from avoiding harvesting methods that damage the habitat.

Conversely, if protected species located within a reserve are completely sedentary throughout their entire life cycle then a perfectly enforced reserve will afford perfect protection from harvesting and the indirect effects of harvesting, but will fail to provide any direct spillovers of harvesting benefits to areas outside of its boundaries. Both extremes---no difference in the harvesting mortality between the reserve and exploited areas (no protection) and perfectly sedentary behavior within a reserve (complete protection)---provide no direct economic benefits from harvesting. However, even with a completely sedentary species, a reserve may still provide indirect benefits such as the avoidance of harvesting practices that might damage habitat (Turner *et al.* 1999), increased biodiversity and greater population persistence.

2.1 Spillovers from Reserves

For the vast majority of exploited populations, reserves afford a degree of protection, and the benefits of reduced mortality ultimately generate positive harvesting spillovers to surrounding exploited areas. This applies equally to species that are sedentary as adults (such as shellfish), because a no-take area can still generate spillovers if juveniles, larvae or eggs migrate beyond reserve boundaries. Thus reserves help create a source-sink dynamic whereby individuals in reserves are afforded a measure of protection in a given location, and can then act as a “source” of recruitment for areas outside of the reserve (Pulliam 1988). Protection of exploited populations (through reduced mortality) and the spillovers from reserves represent trade-offs. That is, the higher is the level of transfer or out-migration from a reserve the lower is the level of protection

offered to any randomly selected animal within a reserve during its lifetime (Beverton and Holt 1957, Polacheck 1990 p. 334).⁶

The ability of reserves to act as source or transfer of individuals to exploited areas depends critically on their effectiveness at raising the abundance of exploited populations within protected areas. Roberts *et al.* (2001), and others, have shown empirically using data from marine protect areas that reserves can generate positive spillovers that improve harvests in adjacent exploited areas. Pezzey *et al.* (2000) and Sanchirico and Wilen (2001) also prove in theoretical models, with density-dependent growth, that a reserve can increase the abundance of the population and, in some cases, may even raise the aggregate harvest in the exploited area. This so-called “double payoff” with sub-optimal harvesting can arise when the chosen area for the reserve is at a low population level such that the marginal benefits of closure (reduced mortality, but with spillovers) outweigh its costs (loss of harvest in previously exploited area).⁷

2.2 Economics of Reserves

To what extent reserves offer benefits over existing fisheries management (such as total harvest and effort controls) can only be judged relative to the goals of management and by incorporating the economics of harvesting with the biological aspects of reserves. One of the first economic models to examine the efficacy of reserves was developed by Holland and Brazee (1996). Using a deterministic framework they show that the relative benefits of reserves depends on their effect on harvesting in exploited areas and the discount rate---the greater the short-term harvest loss through reserve creation and the greater the discount rate, the smaller are the benefits of a reserve and the smaller its optimal size. In simulations, they also find that at higher fishing effort levels a correspondingly higher reserve size is required to generate higher discounted rents. Their work is also noteworthy for stressing the value of reserves as “insurance” to management failure and the inability to control either fishing effort or harvests in exploited areas, but emphasize that if effort (and harvests) can be perfectly controlled then reserves are of little or no value.

In subsequent work, Holland (2000) observes that a reserve can, in some cases, raise harvest and revenues if fishing effort was very high prior to the establishment of the reserve, although this

could also be accomplished with more direct controls on fishing effort or harvest. His conclusion is that reserves are essentially redundant in a deterministic system if the total catch or harvesting effort can be directly and perfectly controlled. This view is supported by Hannesson (1998) who also uses a deterministic model to show that reserves would need to be in the order of 70-80% of a fishing area to yield benefits associated with an optimally controlled fishery and, to the extent that reserves initially reduce harvests in exploited areas, will raise fishing costs and also exacerbate problems of overcapacity.

Sanchirico and Wilen (1999 and 2001) emphasize that establishing reserves will invariably change the level of fishing effort in exploited areas. How fishing effort redistributes after a reserve is established depends on the biology of the species, but also on the costs and returns of harvesting in different locations. Applying this idea to the California sea urchin fishery with a deterministic model, Smith and Wilen (2003) find that discounted rents *fall* with the creation of a reserve in heavily fished area if the spatial behavior of fishers is accounted for, but is predicted to rise if it is not. Thus the location of reserves requires both biological and economic understanding and their placement in, or near to, the most productive habitat need not necessarily be the best tactic (Sanchirico and Wilen 2002).

2.3 Negative Shocks and Reserves

If a reserve reduces the mortality rate for an exploited population it should raise the population level within the reserve of exploited species. Using data from 47 fish families that includes herbivores (6), planktivore/invertebrate eaters (21) and carnivores (20), Halpern (2003) finds, relative to reference sites, that reserves on average appear to double population density, nearly triple biomass and raise size and diversity by 20-30%. Empirical evidence of the benefits of reserves is also supported in various case studies synthesized by Gell and Roberts (2002), and in a meta-analysis of data of 19 marine reserves where abundance of targeted fish species was 28% higher within reserves (Côté, Mosquera and Reynolds 2001).

An increase in the population size within the reserve has benefits beyond the spillovers in harvested areas (Roberts *et al.* 2001, Bhat 2003) because it raises the likelihood that the reserve

population (and also the entire population because of transfers out of the reserve) will not be eliminated due to a negative shock (Doyen and Béné 2003). This is because for many negative shocks, the smaller is the population or the closer it approaches its minimum viable level from above, the greater is the chance of its elimination (Shaffer 1981).⁸

By separating a population into exploited areas and reserves, the nature of the negative shocks to which species are subject to may be different, and may even be mitigated in reserves if the shocks are correlated with the level of harvesting. Consequently, reserves act as a hedge against irreducible uncertainty, especially those associated with harvesting of exploited populations (Ludwig *et al.* 1993, Botsford *et al.* 1997) where harvest rates and population stocks are measured with error and harvests are less than fully controllable (Clark 1996).

Lauck *et al.* (1998) show that reserve size should increase with the size of the negative shocks so as to ensure persistence of the population. In simulations, Mangel (2000a) shows that the longer the desired persistence of the population in the face of negative shocks, the larger should be the reserve. Sumaila (1998) and Mangel (1998) also show the negative relationship between reserve size and the negative shocks in a fishery. Mangel (1998) further derives a “no-take invariant” which implies that a higher maximum harvest level requires a larger reserve size to maintain the sustained harvest. Using the concept of an invariance kernel, Doyen and Béné (2003) also find that the greater the level of uncertainty (size and/or probability of a negative shock), the greater the share of the population required in a reserve to maintain a minimum viable population. They also observe, under certain conditions, that reserves can help maintain a minimum viable population and also raise the “guaranteed” harvests in exploited areas.

Reduced mortality in a reserve may also increase the number of long-lived and larger individuals of a given species, which in turn can increase reproductive success (Bohnsack 1998, Trippel 1995, Jennings 2001).⁹ In addition, the existence of a more fecund population source within a reserve can help offset negative shocks to the exploited population, thereby reducing the overall variance of both the total population and harvest at a given mortality rate. Such a result is important in exploited marine populations that are often subject to very large fluctuations (Ludwig *et al.* 1993, Hoffmann and Powell 1998) and where the fishing capital employed is not malleable. Conrad

(1999) also finds that reserves can reduce the variation of the population, and Sladek Nowlis and Roberts (1998), Mangel (2000b) and Hannesson (2002) all show that reserves can reduce the variation in the catch for a given size of the resource.

In sum, authors that do incorporate stochasticity into their models show that reserves have value under uncertainty by increasing population persistence and that reserves can reduce the variance of fluctuations in the population and harvests. These results have led some researchers to speculate that "...the importance of marine reserves for fishery management will increase once stochasticity is introduced in to the models as the reserves may provide a hedge against the combination of overfishing and unfavourable environmental events" (Gerber *et al.* 2003, p. S61).

Until now the full economic value of reserves under uncertainty has been speculative, despite key papers on the effects of uncertainty on renewable resources (Pindyck 1984, Reed 1988). We address this important issue and show, for the first time, how to determine optimal reserve size under general forms of uncertainty for any density-dependent population. Our paper also shows that reserves can increase discounted resource rents (even with optimal harvesting, a persistent population and risk neutral preferences) and that the value function under uncertainty is concave in optimal reserve size. Such results offer a major step forward in our understanding of marine reserves. Insights from our model also contradict the prevailing wisdom that reserves have no value if harvesting is optimal, reserves only have value if the population is overexploited, reserves need to be of a very large size to offer benefits to fishers and that reserves and output controls are equivalent methods of managing fisheries.

3. A Bioeconomic Model of a Reserve

To address the question of how reserve size for an exploited population may be calculated under a range of realistic scenarios we need to explicitly model uncertainty and the regulations governing harvests. The approach used in this paper is akin to metapopulation dynamics (Levins 1970) where we examine how a reserve mimics nature and how population differences between the reserve and exploited area determine the ability of a reserve to act as a source.¹⁰

One of the earliest metapopulation models in fisheries was by Roughgarden and Iwasa (1986). Tuck and Possingham (1994) examine the problem of optimal harvesting strategies with positive harvesting costs in a deterministic metapopulation model and find that local populations that are sources should incur less harvesting than if all local populations were managed as a single population. Brown and Roughgarden (1997), with a deterministic model, also show the value of preserving some local populations as sources while harvesting in only one location. Most recently, Bulte and van Kooten (1999) use a metapopulation framework and model uncertainty with a diffusion process that differs in two distinct metapopulations, and also allow for migration rates between the populations to differ. They show that changes in the harvest of the populations alter the rate of in and outflows between the sub-populations, as can the nature of the shocks especially if the shocks are negatively correlated (positive shock in one population corresponds to a negative shock in another).

Although the existing literature is insightful, our paper is the first to solve for a rent maximizing reserve size under general forms of uncertainty and to explore the effects of changes in biological and economic parameters on optimal reserve size. We assume a migration or population transfer based on the relative population densities between the reserve and exploited areas, and that the populations experience multiple shocks. Our approach allows us to solve for the proportion of the total population that should be in a permanent no-take area, but does not solve for the optimal location of such a reserve. Before presenting the results with uncertainty, we present the deterministic case as a benchmark.

3.1 Deterministic Case

We assume that the population, without harvesting, is governed by density-dependent growth defined by

$$f(x) = rx\left(1 - \frac{x}{K}\right)^\alpha \quad (1)$$

where x is the population or biomass, $f(x)$ is its growth, r is the intrinsic growth rate, α is a parameter and K is the carrying capacity of the given habitat.

The model assumes the population's value comes from its resource rents. It thus ignores the value of reserves in terms of biodiversity (Hastings and Botsford 2003) and precludes any additional value associated with population persistence. Inter-temporal rents from harvesting the population are defined by

$$\Pi(h, x) = p(h)h - c\left(h, \frac{x}{K}\right) \quad (2)$$

where h is harvest, $p(h)$ is the inverse demand function and $c\left(h, \frac{x}{K}\right)$ is the aggregate cost function where $c_1\left(h, \frac{x}{K}\right) > 0$ and $c_2\left(h, \frac{x}{K}\right) \leq 0$ such that costs rise with the harvest, but do not increase with population density.

In the case of no uncertainty and no reserve, the rent maximizing level of harvest is obtained by solving the following dynamic optimization problem.

$$V(x) = \max_h \int_0^{\infty} e^{-\rho t} \Pi(h, x) dt \quad (3)$$

subject to:

$$\dot{x} = f(x) - h \quad (4)$$

$$x_0 = x(0) \quad (5)$$

where ρ is the discount rate and x_0 is the initial value of the population.

Bellman's fundamental equation of optimality, defined by (6), can be used to solve the rent maximizing harvest trajectory for the problem defined by (3) to (5), i.e.,

$$\begin{aligned} \rho V(x) &= \max_h \left\{ \Pi(h, x) + V_x (f(x) - h) \right\} \\ &= \max_h \left\{ p(h)h - C\left(h, \frac{x}{K}\right) + V_x \left[rx\left(1 - \frac{x}{K}\right)^\alpha - h \right] \right\} \end{aligned} \quad (6)$$

where $V(x)$ is the optimal value function.

In the case of a permanent reserve that protects proportion $s \in [0,1]$ of the habitat of the population, the carrying capacity in the harvested or exploited area is defined by $(1-s)K$. Thus, with a reserve, the growth functions of the population within ($f(x_R, s)$) and outside ($f(x_{NR}, s)$) of the reserve are defined by

$$f(x_R, s) = rx_R \left(1 - \frac{x_R}{sK}\right)^\alpha \quad (7)$$

$$f(x_{NR}, s) = rx_{NR} \left(1 - \frac{x_{NR}}{(1-s)K}\right)^\alpha \quad (8)$$

where x_R and x_{NR} are respectively the population in the reserve and the exploited area. Transfer or migration between the reserve and exploited populations depends on the relative population densities in the two areas whereby a higher density promotes out migration. Thus, in the absence of uncertainty, the dynamic optimization problem with a reserve is defined by

$$V(x_R, x_{NR}) = \max_{s,h} \int_0^\infty e^{-\rho t} \left[p(h)h - c\left(h, \frac{x_{NR}}{(1-s)K}\right) \right] dt \quad (9)$$

subject to:

$$\dot{x}_R = f(x_R, s) - \phi\left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right) \quad (10)$$

$$\dot{x}_{NR} = f(x_{NR}, s) + \phi\left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right) - h \quad (11)$$

$$x_0 = x(0) \quad (12)$$

where the initial total population (x_0) is defined as the sum of the initial population in the reserve and outside of the reserve, and $\phi\left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right)$ is the transfer function that governs migration from the reserve to the exploited areas of the habitat.¹¹

The Bellman equation, given by (13), can be used to solve for optimal harvest trajectory and reserve size for the problem defined by (9) to (12), i.e.,

$$\rho V(x_R, x_{NR}) = \max_h \left\langle \begin{array}{l} \Pi(h, x_{NR}, s) + V_{x_{NR}}(x) \left[f(x_{NR}, s) + \phi \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) - h \right] \\ + V_{x_R}(x) \left[f(x_R, s) - \phi \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) \right] \end{array} \right\rangle \quad (13)$$

We note that a solution for the problem defined by (9) to (12) has $s = 0$ as a special case. In other words, if the optimal reserve size is positive it must be the case that a reserve generates higher discounted rents than no reserve.

3.2 Uncertainty Case

To analyze the effects of reserves on rents and resilience, the model must include uncertainty, and we incorporate this as stochastic shocks that may affect both the reserve and non-reserve population. In particular, we specify two types of shocks: one, a shock that may be either a positive or negative and represents *environmental stochasticity* due to temporal variation in the habitat (Shaffer 1981) and, two, a negative shock that represents a natural, and possibly harvesting induced, *catastrophe* that occurs randomly over time. We define environmental stochasticity by a Wiener diffusion process (Brownian motion) that follows a normal distribution (W_t) and catastrophe as a jump process (q) that follows a Poisson distribution defined by the parameter λ .

The dynamic optimization problem with a reserve under uncertainty and with optimal harvesting of the exploited population is defined by

$$V(x_R, x_{NR}) = \max_{s,h} \int_0^{\infty} e^{-\rho t} \Pi(h, x_{NR}, s) dt \quad (14)$$

subject to:

$$dx_R = [f(x_R, s) - \phi(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K})]dt + g(x_R)dW + \varphi(x_R)dq \quad (15)$$

$$dx_{NR} = [f(x_{NR}, s) + \phi(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}) - h]dt + g(x_{NR})dW + \gamma(x_{NR})dq \quad (16)$$

$$x_0 = x(0) \quad (17)$$

The functions φ and γ differ to reflect the possibility that harvesting may have a deleterious impact on the age structure and habitat such that, for a given negative shock, the consequences may be greater for the exploited than the reserve population. Such an interpretation is consistent with stylized facts in fisheries and has been used by others, including Reed (1988).

Using Ito's Lemma, Bellman's fundamental equation of optimality can be defined by (18) and used to solve for the optimal reserve size and harvest trajectory, i.e.,

$$\rho V(x_R, x_{NR}) = \max_h \left\{ \begin{aligned} & \Pi(h, x_{NR}, s) + V_{x_{NR}}(x) [f(x_{NR}, s) + \phi(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}) - h] \\ & + V_{x_R}(x) [f(x_R, s) - \phi(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K})] + \\ & \frac{1}{2} V_{x_R x_R} g(x_R)^2 + \frac{1}{2} V_{x_{NR} x_{NR}} g(x_{NR})^2 + V_{x_R x_{NR}} g(x_R) g(x_{NR}) + \\ & \lambda [V(x_R + \varphi(x_R), x_{NR} + \gamma(x_{NR})) - V(x)] \end{aligned} \right\} \quad (18)$$

Given the complexity of the stochastic jump-diffusion process it is not possible to find a solution to (18) analytically. To solve for the optimal reserve size and harvest trajectory, we thus use a modified form of the perturbation method introduced by Gaspar and Judd (1997) and Judd (1999).¹² The method involves introducing two auxiliary variables (one for a Brownian diffusion process and another for the jump process) defined as η and ε to the Bellman equation, where if $\eta = \varepsilon = 0$ the deterministic problem specified in (13) results. Following the substitution, the decision function and value function can be defined as $\Pi(h, x_{NR}, s, \eta, \varepsilon)$ and $V(x_{NR}, x_R, \eta, \varepsilon)$, and a n^{th} order Taylor series expansion can be defined around the steady state in the deterministic case. In the first step we solve for the steady state in the deterministic case ($\eta = \varepsilon = 0$) by using the

maximum condition for the Bellman equation, applying the Envelope Theorem and the equations of motion for the reserve and non-reserve populations. In the second step, we differentiate the maximum condition and Envelope theorem equation with respect to the state variables x_R and x_{NR} . In step three, we differentiate the Bellman equation to find V_η and V_ε that are expressions of higher order derivatives with respect to the state variables found in step two. Successive differentiation of the Bellman equation with respect to the auxiliary variables, control variables and state variables allows us to solve with greater precision for required values in a grid-like pattern. This process can be automated to calculate the partial derivatives of the optimal value function and control variables with respect to the state and the auxiliary variables, and to solve for the optimal harvest levels for a given reserve size.¹³ The optimal reserve size is that which maximizes the value function.

4. Optimal Reserve Size: A Numerical Illustration

The desired size of a reserve will depend on many bioeconomic factors including the discount rate, intrinsic growth rate, carrying capacity, transfer or migration function, current resource rent and the magnitude and incidence of shocks. Consequently, reserve size will vary across populations and over time as the underlying biological and economic parameters change. Our perturbation method, however, provides an approach to determine optimal reserve size for multiple populations and under a large number of different scenarios and conditions, provided that the value function is concave and the decision function is convex.

To illustrate the effects of changes in the parameters on reserve size and also to derive ‘rules of thumb’ about reserves we specify the specific forms of the following inverse demand and aggregate harvesting cost functions:

$$p(h) = ah^{-0.3} \tag{19}$$

$$c\left(h, \frac{x_{NR}}{(1-s)K}\right) = \frac{bh(1-s)}{x_{NR}} \tag{20}$$

To generate an optimal reserve size, and for illustrative purposes only, we initially set $a = 0.35$ and $b = 0.2$. Our biological parameters are estimated from a logistic growth function of Canada's northern cod fishery using 30 years of data and are defined as $r = 0.30355$, $K = 3.2$ million and $\alpha = 0.35865$ (Grafton *et al.* 2000). We specify $\rho = 0.05$ and define the transfer function as $0.9375\left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right)$. The diffusion term is given by $g(x_R) = 0.01x_R$ and $g(x_{NR}) = 0.01x_{NR}$, while the probability of the natural catastrophe is 0.2 with a jump amplitude defined as $\varphi(x_R) = 0$ and $\gamma(x_{NR}) = -0.15x_{NR}$. Negative shocks of the same magnitude to both the reserve and exploited population generate qualitatively similar results. We also note that the 'rules of thumb' and policy implications about reserves obtained below are *not* dependent on specific parameter values.

Deterministic Case

As a benchmark, we solve for the optimal reserve size under *no* uncertainty and find that, with an optimal harvest trajectory, a reserve generates no direct economic benefits. This supports the existing deterministic models in the literature that with optimal harvesting that maximizes the discounted rents for the fishery, reserves provide no direct benefits and, in fact, may reduce rents because they increase the cost of fishing effort (Holland 2002). For the parameters specified above, with no uncertainty, we find the value function is monotonically *decreasing* in the reserve size, as shown in Figure 1.

[Put Figure 1 here]

Optimal reserve size

In the case of uncertainty, with a diffusion process and also a jump process, we find that a reserve of size $s > 0$ is optimal under a large range of parameter values. In particular, we find that with uncertainty and optimal harvesting outside of the reserve, a no-take area that protects a little less than 30% of the total population maximizes discounted rents.

Figure 2 illustrates this important and original result, namely, even with optimal harvesting, risk neutrality and a persistent population there is an economic payoff to having a reserve. Moreover

this result holds true given any positive initial population size, because the initial size only has transitory effects on the harvest rate. In other words, the value of the reserve is *not* obtained from initially being at a population level below that maximizes the yield from the population and neither is it a result of risk-averse preferences.

[Put Figure 2 here]

The economic value of a reserve under uncertainty arises because a reserve acts as a buffer that provides a population source for the exploited population that reduces the severity of negative shocks. Thus whenever a negative shock has at least an equal to or greater impact on the exploited than the reserve population, the reserve is able to help the exploited population recover faster and thereby increase harvest levels compared to the case without a reserve. The ability of the reserve to help the exploited population recover can also occur without a jump process provided there is a negative drift of the same magnitude in the diffusion process for the reserve and exploited populations.

Our result does not depend on particular parameter values or the size of the shocks, and we call it a ‘resilience effect’. For the specific parameters specified above the effect is illustrated in Figure 3 where the larger the reserve, the greater is its ability to offset shocks to the exploited population over time. In Figure 3 the few, but large declines, in the population represent the jump process while the small and irregular fluctuations over much smaller time intervals are the effects of the diffusion process.

[Put Figure 3 here]

The ability of the reserve to offset shocks increases the optimal harvest above what it would be in the absence of a reserve, and is illustrated in Figure 4. This result in terms of harvest holds true even if the reserve and exploited population face the same negative shocks, because the greater population density in the reserve allows for a transfer of individuals into the areas subject to harvesting.

[Put Figure 4 here]

Although increasing the reserve size increases the ability of the population to rebound following a shock, an economic trade-off exists in that a larger reserve reduces the population subject to harvesting.

Transfer function

As has been shown by others in deterministic models, the transfer or migration rate from the reserve to the exploited area has an important impact on the value and size of reserves. We also show in Figure 5 that, in the case of uncertainty, the higher the transfer rate, the larger the optimal reserve size. This is also a general result and does not depend on the specific parameter values used in the example. It arises because the greater the number of individuals that leave the reserve and become subject to exploitation the less protection that is provided by a reserve of a given size. Thus the greater is the rate of transfer from the reserve to exploited areas the larger is the required reserve to provide a buffer in the event of a negative shock.

[Put Figure 5 here]

Volatility

A key result is that reserves mitigate negative shocks that are at least as great for the exploited population by raising the rate of harvest through the transfer of the population to the area subject to harvesting. This resilience effect enables the population to recover faster and thus will tend to reduce the volatility of the population, harvest and rents. For the parameters specified above we can show this effect by defining volatility as the standard deviation around the steady-state population without uncertainty, as shown in Figure 6.

[Put Figure 6 here]

Figure 6 shows that volatility is monotonically decreasing in reserve size. It supports the work of Conrad (1999) who showed that uncorrelated net growth between the reserve and exploited area helps smooth biomass levels, and also the results of Sladek Nowlis and Roberts (1998), Mangel (2000b) and Hannesson (2002) who showed that a reserve can decrease variability in catch. We also show that a reserve reduces the volatility of the resource rents, and that this stabilizing effect can be accentuated in the case of rents depending on the price elasticity of demand and the effects of a change in the harvest and population density on harvesting costs.¹⁴

Resilience

The key and general result of the paper is that the resilience of the population is improved with a reserve. We can show the resilience if we define resilience as the mean period of time to return to within one standard deviation of the population level prior to the shock. This effect is shown in Figure 7, where a shorter period of time represents a *higher* level of resilience, and resilience is increasing in reserve size.

[Put Figure 7 here]

The resilience result differs from the work of Lauck *et al.* (1998) who show that a larger reserve increases the probability that a population will be sustained into the future or that of Guénette *et al.* (1998) and also Guénette and Pitcher (1999) who show that a reserve helps maintain a population at a higher level than without a reserve. In our model, the population persists, in part, because the negative shocks are not sufficient to drive the population to ecological extinction, and because we have optimal harvesting and it is not optimal here to harvest until extinction. Thus, irrespective of a reserve's ability to increase a population's persistence and raise its level above the minimum viable level, a reserve still has value even with optimal harvesting because it enables the exploited population to rebound faster after a negative shock, and thereby increases the harvest that would otherwise not be possible without a reserve.

Intrinsic growth rate

The resilience of a population to rebound following a shock is, in part, determined by its intrinsic growth rate. The higher the intrinsic growth rate, the quicker the population can rebound following a negative shock. Given that a reserve helps to increase the resilience of a population, we would expect that the higher is the intrinsic growth rate the less need for a reserve of a given size. This negative relationship between optimal reserve size and the intrinsic growth rate is a general result and, as far as we are aware, is a new insight.¹⁵ The result is illustrated in Figure 8 where optimal reserve size is monotonically decreasing in the size of the intrinsic growth rate.

[Put Figure 8 here]

Negative shocks

Another general result related to the resilience effect is that the larger are the negative shocks to the exploited population, the larger will be the optimal reserve size. Our result arises because the greater is the magnitude of the shock, the greater is the share of the population required to be in a reserve so as to buffer the shock and provide a source to the exploited population. This result is illustrated in Figure 9.

[Put Figure 9 here]

A similar result exists in terms of the probability of the negative shock. Provided that the shock has at least an equal to or greater impact on the exploited than the reserve population, an increase in the probability of the shock will increase the optimal reserve size.

Non-optimal harvesting

Harvesting in a manner that does not maximize the discounted rents from the fishery may involve either harvesting too much or too little of the population. For many wild populations (especially fisheries) sub-optimal harvesting frequently involves harvesting at a rate that exceeds the optimal level (Ludwig *et al.* 1993, Pauly *et al.* 1998, Myers *et al.* 1997). Often this involves the use of *ad*

hoc harvesting rules.¹⁶ Where harvesting consistently exceeds its optimal level---or the harvest that maximizes the discounted rents---the optimal reserve size is larger than if harvesting were optimal. This is because a reserve both reduces the population subject to exploitation that, in turn, increases harvesting costs that reduces the harvest and because a larger reserve provides greater resilience to offset the lower population due to the higher harvest level.

Economic Variables

We can also show that a rise in the discount rate will tend to reduce optimal reserve size and with our numerical example an optimal reserve size greater than zero exists for any discount rate less than 17%. A higher discount rate reduces optimal reserve size because the resilience effect generates value to harvesters only to the extent that future harvests and returns are valuable. Thus the more myopic are the harvesters (or the higher their discount rate) the less valuable is a reserve. Our result under uncertainty is the same as that found by Holland and Brazee (1996) using a deterministic model and is also consistent with Reed (1988) and his result for the exploitation of a renewable resource under uncertainty, namely, that the lower the discount rate the higher the optimal biomass. The importance of the result is in terms of establishing or enlarging reserves. For example, differences in discount rates may help explain some of the reticence that fishers have about the establishment of marine reserves.

The effect of a shift in the inverse demand for the harvested population on optimal reserve size (defined by the parameter a in equation 19) is ambiguous, and depends on the relative magnitude of the resilience effect and what we call a ‘harvest effect’. An outward shift in the inverse demand raises the rent from harvesting, which has an immediate effect of increasing the optimal harvest rate. Provided the population is at a level between its maximum yield and its carrying capacity, the immediate harvest effect reduces the population, but also increases the sustained yield in the exploited population that, in turn, increases its resilience. Thus, the possibility exists in this population range for an outward shift in the inverse demand to lead to a lower optimal reserve size. However, if the initial population is below its maximum yield level then an outward shift in the inverse demand will immediately increase the harvest rate, but also decrease the sustained yield in the exploited population, thereby reducing its resilience. At this population level, a demand or

price increase unambiguously increases the optimal reserve size to compensate for the loss of resilience. Thus, depending on the initial population size, it is possible for the optimal reserve size to first decline (but only if the population is between the maximum yield and its carrying capacity) and then to increase with an outward shift in the inverse demand. Whether or not a ‘J-curve’ relationship exists depends on the parameter values. For the parameter values used from the northern cod fishery an increase in the demand parameter always increases optimal reserve size, as illustrated in Figure 10.¹⁷

[Put Figure 10 here]

It is possible to have optimal reserve size increasing or decreasing with an outward shift in the inverse demand. A general result, however, is that if a rise in the price or demand results in an increase in the optimal reserve size then further price rises will also lead to a larger optimal reserve size. In other words, there is a unique turning point in the inverse demand-optimal reserve size relationship.

The interplay between the harvest effect and resilience effect can also be shown with a change in the cost parameter defined by parameter b in equation (20).¹⁸ An immediate effect of an increase in the marginal cost of harvesting is to lower the current harvest rate. If the population is between the maximum yield and the carrying capacity, the harvesting effect reduces the sustained yield in the population, thus requiring an increase in the optimal reserve size to maintain the desired resilience that maximizes the value function. Consequently, a rise in the marginal costs of harvesting will always lead to an increase in optimal reserve size at this population level. However, if the population level is initially below the maximum yield it is possible for the optimal reserve size to initially fall with an increase in marginal harvesting costs. This is because the harvest effect reduces the current harvesting rate, but in this case it leads to an increase in the exploited population’s sustained yield thereby increasing its resilience. Given that resilience has increased in this case it may be optimal to reduce the reserve size. Thus, as in the case of an outward shift in the inverse demand, we may obtain a ‘J-curve’ and with a unique turning point. It also follows that if a rise in the marginal harvesting cost initially increases the optimal reserve size then any subsequent cost rise will also lead to further increases in the optimal reserve size.

5. Reserves and ‘Rules of Thumb’

The results provide a number of important insights when establishing or enlarging reserves for harvested populations. First, and foremost, we have shown a resilience effect where reserves have a positive economic value under uncertainty, even if harvesting is economically optimal. By contrast, in the deterministic case, we show that reserves have a negative economic value if there is optimal harvesting. The beneficial effect of reserves in terms of increasing discounted rents arises whenever the magnitude of a negative shock for an exploited population is equal to or greater than the shock for the reserve population. In such circumstances, a reserve will *always* increase resilience and allows the exploited population to rebound faster increasing the harvests that would otherwise not be possible without a reserve.

Our resilience result is in direct contrast to existing deterministic models that suggest that effort controls and reserves are equivalent (Botsford *et al.* 2003, Hastings and Botsford 1999). Moreover, the value of reserves in our model is separate from any value a reserve may generate under uncertainty by helping to ensure population persistence (Lauck *et al.* 1998). Our result also holds true for any positive initial population level and contradicts the common presumption that reserves only have value when population levels are low and current harvesting results in a decline in recruitment (Gerber *et al.* 2003, p. S58).

We have a general result that the value function is concave in reserve size, given that it is optimal to have a reserve. This implies that if it is optimal to have a reserve, then any marginal increase in reserve size at less than the optimal size increases both resilience and the discounted rents from harvesting. This ‘double-payoff’ has important policy implications, namely, that even a small reserve that is less than its optimal size renders higher economic benefits to harvesters under uncertainty than no reserve. The zone in reserve size between no reserve and its optimal size may be described as a ‘win-win’ in the sense that a marginal increase in reserve size offers both biological and economic benefits. Thus by initially establishing small reserves for a population, and in different locations, resource managers can collect the data necessary, and also experiment, to help determine the optimal reserve size.¹⁹

The concavity of the value function with respect to reserve size, and the fact that a positive optimal reserve size is obtainable under a wide range of parameter values, suggests that an adaptive reserves policy, with initially small reserves, would be superior to having no reserves for many harvested populations. Such an approach to reserve creation may be described as active adaptive management---an approach to management that has been proposed as a means to help address the irreducible uncertainty inherent in the management of wild populations (Walters and Hilborn 1978). Roberts *et al.* (2003, p. S221) also observe that refinements about reserve size can follow scientific study and that postponing reserve creation because of scientific uncertainty is likely to be a poor strategy (Roberts 1998). Establishing initially smaller reserves is also consistent with the latest synthesis of the effects of reserves where it has been found that a small reserve has the same proportional effect on biomass as a large reserve (Halpern 2003).²⁰

Given the daunting task to obtain the data necessary to calculate optimal reserve size, especially the transfer rate of juveniles of eggs, larvae and juveniles between reserves and adjacent areas (Allison *et al.* 1998, Gerber *et al.* 2003, Palumbi 2003, Sladek Nowlis and Roberts 1998), decision makers require ‘rules of thumb’ to assist them in establishing reserves. Our results provide a number of general and important ‘rules of thumb’ that extend existing criteria for the establishment of reserves based on biological integrity and productivity criteria (Roberts *et al.* 2003). We find that optimal reserve size will increase the greater the rate of transfer from the reserve to areas subject to harvesting, the greater the magnitude or likelihood of negative shocks, the more the actual harvest exceeds the optimal harvest, the lower the discount rate and the lower the population’s intrinsic growth rate. We also find that if the population is between the maximum yield and its carrying capacity, an increase in the marginal harvesting cost will *always* increase the optimal reserve size. If the population level is between zero and its maximum yield then a rise in the price per unit harvested or demand will *always* increase optimal reserve size.

6. Concluding Remarks

The paper develops a perturbation method to determine optimal reserve size for a harvested population subject to stochastic shocks in the form of a diffusion process and jump process. The

results indicate that existing deterministic models understate the value of reserves and that even with optimal harvesting, risk neutrality and a persistent population a reserve can increase the present value of resource rents, provided that the effects of negative shocks on the reserve are at least as great for the exploited population. Our results are in stark contrast with the existing literature that has emphasized that if harvesting or effort can be controlled optimally, reserves are redundant.

The reason a reserve has value in terms of increasing discounted rents is because it increases an exploited population's resilience, or the speed at which it returns to a neighborhood of its initial level following a natural catastrophe. In turn, increased resilience allows for a greater harvest following a negative shock and can increase the resource rents. This outcome is true for any positive initial population size, and is in contrast to the presumption in the literature that reserves only have value for overexploited populations or for populations particularly prone to extinction.

The results provide important 'rules of thumb' about the establishment or enlargement of existing reserves. Such rules are needed because many decision makers currently lack the data, or have imprecise data, to properly calculate optimal reserve size using our perturbation method. In particular, we show that optimal reserve size will increase: the greater the rate of transfer from the reserve to areas subject to harvesting, the greater the magnitude or likelihood of negative shocks, the more the actual harvest exceeds the optimal harvest, the lower the discount rate, and the lower the population's intrinsic growth rate. If the initial population is between its maximum yield level and its carrying capacity, an increase in the marginal cost per unit of harvesting will always increase optimal reserve size. If the initial population is between zero and its maximum yield, an increase in the price per unit harvested, or an outward shift in the inverse demand, will always increase the optimal reserve size.

If an optimal reserve size greater than zero exists, which is the case under a wide range of biological and economic parameters, the value function is concave with respect to reserve size under uncertainty. Concavity implies that even a small (but less than optimal) reserve size is economically beneficial to harvesters while also rendering biological benefits. The policy insight of this result is that, for many harvested populations, a positive economic return will likely arise

from initially establishing small reserves where reserves currently do not exist, provided that the cost of monitoring and enforcing these reserves is low. An adaptive reserves strategy---initially establish small reserves and gather information to adjust to a more optimal size later---would provide the opportunity to experiment and collect data to obtain a better understanding of key parameters, such as the transfer rate from reserves to exploited populations. An adaptive reserves strategy, a method to solve for optimal reserve size under uncertainty, and ‘rules of thumb’ about establishing reserves collectively offer a major step forward to our understanding of marine reserves and their economic value.

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End Notes

¹ The WSSD plan of implementation (article 32(c)) requires "...the establishment of marine protected areas consistent with international law and based on scientific information, including representative networks by 2012..."

² The Plan Development Team recommended a minimum 20% reserve in the southern Atlantic coast of the United States and a 20% target for the US is proposed by the National Research Council (2000). Using a bioeconomic model of the North Sea ecosystem Beattie *et al.* (2002) recommend a reserve size of between 25-40% of its surface area.

³ Gell and Roberts (2002) provide a synthesis of existing empirical studies of the effects of marine reserves. Many individual case studies show the biological benefits of reserves.

⁴ See Dixit and Pindyck (1994) and Malliaris and Brock (1982) for further details.

⁵ Pimm (1984, p. 325) defines resilience as the *speed* at which a species composition returns to an equilibrium following a shock. Holling (1973, p. 20) measures it in two ways: one, the extent to which a domain of attraction of the trajectories for a group of species does not include points of extinction and two, the *magnitude* of a shock required to place a group of species into a trajectory that leads to extinction. Our notion of resilience refers to a single species and the speed with which it rebounds from a shock to return to within a neighborhood of its value immediately before the shock.

⁶ This trade-off between the size of the spawning biomass in the reserve and the transfer rate from a reserve to exploited areas has subsequently been shown by DeMartini (1993), Guénette and Pitcher (1999) and Apostolaki *et al.* (2002), among others.

⁷ Pezzey *et al.* (2000) show that the equilibrium catch will rise if the ratio of the population to its carrying capacity before the creation of the reserve (with open access) is less than half.

⁸ Shaffer (1981, p. 132) defines the concept of a minimum viable population as "...the smallest isolated population having a 99% chance of remaining extant for 1000 years despite the foreseeable effects of demographic, environmental and genetic stochasticity, and natural catastrophes."

⁹ Reserves may also impose selective pressure for shorter dispersal distance (Botsford *et al.* 2001) that would, in general, not be beneficial in terms of generating spillovers to adjacent exploited areas.

¹⁰ In his classic paper Levins (1970, p. 77) describes a metapopulation for a species as a "population of populations". A substantive review of the metapopulation models in fisheries is provided by Smedbol *et al.* (2002).

¹¹ The transfer function implicitly assumes larval pool, equal redistribution (LPER) and is likely to be overoptimistic in terms of the spillovers from reserves to exploited areas (Gerber *et al.* 2003).

¹² The case for solving more realistic, but complicated models, by numerical methods in place of more simple models where analytic solutions and theorem-proving are available is made forcefully by Judd (1997). A general topological proof for the existence of an optimal solution (and a concave value function) in a system similar to (18), but without the jump process, is given in Atakan (2003).

¹³ MAPLE v. 8.0 was used to automate the process.

¹⁴ The more elastic is the demand, or the more sensitive are harvesting costs to changes in population density, the greater will be the stabilizing effect of a reserve on resource rents.

¹⁵ Using a deterministic and static model Reithe (2003, p. 6) obtains a different result, namely that a higher intrinsic growth rate increases the chance that a reserve will generate a higher return.

¹⁶ Various harvesting rules have been applied in fisheries. The most commonly applied is the rule to harvest at a fishing mortality rate of $F_{0.1}$ that corresponds the point where the yield-per-recruit curve is one tenth of its initial slope when fishing mortality is very close to zero, and which generates a lower harvest rate than that which maximizes yield per recruit (Beverton 1998).

¹⁷ We can obtain a J-curve using a different set of parameter values. These parameter values are available from the authors upon request.

¹⁸ In some circumstances the creation of reserve may increase b if it forces fishers to travel further to fishing grounds thereby increasing the cost of fishing effort.

¹⁹ Holland (2002) emphasizes the complexity of modeling marine reserves and that much of the data required for this purpose is currently not available. An 'adaptive reserves' policy with experimentation offers a means to better identify key parameters of metapopulations.

²⁰ Larger reserves, however, may generate proportionately larger benefits in terms of biodiversity than smaller reserves, but this is a separate issue in terms of setting an optimal reserve to maximize the present value of the resource rents.

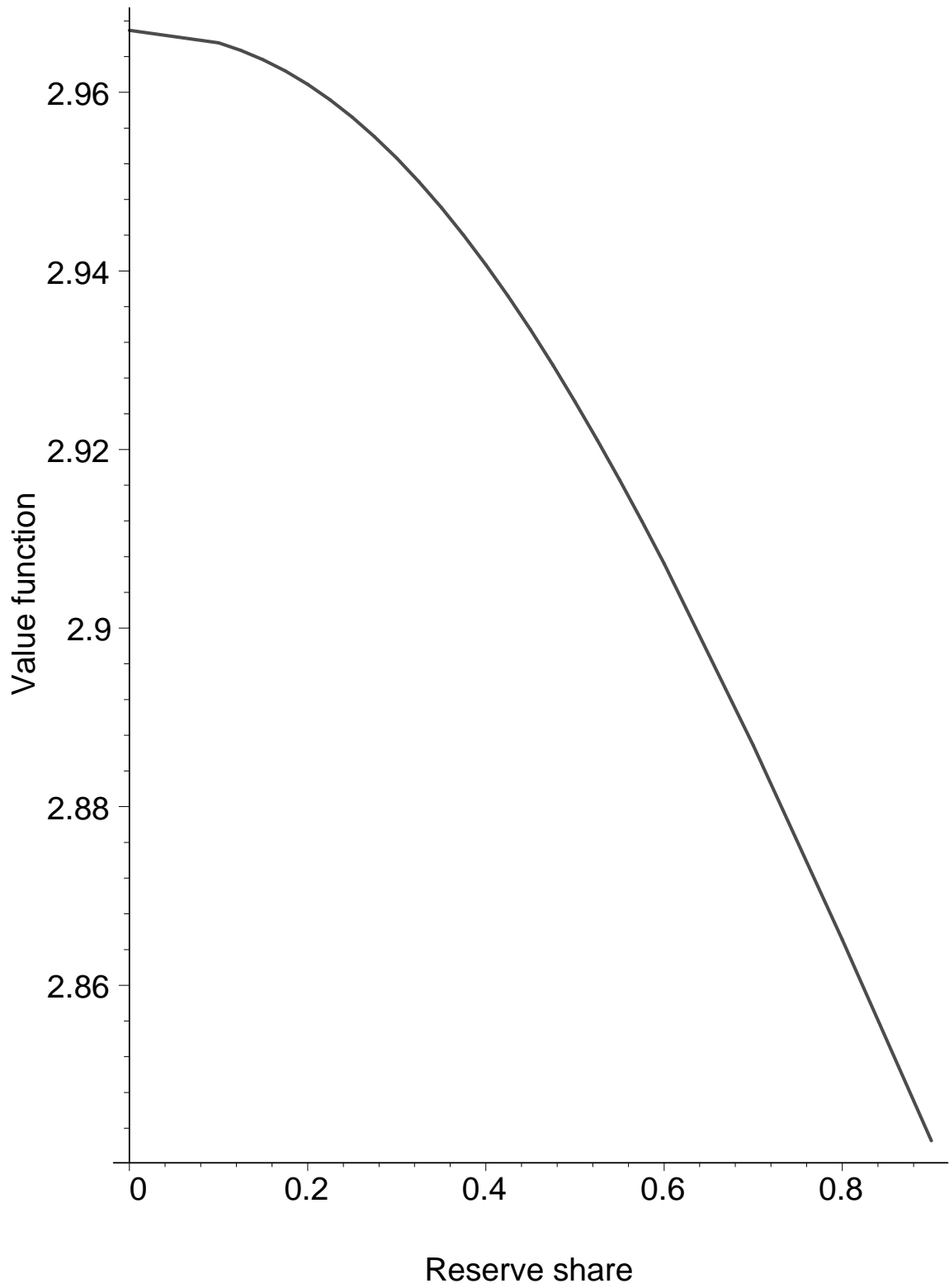


Figure 1: The value function and reserve size with no uncertainty

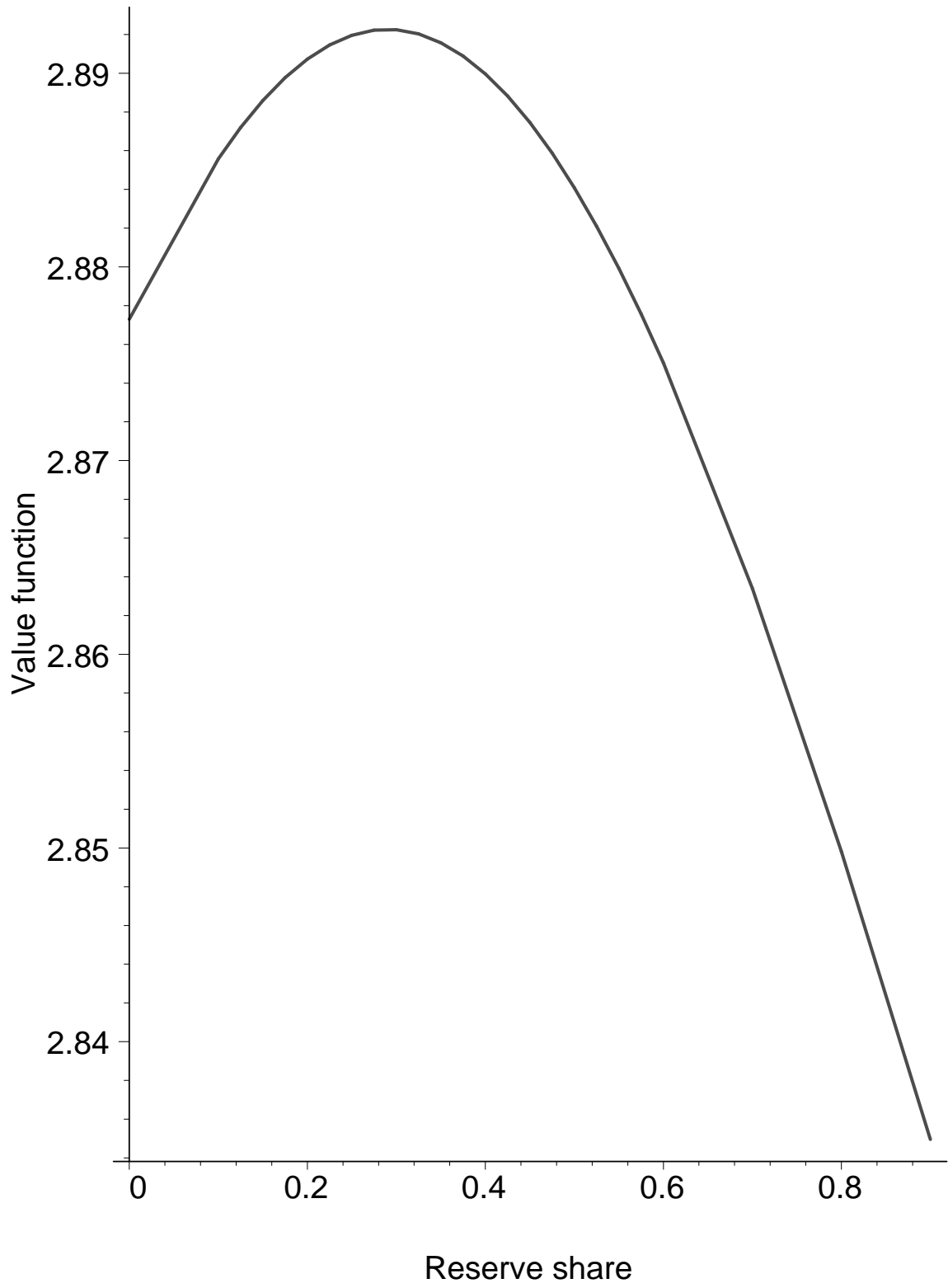


Figure 2: The value function and reserve size with uncertainty

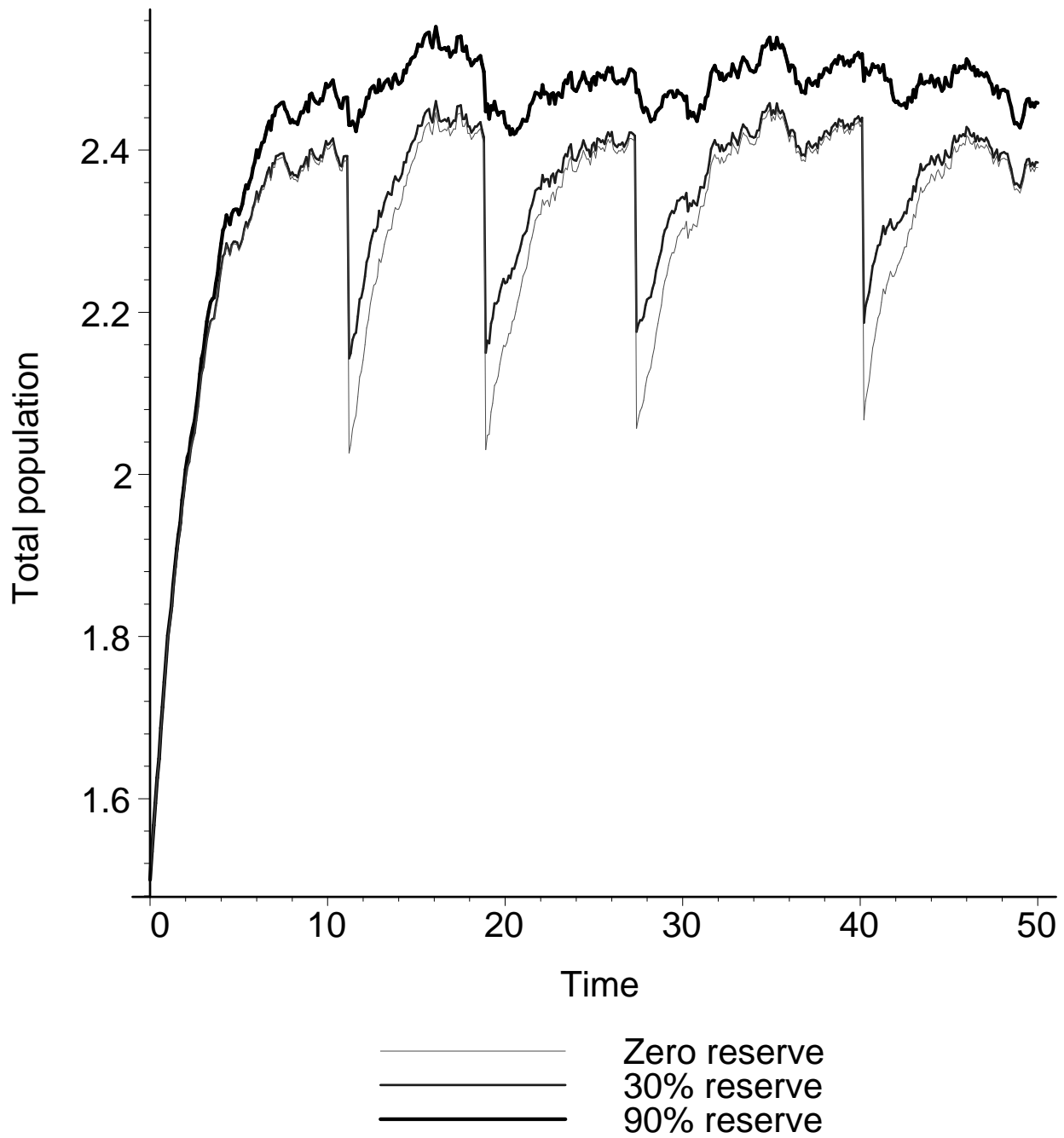


Figure 3: Relationship between the total population and reserve size

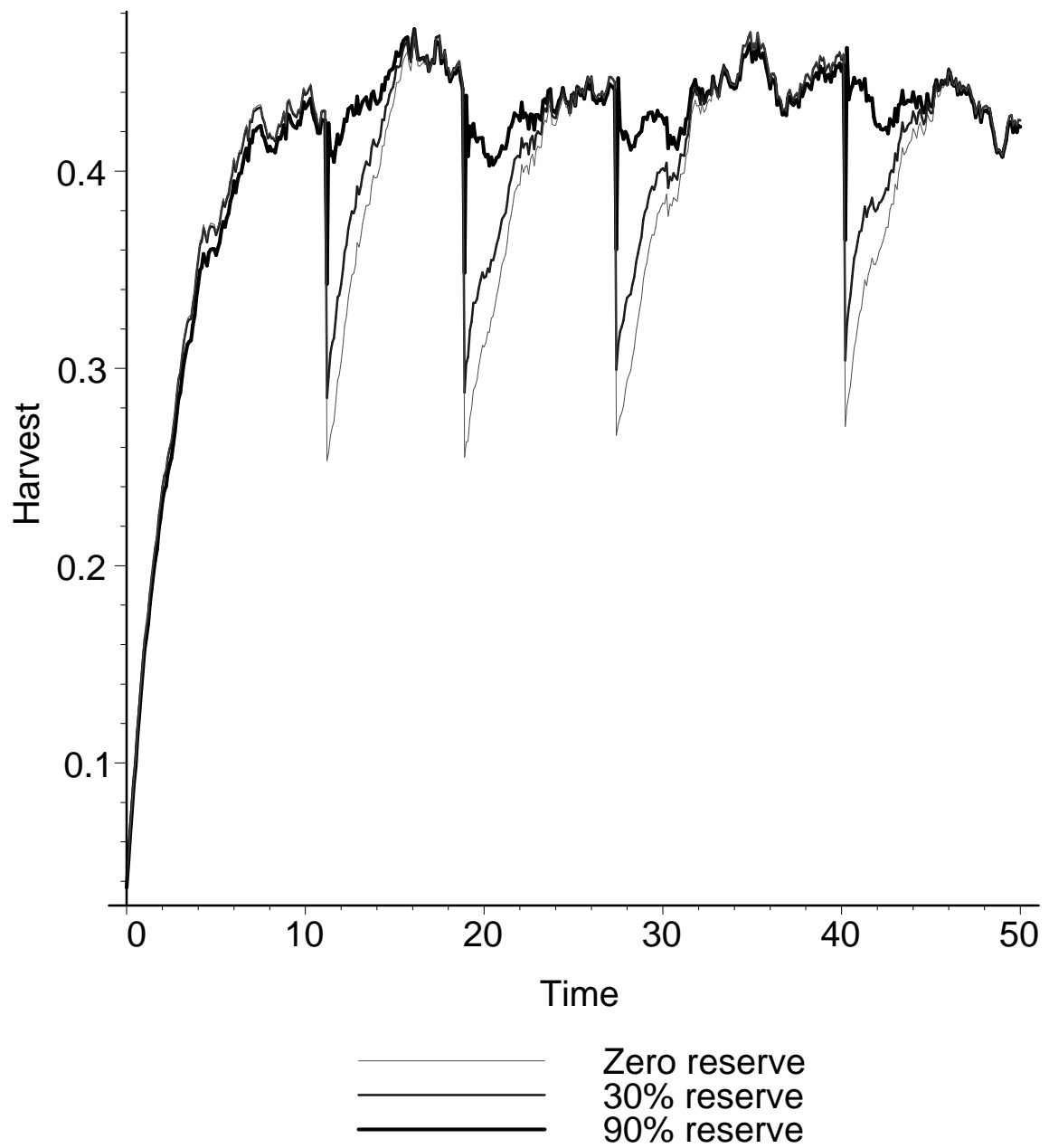


Figure 4: Relationship between harvest rate and reserve size

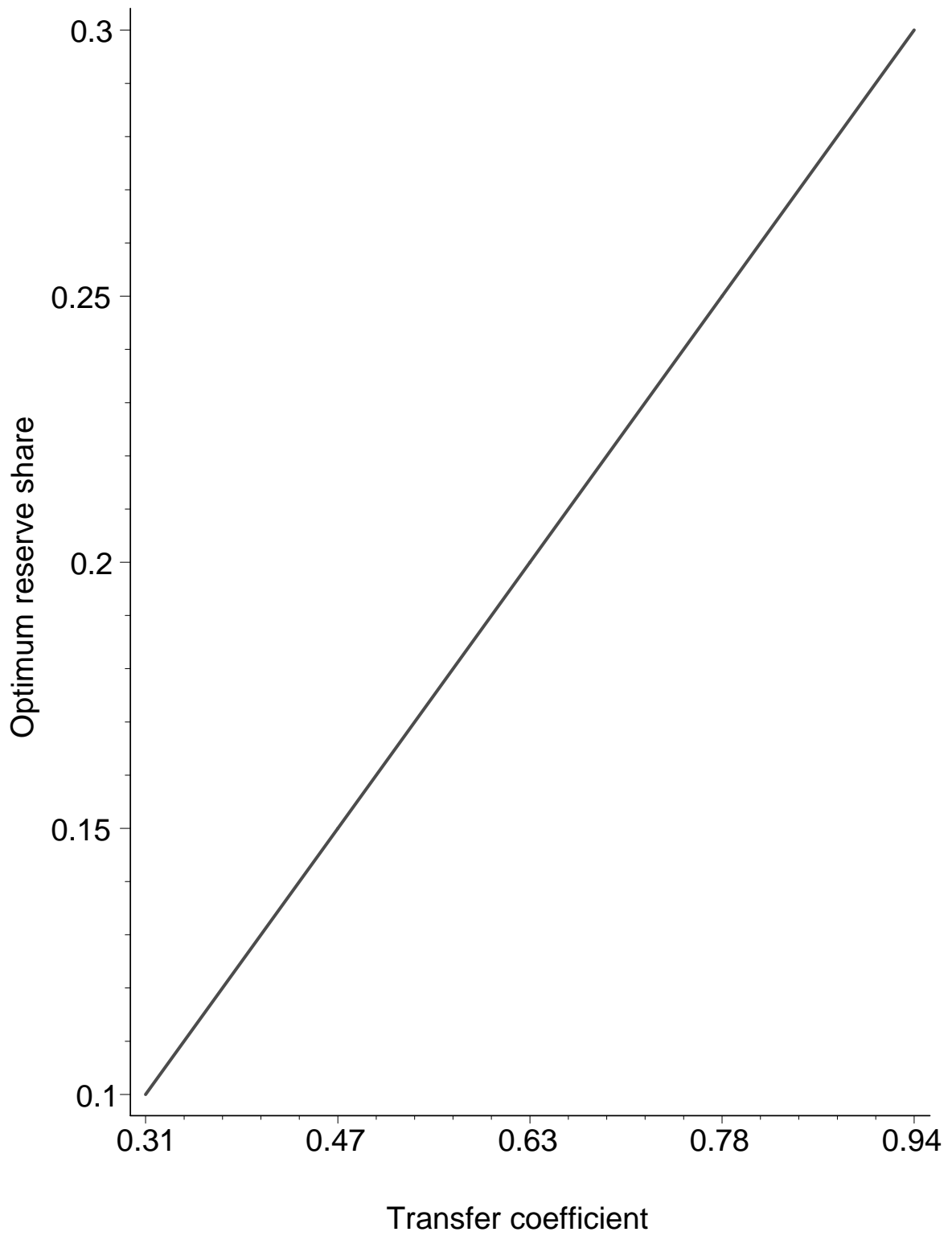


Figure 5: Relationship between the optimum reserve size and transfer rate

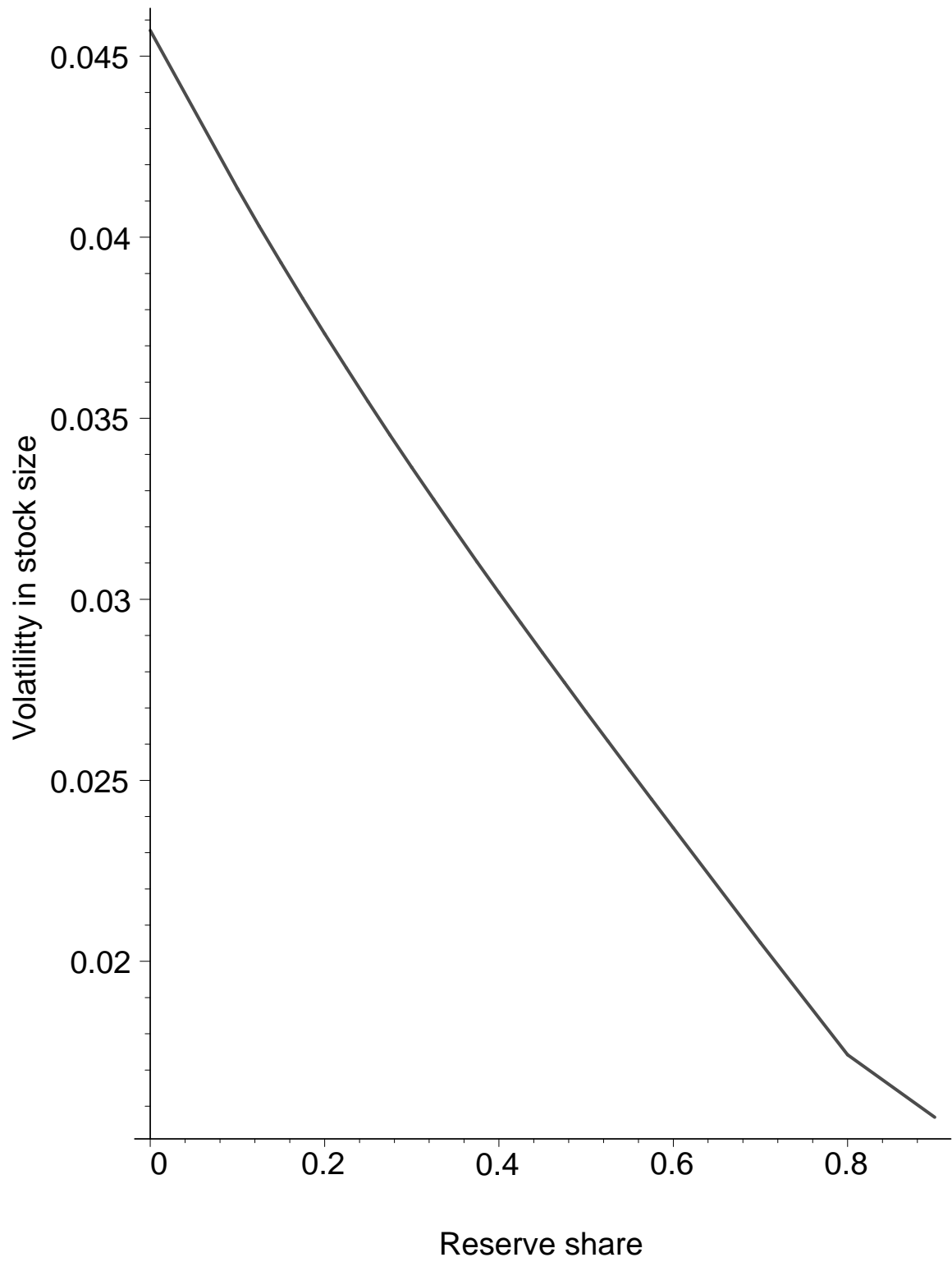


Figure 6: Relationship between volatility in population in non-reserve area and reserve size

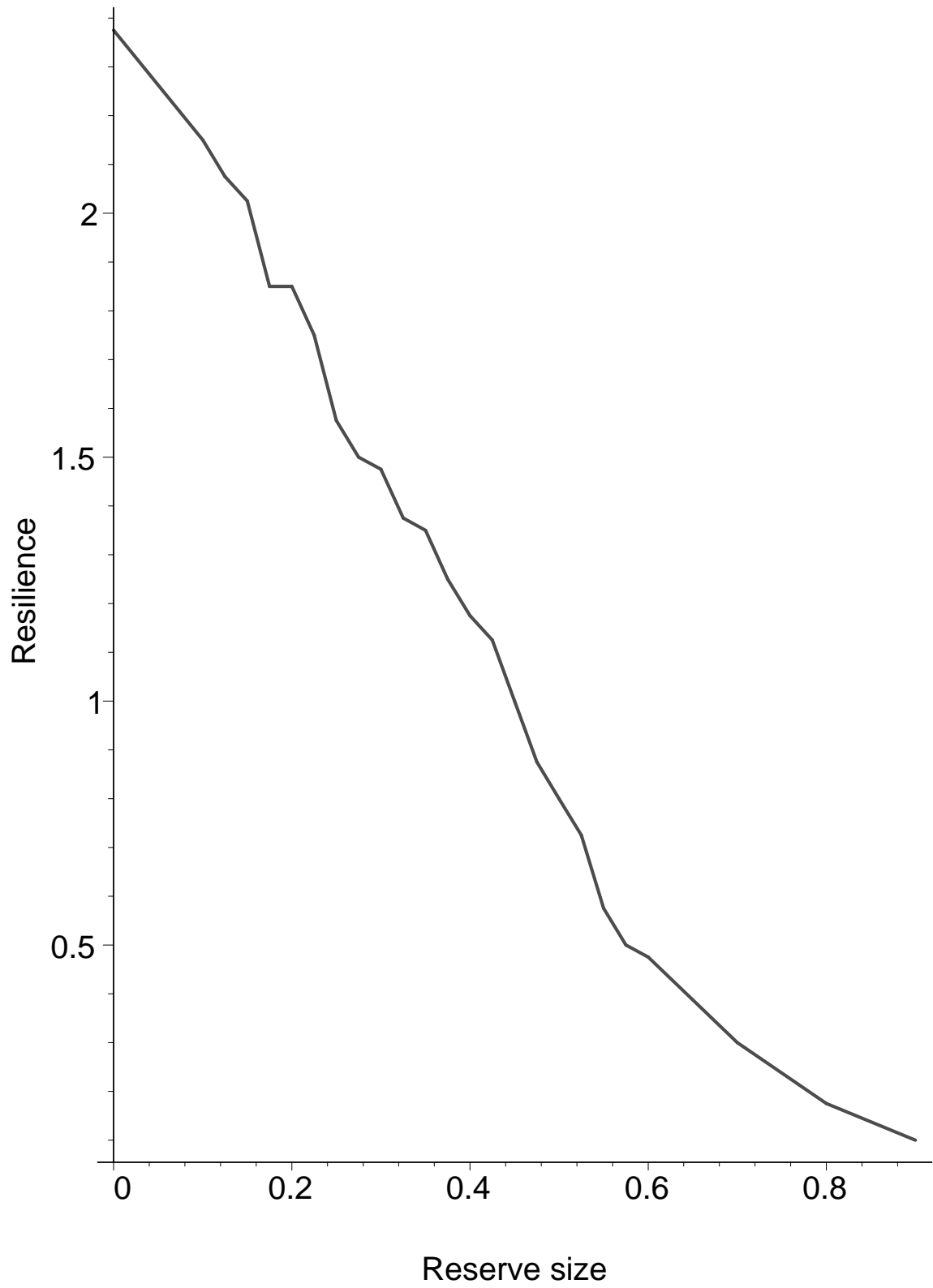


Figure 7: Relationship between resilience of the population in non-reserve area and reserve size

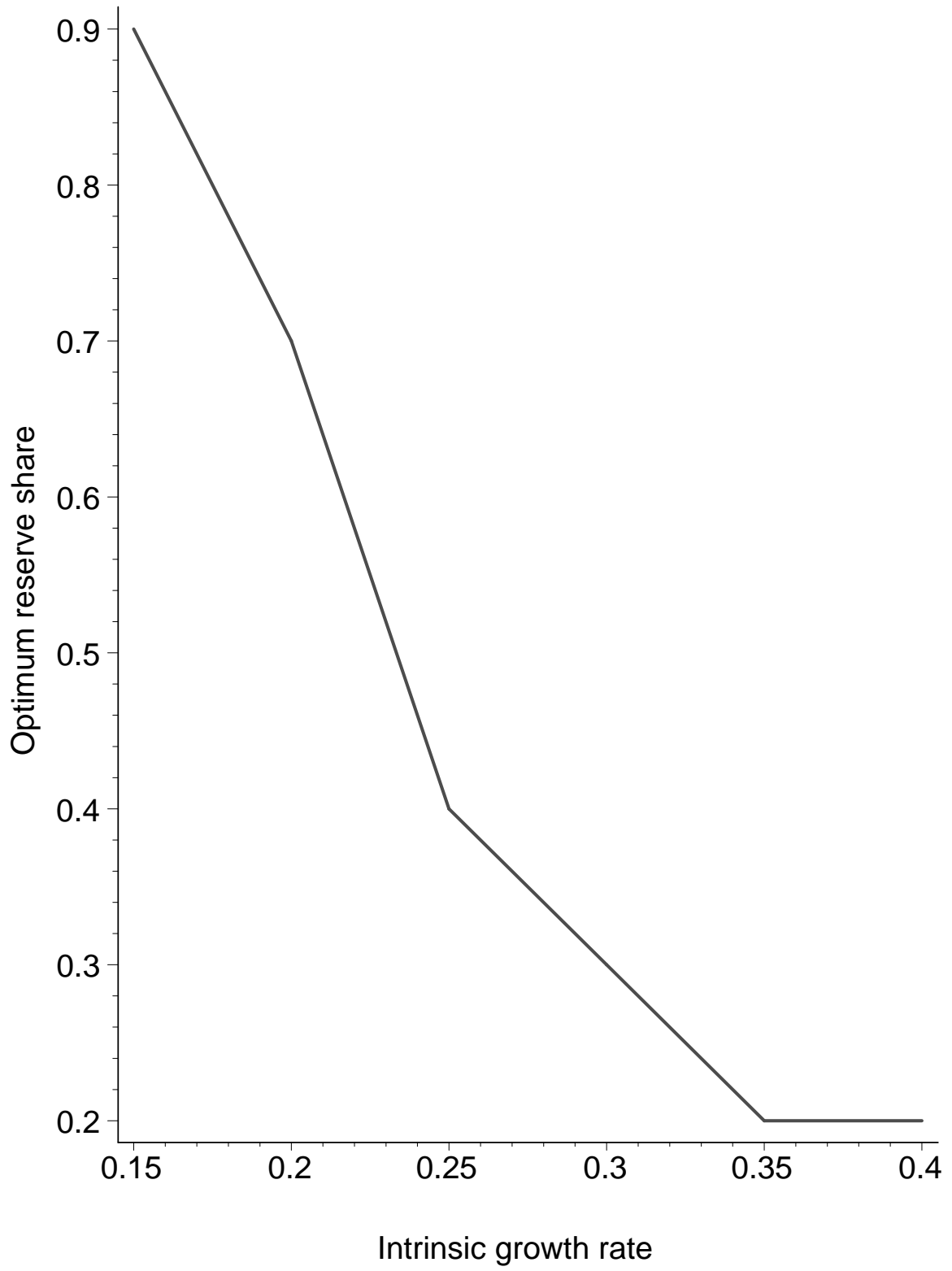


Figure 8: Relationship between the intrinsic growth rate and reserve size

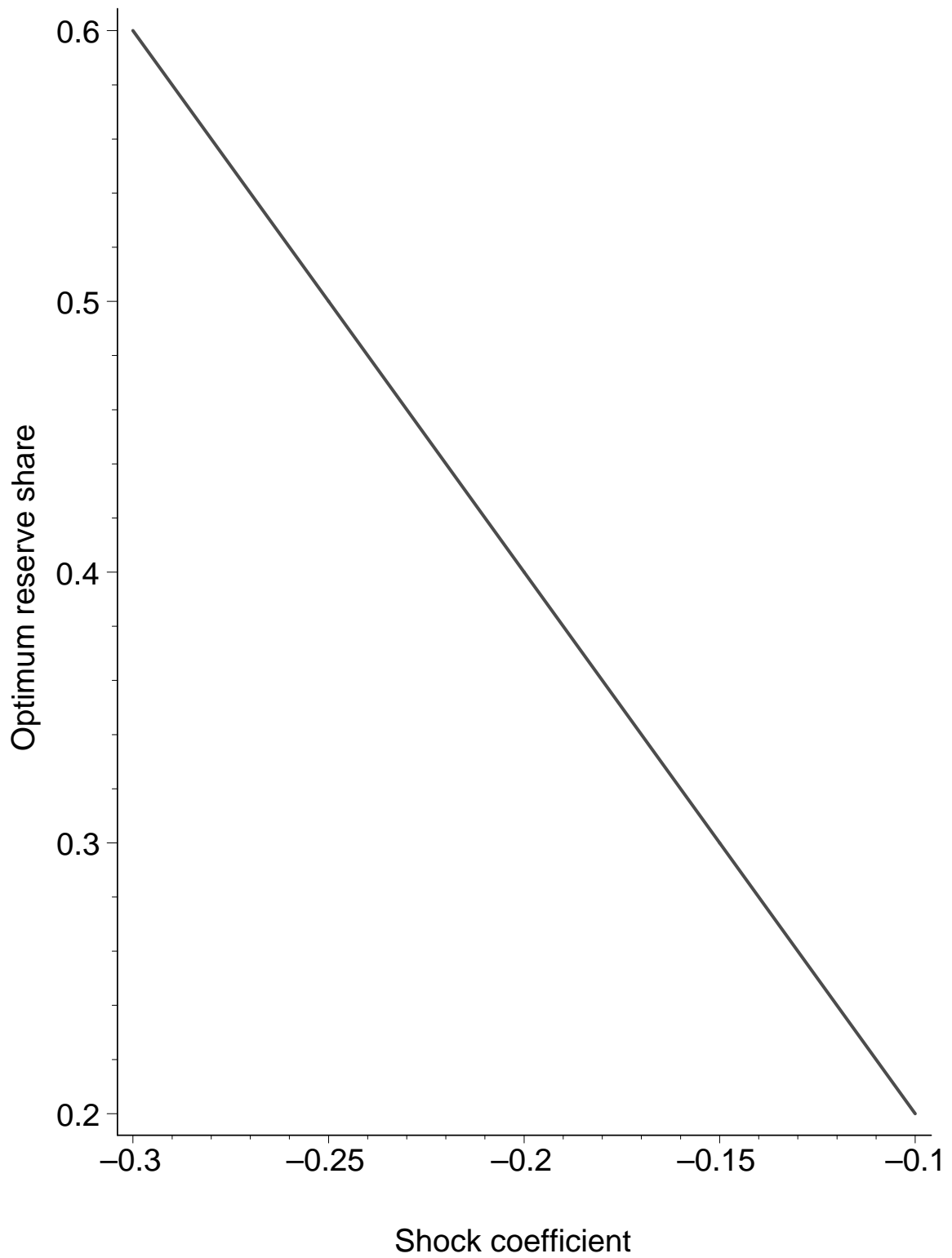


Figure 9: Relationship between magnitude of negative shock and reserve size

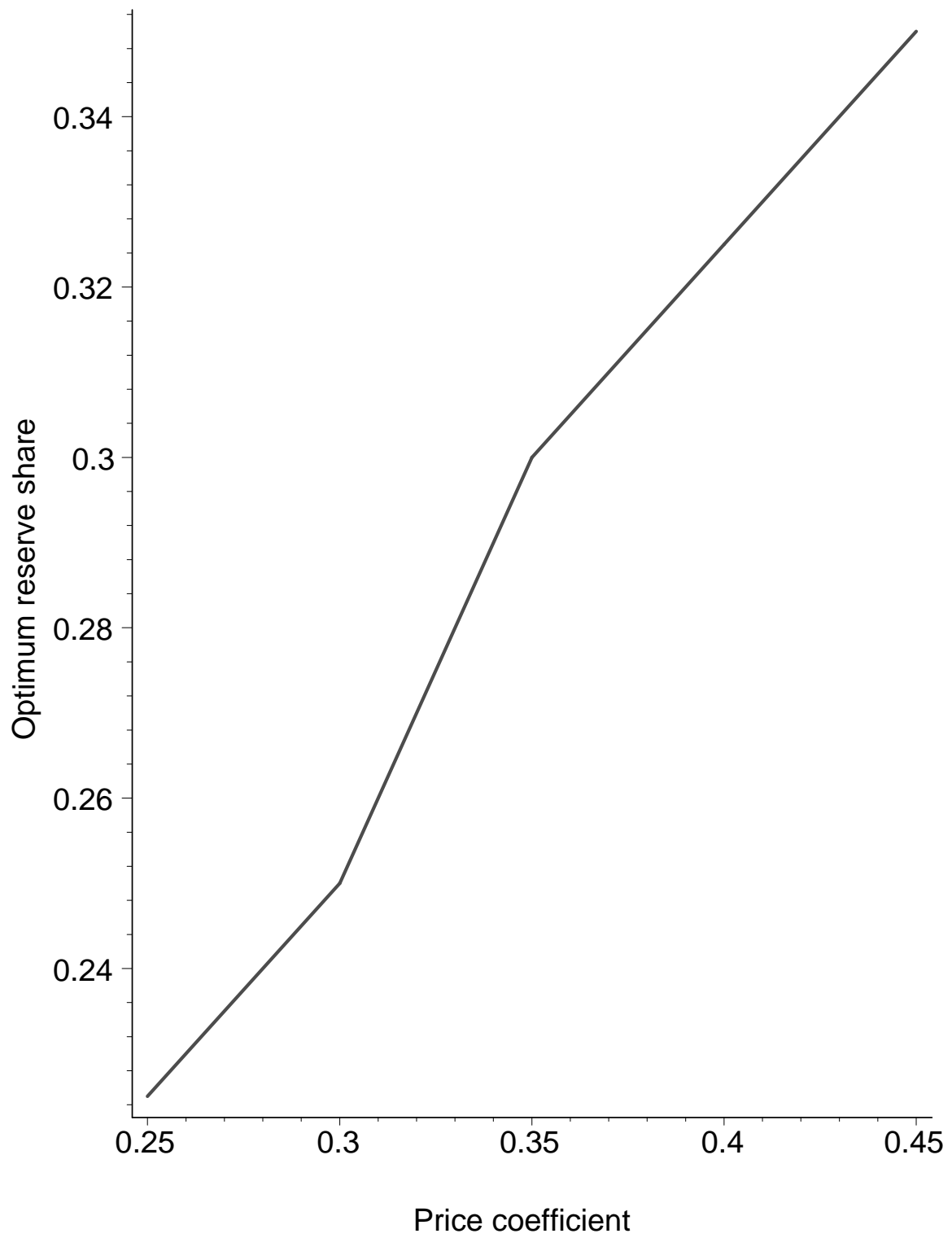


Figure 10: Relationship between demand parameter and reserve size