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# Virtual Population Units: A New Institutional Approach to Fisheries Management

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**Abstract** *This paper describes an alternative, rights-based approach to the economic problems of fisheries management and governance. The approach is based on the concept of a Virtual Population (VP), which provides an alternative way to define use rights in a fishery management system. Included is a comparison of harvest rates under the VP regime, "sole-owner," and open-access regimes. In comparison, a VP solution is more efficient than open access and can approach that of a sole owner. More importantly, in our opinion, the approach contains a higher degree of local control over issues such as concentration of ownership and, unlike some community-based systems, provides an explicit, decentralized incentive for conservation. It also contains a built-in incentive mechanism for end-of-year conservation that is absent from individual transferable quotas (ITQs).*

**Key words** Virtual populations, virtual population units, ITQs, marginal valuation.

JEL Classification Codes Q220, Q590, C720, D830.

## Introduction

Fishery economics plays a significant role in proposing management policies to improve the economic efficiency of a fishery and can finesse some of the distributional concerns of fishing communities, even if there may be some loss of economic efficiency relative to that of an unattainable ideal. This study compares fishers' harvest patterns under a Virtual Population (VP) regime with those under sole ownership and open-access regimes. These comparisons are made because they are conventional reference points. Specifically, the sole-ownership regime is considered the "Gold Standard" of fisheries economics, while the open-access regime illustrates the case for intervention. Both these reference points are, of course, unrealistic since most fisheries fall somewhere between the two. However, there are many intermediate possibilities, and the choice between imperfect possibilities involves much more

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than ordinal measures of efficiency. Fishers are often hostile to policies based solely on economic efficiency, and fishery managers find it difficult to reach a consensus among disparate groups of fishermen. Because of the governance implications, an alternative institution may be more acceptable to fishers. One such institution may be a VP and its "sole-owner," termed a Virtual Population Unit (VPU).[1] Such a system assigns exclusive use rights to groups of fishers and provides a strong feedback incentive for conservation investments.

## Sole Ownership and Virtual Populations

A paper by Gavaris (1996) provides a basis for imagining a continuum from sole ownership to community-based management via appropriately defined use rights. Using the term "partial populations" he imagined "Population Stewardship Rights" (PSR) for a fishery system. His paper did not develop the concept algebraically, so much of what follows is our interpretation and extrapolation of his basic ideas. The key concept is one of accounting via "partial populations." His choice of the phrase "partial populations" is descriptive of his implicit biological model (dynamic pool) in which each age class is a "partial population." Partial population is a less descriptive term when a surplus production model is used. Furthermore, his emphasis was on biological concepts rather than human behavior. A better phrase, in our opinion, is "Virtual Populations"(VPs), because it expresses the abstract accounting nature of the concept rather than focusing on the various age classes.

In this VP/VPU institutional structure, exclusive access to a portion of a population is delegated to the care of fishermen or groups. A VP is a shadow of a real population. Accounting procedures enable humans to create an artificial firm on paper to measure and monitor the flow of funds through real firms. Similarly, a VP is an accounting unit that can be scaled arbitrarily. A legal entity (individual, port, region, *etc.*) is given sole right to manage its own VP. A VPU is a sole owner of access rights to a VP. This matters because the VPU's incentive structure is based not on the behavior of everyone, but on its own behavior. The size of a VP is dependent on the VPU's initial allocation, subsequent catches, and contribution to growth of the resource.

The growth of real populations is diffused, via capture, over all fishermen in the real fishery. Under unregulated open access or a conventional quota management system, if one fisherman reduces his harvest, the increased stock at a later time period belongs not only to the contributing fisherman, but to all other fishermen including those who deplete their VPs. In this case, other fishermen can benefit from the increased stock size without paying any additional costs or deferred benefits. There is an incentive for other fishermen to free ride, and this dilutes individual and group incentives for conservation. However, for a particular VPU, growth emanating from its conservation decisions is allocated to its own VP.

In the course of rewriting this paper, we discovered a series of papers by Townsend (1992, 1995a,b,c). Viewed collectively, these papers assert some of what is discussed in this paper. However, the approach taken is different, the connections are not explicitly developed, and there are some technical issues associated with growth accounting that are not discussed in Townsend's work. Townsend also uses Gavaris' (1996) focus on partial populations and regulating harvest rates of each age class; a focus that leads the reader to suppose the approach is inextricably linked to

[1] This institution involving VPs and VPUs has no connection with the "virtual population" analysis used in fishery population dynamics.

regulating the exploitation rate by age class. We think the silence that has greeted the partial populations idea is undeserved and has to do, at the least partially, with its implications of being poorly understood. We hope that using the adjective "virtual," instead of "partial," will help understanding. Also, specialization and division of labor in the social sciences may have lessened the attractiveness of a conceptual bridge, which helps to connect the disparate viewpoints of efficiency versus community-based advocates in fisheries management. We will try to connect these threads in due course, beginning with an explanation of a VP and a VPU. We find the greatest difficulty among readers is an unnecessarily concrete interpretation of a "fish stock." We seek to break through this rigidity by deliberately defining an abstract "virtual" population. Obviously, dividing a real population is hard to imagine; not so a virtual one. To close the circle, we demonstrate numerically that calculations from virtual populations can conserve a real one. This demonstration is not intended as a proof that a VPU regime will necessarily work. It is, rather, a demonstration that it could work under conventional self-interest behavioral assumptions.

## Management with Virtual Population Units

The basic VP model starts with the assumptions of perfect information, no uncertainty, and no biological and production interdependency. These assumptions are also standard in the case of sole ownership of the entire resource.[2] While unrealistic, these assumptions simplify the exposition. We have also found that it is easier to begin from the simplest case because it is well understood. A sole owner has exclusive property rights for own stock. In the trivial case, the stock is physically separable into small stocks as in aquaculture. A sole owner's harvests cause no externality to any other producer. In this case, the distinction between the virtual and actual resource is not even necessary; it is natural to suppose they are the same. In a later section, a more complex case with biological and production interdependency will be presented. For simplicity and brevity, it is assumed that least cost input proportions within each VPU are always attained. This assumption is made because the problem of input stuffing is well known and we have nothing to add to it. However, we believe that under a VPU system, the focus on incentives, peer pressure, and the smaller size of a VPU make efficient input proportions more likely than in the absence of such a system.

## A Separable Fishery Model

The simplest model has stocks that are physically separable and abstracts from biological and production interdependency. Such a fishery is analogous to an idealized aquaculturist with complete property rights and exclusivity of other fishermen due to physical separation and territorial rights on farms.[3]

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[2] Since a fish stock is common pool resource, an individual fisherman's production affects other fishermen's production. The stock is not separable into sub stocks corresponding to groups of fishermen (VPUs).

[3] An idealized aquaculturist has certainty and full information of harvest amount since the owner plans the amount of harvest according to the own profit function. Since an idealized aquaculturist has tenure security, full information, no biological or harvest interdependency, and complete private property rights, each aquaculturist is a sole owner, and individual stock change is affected by an individual growth function and harvest rate. A colleague, whose opinion we respect, suggested this well-known case as an introduction to the more complex case.

In this simplest case, the resource population can be partitioned into independent components; *i.e.*:

$$X = \sum_i x_i, \tag{1}$$

such that:

$$\frac{dx_i}{dt} = g_i - h_i \tag{2}$$

$$H = \sum_i h_i, \tag{3}$$

where $h_i = ae_ix_i$ denotes individual harvest at time $t$, $x_i$ denotes the biomass of the fish stock at time $t$, $g_i$ denotes growth rate of $i^{\text{th}}$ stock,[4] $e_i$ denotes $i^{\text{th}}$ fishing effort, $a$ denotes catchability coefficient, and $X$ and $H$ are aggregate analogs of $x_i$ and $h_i$, respectively. For brevity, we omit the time subscript unless needed for clarity.

Each partitioned population unit has a sole owner (individuals or groups of cooperating individuals), and harvest behavior depends on own fishing effort and stock; *i.e.*, there is no biological or harvest interdependency. Then, each partitioned population unit is used according to the solution of maximizing profits for the sole owner as follows:

$$\text{Maximize } \int_0^\infty \pi_i(e_i, x_i, p)e^{-\delta t}dt \tag{4}$$

$$\text{s.t. } \frac{dx_i}{dt} = g_i - h_i$$

$$x_i, h_i \geq 0, \text{ all } i,$$

where $\pi_i$ denotes the profit function for the $i^{\text{th}}$ sole owner, $p$ denotes price of unit harvest, and $\delta$ = interest rate.

In this fishery, a sole owner approach to management would provide maximum resource rents, cost-effective harvest costs, and optimal resource conservation. There is neither a race-to-fish nor input stuffing, and there are no gear conflicts or market gluts.

## A Common Pool Fishery and Virtual Population

In this more complex case, the fish stock is a common pool resource, since fish are mobile and property rights for fish are not well defined. Stock growth rate depends on the total stock size, and the stock has a biological interdependency since it is not separable into sub-stocks corresponding to groups of fishermen.

Since the fish stock is not separable and has biological and production interde-

[4] A simple logistic growth function is assumed.

pendency, it is not feasible to separate the stock and assign sole ownership to it. There is joint production from the resource stock according to the production function:

$$h_i = ae_iX. \tag{5}$$

In addition, the stock exhibits mixing, so a physical partitioning of the real stock among resource users/harvesters is not feasible; there is no way to disaggregate X into individual $x_i$. However, by introducing the accounting concept of a VP, it is feasible to separate the mobile stock and assign it to any legal entity, such as fishing communities or an industry sector and to relax the assumptions in the preceding section in which no biological and production interdependency were assumed. To this end, a useful construct is a VPU whereby each "owner" (VPU) has a VP, $v_i$, defined as follows:

$$\sum_i v_i = V = X \tag{6}$$

$$\frac{dv_i}{dt} = s_i(0)G\big[V(0)\big] + \Delta^{t0}G\left(\frac{\Delta^{t0}v_i}{\Delta^{t0}V}\right) - h_i, \tag{7}$$

where $V = X$ which is required for accounting purposes, and $v_i$ denotes $i^{\text{th}}$ VPU's share of the aggregate VP at time $t$; $X$ denotes aggregate actual population at time $t$; $s_i(0) = i^{\text{th}}$ VPU's share of the initial aggregate virtual population;[5] $G[V(0)]$ = aggregate growth function evaluated at initial time 0; $\Delta^{t0}G = G[V(t)] - G[V(0)]$ = change in aggregate growth rate change, time $t$ versus initial time; $\Delta^{t0}v_i = v_i(t) - v_i(0)$ = change in $i^{\text{th}}$ VPU's virtual stock; time $t$ vs time 0; $\Delta^{t0}V = V(t) - V(0)$ = change in aggregate virtual stock; time $t$ vs time 0.

Note the use of $\Delta^{t0}$ to denote the use of a $t^{\text{th}}$ order difference; $\Delta^{t0}X$ denotes $X(t) - X(0)$. $\Delta^{30}X$ denotes $X(3) - X(0)$.

Under the assumption of perfect information and no stochastic events, the sum of individual VPs is equal to the aggregate VP and to aggregate actual population [equation (6)].[6]

Suppose each VPU maximizes own profits as follows:

$$\text{Maximize} \int_0^\infty \pi_i(e_i, v_i, p)e^{-\delta t}dt, \tag{8}$$

subject to: equation of motion (7); initial virtual stock $v_i(0) = v_{i0}$; consistency requirement of equation (6) and non-negativity, $v_i$, $g_i \geq 0$, all $i$ and $t$. The aggregate equation of motion for the real population is: $dX/dt = X = G(X) - H$, where aggregate real growth: $G(X) = G\ (V)$.

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[5] The coefficient $s$ is, in Townsend's (1995a) terminology, a "fractional share." We introduced these before reading his paper but the fractional shares approach also has behavioral advantages as discussed by Townsend. His assertions about the political economy of "fractional licensing" also seem applicable here.

[6] Stochastic events can pose problems for any management regime, including a VP regime. Finding ways to deal with uncertainty is not fundamentally different here than, for example, a sole owner regime. Periodic recalibration is necessary in both cases. To the extent that uncertainty raises the implicit discount rate, the optimal harvest rate is also affected. We return to this point in our concluding remarks.

Since there is a biological interdependency and the aggregate growth function is non-linear, an individual VP's growth function cannot be calculated simply by dividing the aggregate growth rate according to the initial ratio of stock assignment. The following section develops the growth equation for a representative VPU and its contribution to aggregate growth. This is a point where the verbal discussion by both Townsend (1992, 1995a,b,c) and Gavaris (1996) is uninformative. Suppose, for example, that $VPU_1$ conserves and allows its VP to recover, while $VPU_2$ depletes its virtual population. The change in the real population depends on the relative magnitudes of the actions taken by the two VPUs. Are both to be given the same growth rate? We think not. If incentives are to be effective, they must reflect the different choices made by the two VPUs. The growth accounting must reflect the actual conservation decisions of the participating VPUs. This is critical to a decentralization of incentives.

## Virtual Population Growth

Carrying capacity is the maximum biomass that the environment can attain and is denoted as K. The intrinsic growth rate for the stock is denoted as $r$. $V(0)$ is the initial aggregate virtual population, and $v_i$ is the $i^{\text{th}}$ VPU's share of which must also satisfy equation (6). Initial VPs can be decided in the same ways individual quotas (IQs) or individual transferable quotas (ITQs) are allocated by a rule, such as historical harvests. $G$ is the aggregate growth rate at time $t$, and $G$ increases as the aggregate virtual population, $V$, increases if $V$ is smaller than the half of the carrying capacity, K:

$$G(X) = G(V) = rV\left(1 - \frac{V}{K}\right). \tag{9}$$

VP growth is given by equation (7) which, on multiplying by $\Delta^{t0}V$, may also be written as (10):

$$g_i \Delta^{t0}V = s_i(0)G\big[V(0)\big]\Delta^{t0}V - \Delta^{t0}G\Delta^{t0}v_i \tag{10}$$

$$g_i = s_i(0)G\big[V(0)\big] - \Delta^{t0}G\left(\frac{\Delta^{t0}v_i}{\Delta^{t0}V}\right). \tag{10a}$$

Equations (10) and (10a) are equivalent, but (10) is preferred for numerical modeling in which one or more elements may approach zero during an iterative procedure.[7] Equation (10a) partitions the growth of a VP into its "initial growth endowment," $s_i(0)G[V(0)]$ , plus a growth increment or decrement, $\Delta^{t0}G$, that reflects own contribution to aggregate cumulative growth, weighted by its share of cumulative stock change, $(\Delta^{t0}v_i/\Delta^{t0}V)$ . After initial time, a VPU continues to receive the "initial endowment" of growth, $s_i(0)G[V(0)]$, plus a fraction of aggregate growth change, $\Delta^{t0}G = G[V(t)] - G[V(0)]$. The fraction received depends on the ratio of own cumulative conservation success to aggregate conservation success. This institu-

[7] We are not suggesting that zero growth is optimal; only that it is unwise to structure a numerical model in a form which invites explosive calculations. Numerical optimization methods involve iterative calculations in which a (near) singularity may arise.

tional rule may seem unnecessarily complicated, but, in fact, it leads to simple constraints on state variables in a mathematical programming representation.

Virtual populations vary over time according to the harvest decisions of the individual VPUs and the contributions of each to the aggregate change in growth rate at the current time, $t$, compared to the initial growth rate. An increase in own virtual population is reallocated only to the VPU that increases own VP. In the real world fishery, it is not feasible to distinguish individual contributions to the real stock increase. By using VPs, it is possible to reallocate the contribution only to the contributor. This coincidence of costs and benefits of conservation affects individual VP size and the incentives for rational behavior. $G$ is affected by $V$, so $G$ will reflect cumulative conservation and depletion decisions. Since the sum of individual growth rates is equal to the aggregate growth rate:

$$\sum_i s_i(0) = 1 = \sum_i \frac{\Delta^{t0} v_i}{\Delta^{t0} V}, \tag{11}$$

$\Delta^{t0} v_i$ is the difference between the individual initial VP at time $t$ and at time 0. $\Delta^{t0}\mathrm{V}$ is the difference between the aggregate VP at time $t$ and aggregate initial VP as indicated in equation (7). These cumulative definitions of $\Delta^{t0} v_i$ and $\Delta^{t0}\mathrm{V}$ enable allocation of cumulative growth or depletion to the VPs whose conservation investments produce the growth. The growth function is non-linear and cannot be easily scaled in a consistent way to preserve $\Sigma_i\, g_i = G$ since:

$$\sum_i v_i\left(1 - \frac{v_i}{K}\right) \neq V\left(1 - \frac{V}{K}\right). \tag{12}$$

The growth of the $i^{\text{th}}$ VP, denoted by $g_i$, is calculated using equation (10a).[8] Because of this, an individual VP adjusts according to equation (7) in which $\Delta^{t0}G(\Delta^{t0}v_i/\Delta^{t0}V)$ measures the cumulative contribution of the $i^{\text{th}}$ VPU to the aggregate cumulative growth change compared to the initial growth rate. The contribution of an individual VPU's harvest decisions to the growth rate increases or decreases own VP for the next period.

## Deterministic Simulation

This section illustrates how a VP/VPU system might work. To this end, suppose three VPUs make arbitrary, non-optimal harvest decisions during six periods. Calculations, below, illustrate the consequences for each VP of those harvest decisions. Later, we will introduce the findings from numerical optimizations using mathematical programming. Carrying capacity for this stock is K = 1,360,000MT and the intrinsic growth rate is $r = 0.8$. The initial aggregate growth rate, G(V), is 255,000MT at the aggregate initial virtual population of $V(0) = 510{,}000$MT.[9]

The arbitrary harvesting scenarios illustrate the calculations involved in accounting for the growth or decline of VPs by individual VPU harvests (figure 1).

[8] Neither Gavaris (1996) nor Townsend (1992, 1995a,b,c ) cover this point. In effect, a VPU receives two initial allocations; a *stock* allocation and a *growth* allocation: (a) $s_0(0)G[V(0)]$ and (b) $s_0(0)X(0)$.

[9] $G[V(0)] = 0.8*510*(1\text{-}510/1360) = 255$. The parameter values shown are from the Northwest Atlantic herring fishery. This is a fact not especially germane to the paper, but one the reader should be aware of.

$VPU_1$ follows the initial harvest level (85,000MT) during all time periods. $VPU_2$ harvests more than the initial harvest level, and $VPU_3$ harvests less than initial harvest level.[10] $VPU_1$'s virtual population does not change over time since the arbitrary constant harvest was chosen to do this. $VPU_2$'s virtual population decreases its overexploiting behavior. Even though the aggregate VP after time period 3 is smaller than the aggregate initial VP in the right figure, $VPU_3$'s virtual population is greater than its initial VP because of its conservation behavior (figure 1, right panel).

## Stochastic Considerations

Successful implementation of VPs in real-world fisheries depends on the accuracy of VPs for the real population. VPs are a representation of a real population in the same way that accounting represents the financial flows of real firms. If there is a huge discrepancy between the VP and real population, VPs do not represent real populations any longer, requiring periodic recalibration of VPs.

There are stochastic factors in most fisheries, as in most industries. There also can be misreporting and underreporting of actual harvests. Both stochastic events and inaccurate reporting of catches can cause errors in population calculations. When there is a significant difference between the VP and the real population, $v_i$ can be adjusted to the real population according to the ratio of the individual virtual population for the time period. Total real population, $X$, can be used for the individual virtual population, $v_i$, according to the ratio of individual virtual population, $v_i$, to the aggregate virtual population, $V$. $s_i$ measures this ratio:

$$s_i = \frac{v_i}{V}. \tag{13}$$

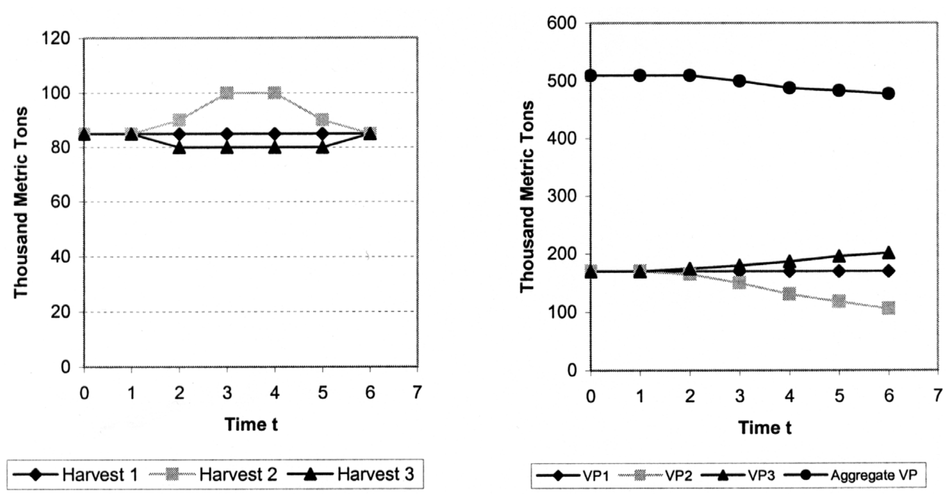


**Figure 1.** Harvests (left) and Changes in VPs (right)

[10] The sum of initial harvest levels is set to be equal to the initial aggregate growth rate for the steady-state condition.

Equation (13) could be used for bridging the possible discrepancy between the VPs and real population using the ratio of individual VPs from the aggregate VP. Adjusted individual VP at time $t$ is $v_i = s_i X$. This adjustment is equivalent to restarting the process with new initial conditions at time $t$.[11] This is a neutral adjustment in the sense that while each VPU is accountable for the depletion or conservation that it causes, the penalty or reward assigned to VPUs is proportional to their depletion or conservation. The need for recalibration is assumed to arise from exogenous events rather than from more sinister inferences. Note that this presumes an effective enforcement and compliance regime for harvests. More elaborate recalibration rules can be devised, but may be extremely controversial.

## Fisheries and the Shadow Value of Resources

Without rights-based management, fishers are not assured a predictable share of the total allowable catch (TAC) and are inclined to harvest competitively. This causes problems such as appropriation externalities and technological externalities.[12] Individual fishers' harvests subtract from the residual fish available to others. This subtraction lowers the marginal product of additional fishing effort and increases the marginal costs of harvesting additional fish. Thus, the increased cost of harvesting due to reducing the available fish stock affects not only the fishers who harvested the fish, but also all fishers who fish that stock.

Sole access to a VP is reserved for fishers in the associated VPU. However, an externality still exists. Even though each VPU has its own VP, catch per unit effort (CPUE) still depends on the aggregate stock size. Although rights are incomplete, individual VPUs have a high degree of control over own VP, and each VPU's contribution to the aggregate growth rate is evaluated and credited (or debited) where it is due. As mentioned before, this sharply penalizes a VPU if the it depletes its own VP below the initial stock size. Furthermore, an individual VPU's marginal valuation of resources is greater than that of an individual fisher under an open-access fishery. With a greater marginal valuation of the stock, individual VPUs are expected to harvest more slowly than individual fishers in an unregulated fishery (see below). How important this residual problem is can be determined on a case-by-case basis using numerical methods.

Arnason (1990) compared the resource shadow value between optimal and unregulated fisheries. This section discusses the resource shadow value under three management regimes: sole owner, VP, and an unregulated fishery. The sole owner's problem and that of the unregulated individual fisher follow Arnason's proof in "Minimum information management in fisheries."

Suppose $N$ fishers exploit a single stock of fish, $X$, and have identical log-linear production functions with unitary partial elasticities:

$$h_i = q(e_i, X) = ae_iX; \quad i = 1, 2, \ldots, N.$$

[11] The problem of recalibration increases uncertainty, but is common to most fishery management regimes, including a sole owner regime. We presume that safe minimum standards on VPs would be included as a fail safe measure.

[12] Appropriation externalities arise because fishers subtract fish from a common stock without taking into account the effects of their harvest upon each other. Technological externalities (crowding phenomena) arise when fishers physically interfere with each other in harvesting, such as gear conflicts (Ostrom, Gardner, and Walker 1994).

To simplify the notation, redundant functional subscripts are suppressed below. We continue to denote total real stock as $X$, and individual virtual stock (VP) is denoted as $v_i$. Total growth rate is denoted as $G$, and growth share for individual VPU is indicated in equation (7). The cost functions are:

$c(e_i)$ $i = 1,2,$ $,N$; where $c(.)$ is increasing and strictly convex in effort, $e_i$.

As before, $p$ and $\delta$ represent the market price of catch and the discount rate, respectively.

## Optimal Fishing Problem

The stylized problem for the fishery manager or social planner is to maximize the present value of the profits of all fishers in the fishery with respect to fishing effort. An individual fisher is required to take account of their own direct costs and the cost imposed upon other users of the resource stock:

$$\text{Maximize} \int_0^\infty N\pi(e_i, X, p)e^{-\delta t}dt \tag{14}$$

$$\text{s.t. } \dot{X} = G(X) - Nq(e_i, X)$$

$$X,\ e_i \geq 0$$

$$\text{initial condition, } X(0) = X_0$$

$$E = Ne_i = \text{aggregate effort; } N = \text{number of firms.}$$

The current value Hamiltonian for the problem is:

$$H = N\big[pq(e_i, X) - c(e_i)\big] + \mu\big[G(X) - Nq(e_i, X)\big]. \tag{15}$$

For each of the identical fishers, the first-order conditions involve choosing the level of effort, $E(=Ne_i)$, for all fishers so that an optimal condition is $H_E = 0$:

$$pq_E - c_E - \mu q_E = 0 \quad \text{or} \quad (p - \mu)q_E = c_E, \tag{16}$$

where $\mu$ represents the current shadow price of an additional unit of stock along the optimal time path. Along this path, the net marginal benefit of effort is the marginal benefit of selling fish at the market price less the imputed shadow price of stock. This net marginal benefit equals the marginal cost of effort.

The co-state condition for the movement of the shadow value along the optimal path is $\dot{\mu} - \delta\mu = -H_X$:

$$\dot{\mu} - \delta\mu = -Npq_X - \mu\big[G'(X) - Nq_X\big]. \tag{17}$$

The equilibrium solution of these equations is found by setting the growth rate equal to the total harvest, $G(X) = Nq(e_i, X)$. In the equilibrium $\dot{\mu} = 0$. The shadow value of stock in equilibrium is from the equation (17):

$$\mu = \frac{pq_X N}{\delta + q_X N - G'(X)}. \tag{18}$$

The shadow value of stock depends on the harvest function, stock growth function, market price of catch, and the discount rate.

## Unregulated Individual Fisher's Problem

The problem faced by the individual fisher who shares the fishery is different to the extent that each is concerned only with private costs and benefits. An individual fisher takes account of own direct costs, but not the cost imposed on other users of the resource. Since an individual fisher does not benefit from taking account of the costs imposed on other users, no value is placed on conserving the resource. Each fisher attempts to maximize own profits given the fishing effort by other fishers. Arnason (1990) assumes that the fishers behave as if each forms predictions or expectations concerning the fishing effort of other firms. On these assumptions the individual fisher attempts to maximize the following:[13]

$$\text{Maximize} \int_0^\infty \pi(e_i, X, p)e^{-\delta t}dt \tag{19}$$

$$\text{s.t.} \quad \dot{X} = G(X) - Nq(e_i, X)$$

$$X, e_i \geq 0$$

initial condition $X(0) = X_0$
E = $Ne_i$ aggregate effort; $N$ = number of firms.

The stock constraint includes the fishing effort of all fishers. The current value Hamiltonian for the problem is:

$$H = pq(e_i, X) - c(e_i) + \sigma[G(X) - Nq(e_i, X)], \tag{20}$$

where $\sigma$ is the marginal valuation of the stock to the individual fisher.

The first-order conditions $(H_{e_i} = 0)$ are:

$$pq_{e_i} - c_{e_i} - \sigma q_{e_i} = 0 \quad \text{or} \quad (p - \sigma)q_{e_i} = c_{e_i}, \tag{21}$$

which is identical to the first-order conditions in optimal fishing problem with $\sigma$ substituted in the place of $\mu$. Equation (21) also states that the net marginal benefit should be equal to its marginal effort costs.

The co-state condition is $\dot{\sigma} - \delta\sigma = -H_X$:

$$\dot{\sigma} - \delta\sigma = -pq_X - \sigma\left[G'(X) - Nq_X\right]. \tag{22}$$

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[13] Levhari and Mirman (1980) provided an example using a dynamic Cournot-Nash solution and compared the harvest pattern between cooperative and non-cooperative management.

In equilibrium, $\dot{\sigma} = 0$ and equilibrium marginal stock valuation is:

$$\sigma = \frac{pq_X}{\delta + q_X N - G'(X)}. \tag{23}$$

## Individual VPU Problem

Individual VPUs have exclusive right to exploit their own VP. Even though there is a possibility that CPUE may decrease or increase according to the harvest behavior of other VPUs, individual VPs are mainly controlled by the associated VPU. There is a sole access right to own a VP and each VPU can defer own harvest, if it chooses to do so, and receive credit for growth of own VP. Individual VPUs take account of own direct costs. This section presents the comparative statics of alternative institutional regimes. We do this by examining the steady-state equilibria of each regime and noting how they differ. Each VPU attempts to maximize its own profits given the fishing effort by other VPUs.

The $i^{\text{th}}$ VPU attempts a conditional maximization of the present value of profits:

$$\text{Maximize} \int_0^\infty \pi_i(e_i, X, p)e^{-\delta t}dt \tag{24}$$

$$s.t. \;\; x_i = g_i(X) \; \square \; q(e_i, X)$$

$$x_i, e_i \geq 0$$

$$\text{initial condition } x_i(0) = x_{io}$$

$$E = Ne_i = \text{aggregate effort; } N = \text{number of firms,}$$

where $x_i = i^{\text{th}}$ VPU

$$g_i = s_i(0)G[V(0)] + \Delta^{t0}G\left(\frac{\Delta^{t0}v_i}{\Delta^{t0}V}\right).$$

The harvest behaviors of other VPUs are partially incorporated into the harvest function and stock constraint.[14]

The current value Hamiltonian for the problem is:

$$H = pq(e_i, X) - c(e_i) + \lambda[g_i(X) - q(e_i, X)]. \tag{25}$$

The first-order conditions for each identical VPU are to choose the level of effort, $e_i$, so that $H_{e_i} = 0$:

$$pq_{e_i} - c_{e_i} - \lambda q_{e_i} = 0 \quad \text{or} \quad (p - \lambda)q_{e_i} = c_{e_i}, \tag{26}$$

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[14] The harvest function is $ae_iX$, not $ae_ix_i$, so each CPUE still depends on the total stock size. The growth function also still contains total stock change $\Delta^{t0}X$.

where $\lambda$ is the current shadow price of an additional unit of stock along the optimal time path. The optimality conditions for the three regimes are expressed by equations (16), (21), and (26), respectively. All three are equivalent, so the net marginal benefit is equal to its marginal costs of effort. For a simpler notation, $g(X)$ will be used below for the growth function of each VPU, $g_i(X)$.

The virtual stock transition equation uses the change in individual VPs. However, the own growth function of a VP is still dependent on the aggregate population change, and CPUE depends on the aggregate population.

The co-state condition for this problem is $\dot{\lambda} - \delta\lambda = -H_X$:

$$\dot{\lambda} - \delta\lambda = -pq_X - \lambda[g'(X) - q_X]. \tag{27}$$

In equilibrium, $\dot{\lambda} = 0$ and the equilibrium marginal stock valuation is:

$$\lambda = \frac{pq_X}{\delta + q_X - g'(X)}. \tag{28}$$

## Ordinal Comparison of Marginal Valuations

The marginal stock valuations by fishers under different regimes are $\mu$ = social optimum, $\lambda$ = VPU, and $\sigma$ = open access imputed marginal value of stock:

$$\mu = \frac{pq_X N}{\delta + q_X N - G'(X)} \geq \lambda = \frac{pq_X}{\delta + q_X - g'(X)} \geq \sigma = \frac{pq_X}{\delta + q_X N - G'(X)}. \tag{29}$$

By multiplying $N$ in the numerator and denominator of $\lambda$, the following inequality is inferred:

$$\mu \geq \lambda = \frac{pq_X N}{\delta N + q_X N - g'(X)N}. \tag{30}$$

The denominators are $\delta + q_X N - G'(X) \leq \delta N + q_X N - g'(X)N$ since $\delta \leq \delta N$ for $N > 1$, on the condition that $N$ fishers are identical and have identical VPUs.[15] For a typical homogeneous VPU, the growth function is as follows:

$$g(X) = g_i(X) = (1/N)G[X(0)] + \Delta^{t0}G(1/N) = G_t/N. \tag{31}$$

Therefore, $g'(X)N = G'(X)$.

Comparing $\lambda$ and $\sigma$, denominators are $\delta + q_X - g'(X) \leq \delta + q_X N - G'(X)$, respectively. After canceling out the discount rate, we find:

$$q_X - g'(X) \leq q_X N - G'(X). \tag{32}$$

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[15] In numerical modeling we do not require identical VPUs. This flexibility is useful for a management agency. However, it is extremely difficult to extract general conclusions under heterogeneity because equilibrium also depends on ancillary assumptions about transferability of assets or harvesting technology and unsegmented markets. We will return later to this point.

In steady-state equilibrium, harvest is equal to growth rate:

$$Nq(e, X) = NaeX = rX(1 - X/K) = rX - rX^2/K\ .$$

After canceling out the stock, the remainder is $Nae = r - rX/K$. Since $G'(X) = r - 2rX/K = Nae - rX/K$ and $Nae = q_X N > G'(X)$; therefore, $q_X - g'(X) \leq q_X N - G'(X)$ and $\lambda \geq \sigma$.

From equation (29), the marginal valuation of stock is only equal to the socially optimal valuation when the number of the decision-maker (whether a VPU or fishermen), $N = 1$, that is $\mu = \lambda = \sigma$. Otherwise $\mu > \lambda > \sigma$ for given $X$ and $e$. Therefore, the social shadow value of biomass is at least as great as individual VPU's shadow value, and the individual VPU's shadow is also at least as great as the private shadow price in an unregulated fishery. The equilibrium for the decision-maker may be characterized as a Nash-Cournot equilibrium, where each decision-maker correctly predicts the catch of the other fishers and then chooses own optimal harvest level accordingly.

From the results above, the marginal valuation ($\lambda$) of stock under a VP regime is greater than under open access. Fishers under a VP regime value fish stock more than fishers in an unregulated fishery. The comparison of the marginal valuation shows fishers under a VP regime harvest more conservatively than fishers in an unregulated fishery since individual VPUs have control over their own VP, but not as completely as a sole owner in an aquaculture case. The results show also that a VP regime would be less conservative than the social optimum. How much less is a quantitative question, which cannot be answered with an ordinal analysis such as that just given.

As shown in the optimal fishing problem, if individual fishers take account of the resource user cost, depletion is not a problem and the solution is independent of the number of fishers who have access to the fishery. However, as the history of world fisheries has shown, individual fishers do not take account of user cost; as the number of fishers increases, the equilibrium stock declines asymptotically towards the open-access equilibrium, and the shadow price of the resource to the fishers declines to zero (Hanely, Shogren, and White 1997). Since individual fishers cannot know the magnitude of impact they impose on stock growth (nor would they take account of it if they did), they are unlikely to revise their behavior. The VP/VPU institutional structure provides a framework of accountability, which decentralizes incentives to the level of individual VPUs.

## Numerical Simulations using Mathematical Programming

In an earlier section, arbitrary harvesting scenarios illustrated how a VP/VPU institutional structure passes the consequences of conservation/depletion decisions back to the responsible VPU. This section reports the results of some numerical simulations. To do this, the VPU's problem was formulated as an iterative mathematical programming problem.[16] In this simulation, we did not allow inter-VPU differences in technical efficiency. Should such differences exist, sales of assets or transfer of labor and technology may erase the differences over time. However, a collective agreement among VPU members would presumably be required for asset transfers. There is a tradeoff here between efficiency and regional benefit distribution. In this

[16] We used the General Algebraic Modeling System (GAMS) with the Conopt2 solver.

respect, a VP/VPU system resembles the sectoral allocation systems currently being proposed in New England (*Federal Register* 2004).

In iteration 0, each VPU is assumed to hold expectations (randomly chosen by us) about the harvests of other VPUs. Each VPU then makes conditionally optimal harvesting decisions for 10 years. The decisions are conditional on the expectations of behavior of other VPUs. At the end of iteration 0, the conditionally optimal decisions are aggregated and used to revise expectations. Iteration 1 then begins, *etc.* After 5–30 iterations, the conditionally optimal decisions matched in the sense that the sum of squared deviations between expected and conditionally optimal harvest rates were less than a tolerance factor, so that an approximate Nash-Cournot equilibrium had been attained (figure 2).

At this equilibrium, individual VPU harvest rates were the same (as would be expected for identical VPUs), and aggregate harvest trajectories differed only trivially from a sole owner solution. This is an indication that the proposed institution could work quite well. It is not a proof that it necessarily will. Because it is trivially easy to impose Safe Minimum Standards (SMS) in a mathematical programming model, lower bounds on stocks and upper bounds on harvest were included. These proved to be ineffective constraints with zero shadow prices. It is, of course, possible that they maintained the iterative process within the SMS limits during the convergence to equilibrium, just as it is common practice for upper or lower bound primal variables to more narrowly define the policy-relevant search space. In addition, the existence of such SMS on VPs may, if enforced, reassure all participants that the regime will work and that expectations can become self fulfilling. Also, the random initial expectations of each VPU for the harvests by other VPUs were constrained to not violate the SMS of the other VPUs. To reiterate, an effective enforcement and compliance regime is critical. Lacking such SMS, expectations could be more volatile.

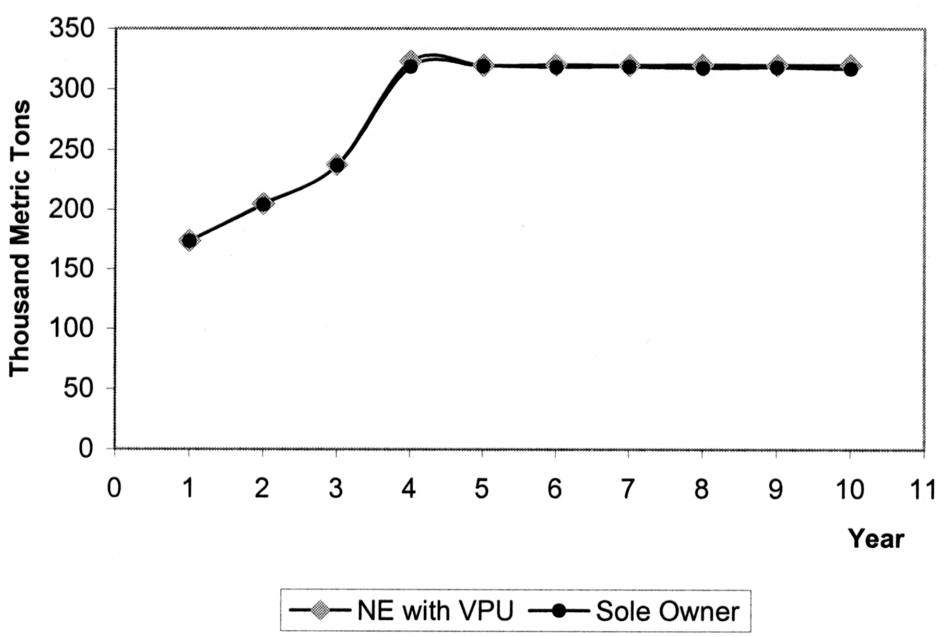


**Figure 2.** Harvest Rates

## Optimal Biomass and Fishing Mortality

Figure 3 shows the trajectories of optimal biomass for the sole-owner and VPU institutions. It will be seen that the two differ trivially. The initial biomass was deliberately chosen at a relatively low level to see if the VPUs would invest in rebuilding their respective VPs.

Figure 4 shows the optimal aggregate fishing mortality trajectory for the sole-owner and VPU regimes. Under both regimes, it is held at low levels initially while stock rebuilds, then rises rapidly toward the steady state level.

## Concluding Remarks and Discussion

The possibility of fishery management using VPUs has been examined and fishers' behavioral pattern toward the resource compared under a limited set of alternative regimes. A comparison of marginal resource valuations illustrated how VPUs would be expected to exploit more conservatively than individual fishers in an unregulated fishery. It is sometimes said that if fishers are to address management effectively, they must first recognize that their actions negatively affect each other. In our experience, this is an elliptical statement; most fishermen already recognize very well their effects on each other, but there is insufficient incentive to behave differently.

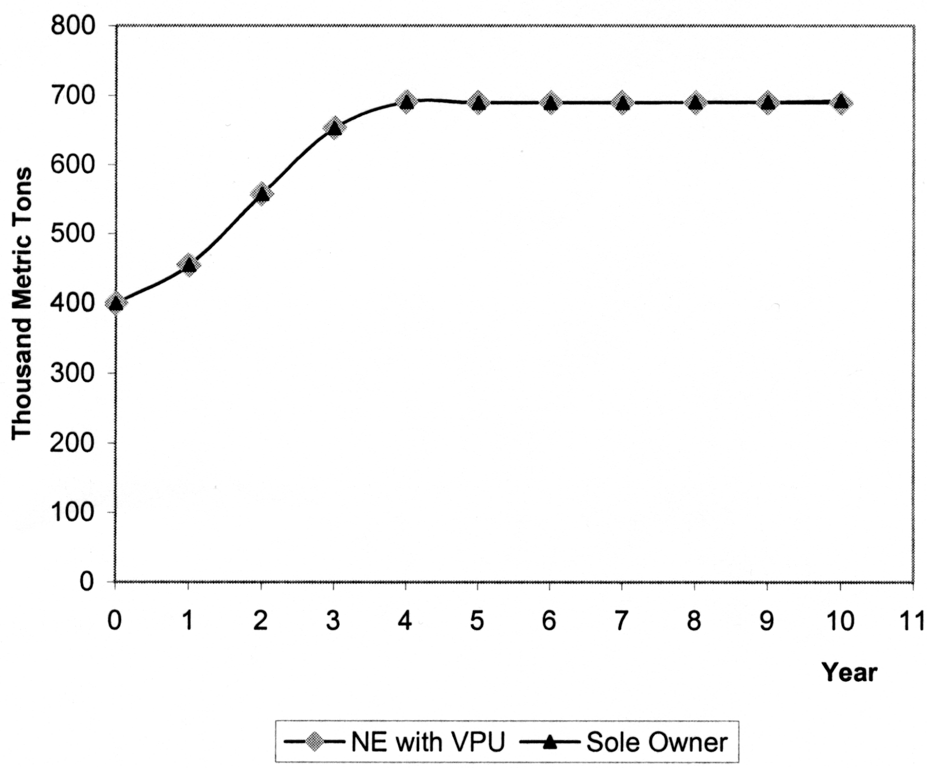


**Figure 3.** Optimal Biomass

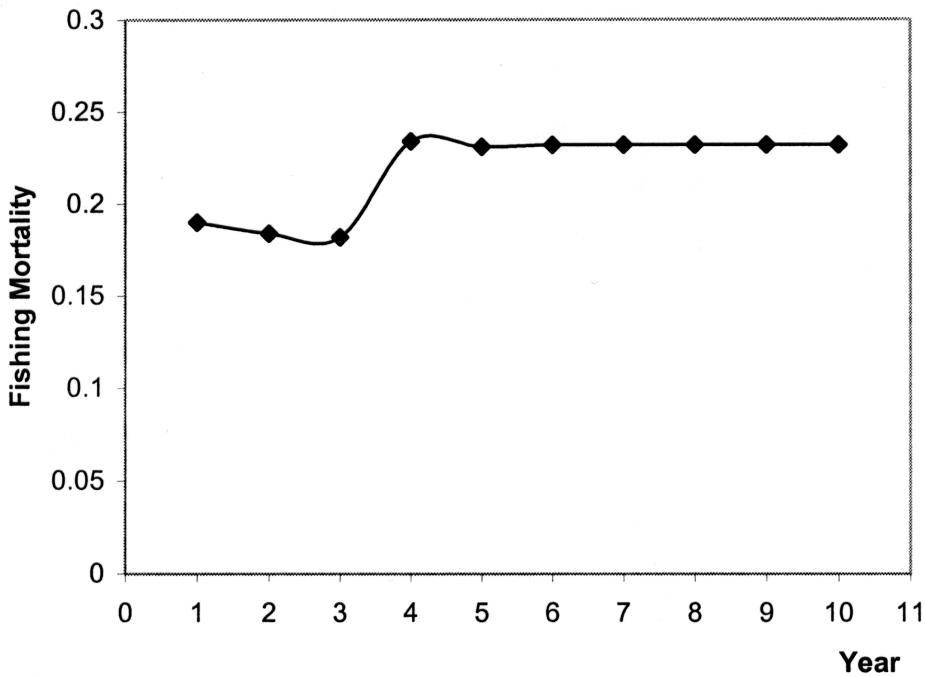


**Figure 4.** Optimal (Aggregate) Fishing Mortality

We perceive a need for an institutional structure that contains adequate, decentralized incentives for conservation investments. Such incentives may well emerge in a VP regime as VPUs recognize how their own VP changes according to own and other fishers' actions. If VPs are entrusted to communities, it might be easier for them to interact with each other at a local level leading voluntary collective solutions with their own voluntary enforcement within and among communities.

Another positive aspect of this approach (which Townsend (1992, 1995a,b,c) also recognized), is that the VP/VPU approach finesses the "year-end" problem under ITQs. The holder of an ITQ is in a position similar to a research grant manager or a department chair as the year-end approaches. Economic efficiency would suggest a carry-over mechanism. Typically, however, year-end funds (or ITQs) are "lost" when the new accounting period begins. Obviously, a VP/VPU system is not the only way to address the problem; we observe merely that it does so automatically. Unfortunately, a VP regime may not be a panacea; there still exists an externality in a VP system. Even though a VPU has its own VP, CPUE still depends on the total stock size. This issue is of particular concern if, as seems likely, there will often be a residual or "exogenous" sector outside the VPU regime. As the relative size of this exogenous share increases, it seems likely that the incentive for more conservative behavior may be diminished. This could be especially true if the "exogenous" sector is not subject to rigorously enforced restrictions on total catch.

A sector allocation regime has some similarity to a VPU regime in that a sector has a TAC. However, a sector cannot increase its future TAC by harvesting less than its current TAC. A VPU can do so and, therefore, has an incentive to conserve. Neither (at present) can a sector decentralize further by creating internal ITQs. The VP/

VPU approach can be viewed as an alternative pathway to decentralization. If a VPU chooses to devolve rights internally, several scenarios are obvious. If the basis for devolution is historical catch shares, the result is IQs or possibly ITQs with full or restricted transferability allowed by rules chosen by each VPU. If the basis is effort, the result is individual days at sea or individual transferable days at sea, if transferability is allowed. The most likely forms of transferability are internal (within the VPU) and short-term leases, rather than outright rule. If a geographic basis is used, the result is area-based management, or territorial use rights in fisheries. If further devolution is not done, the result is similar to community development quotas but without explicit quotas or to "Sectoral Allocations" but with stronger incentives for conservation. Thus, a VPU and its associated VP are quite compatible with the ideas expressed by Townsend (1995b) in his paper on self-governance. The VP/VPU concept devolves the fine details of allocation to local levels and can allow a variety of institutional alternatives as special cases.[17] Notice, however, that any legal entity can form a VPU; unanimity of approach among all VPUs is not necessary. Progress can be made incrementally. If rights are not transferable between VPUs, it is possible that full economic efficiency will not be attained. However, to the extent that effort and technology transfers tend to erase differences in technical efficiency, this potential source of economic inefficiency may be attenuated.[18] Another source of heterogeneity is associated with segmented markets. In the Northwest Atlantic herring fishery, there are inshore-offshore, gear, and market differences which are linked. A VPU that is organized around purse seine vessels would probably focus on the domestic bait market. A VPU organized around mid-water trawl gear with onboard refrigerated seawater systems would be higher cost but would produce a higher quality product for higher-valued export markets. To further illustrate heterogeneity, the export market is much more volatile and depends on cycles in the Northeast Atlantic-Arctic Ocean herring stocks. Under such conditions, it may well be rational and socially optimal to deplete stocks somewhat during periods of high export demands. At present, such heterogeneities fuel economic warfare among the user groups rather than voluntary exchanges under a rights-based system (Cho and Gates 2002).

We believe that the devolution/decentralization of rule-making authority is very important for fisheries. The experience with regional (but still highly centralized rule-making) is often one of stalemate. Decisions require near unanimity among heterogeneous groups. Little is resolved until everything is resolved, which is to say, rarely. A devolution of management such as that enabled via a VP/VPU system does not imply an abdication of public responsibility for fishery management. The relationship between a management authority (MA) and VPUs can be contractual; each VPU enters into a contract with the MA to manage its VP. This raises a myriad of practical, legal, and administrative questions, which remain to be addressed. Some of these can draw on general principles for contracts. Others will be peculiar to fisheries. Obvious candidates for inclusion are: SMS on each VPU (Ciriacy-Wantrup 1952); provision for adjusting VPs in response to exogenously induced stock fluctuations; closure authority if a VP violates its SMS; and authority of a VPU to discipline its members for violation of own or MA rules.

While a VP/VPU institutional approach offers the possibility of greater decentralization of decision-making and offers incentives for investing in conservation,

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[17] Although we have focused on output controls, it is also possible to use the VPU approach in conjunction with input controls. This may be more attractive in a multispecies fishery.

[18] In an echo of the Stolper-Samuelson trade theorem, inefficient VPUs might sell their VP or import more efficient men and machines. If they are institutionally able to do so but elect not to, the tradeoff between pecuniary and non-pecuniary motivations is made at a local level, which accords well with American governance concepts and the subsidiary principle of the European Union.

the variability of fisheries makes it uncertain that VPUs would, in fact, be as conservative as we have suggested.[19] The same can be said of a sole owner solution in an uncertain world. In both cases, SMS may be desirable supplements. If monitoring and enforcement of harvests are inadequate, resource trajectories would become unnaturally uncertain. For potential incentives to be operative, adequate monitoring and enforcement of catches would be imperative. The same must be said of other input- and output-based control systems. In principle, the VP/VPU approach could be used with an input-based control system, but the usual difficulties would apply. It is likely that catchability coefficients would differ between VPUs so that good data on catches would still be needed to calibrate the growth of VPs.

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[19] We are indebted to James Anderson for drawing this to our attention.