Virtual Populations: A new Arrow in the Quiver of Rights-Based Fishing?

Jungsam Lee, John M. Gates[1]

Environmental and Natural Resource Economics, University of Rhode Island,Kingston, RI 02881, USA,
jlee8793@mail.uri.edu, jgates@mail.uri.edu

ABSTRACT

Quota management systems (QMS) provide faith-based incentives for individual quota holders to conserve the resource voluntarily; quota holders expect the system to work and to be enforced and their expectations are usually realized despite imperfect incentives and significant enforcement burdens. Even with QMS there is never an individual incentive to invest in conservation by harvesting less than the quota. Fish are mobile in varying degrees and fishers do not have their own growth function as does the hypothetical sole owner made famous by Gordon's paper (Gordon, 1954). To provide incentives for voluntary conservation, "Virtual Population Units" (VPUs) can be used. An economic agent (individual, port, region etc) is given exclusive right to manage its own virtual population. However, the suggested harvest levels (quotas under a QMS) next year will be based not on behavior of others, but on how that VPU managed the virtual population to which it has exclusive access rights.

In this paper we apply a VPU regime to the Atlantic herring fishery in New England to illustrate numerically how multiple VPUs as economic agents might rationally allocate their efforts to optimize the present value of own profits and to measure the discrepancies from a sole owner solution.

Keywords: Rights-based fishing; decentralized management, Virtual Population

INTRODUCTION

There is a phenomenon called a "Derby fishery" in fisheries under TAC management regimes. Since there is no share guarantee (or limit), fishermen invest in technically more efficient gears and vessels. This input stuffing increases the cost of fishing and contributes to market gluts. Often there are more gear losses and conflicts. Fishermen fish under less safe conditions and go to sea in bad weather conditions to catch more before the TAC is exhausted. The quality of fish decreases and the open seasons become shorter. A race-to-fish often results in increased bycatch and habitat degradation (NMFS, 2004). Unwanted or undersized fish are discarded with higher probability of death when fishermen compete in a derby fishery. The race-to-fish and resulting market gluts require more processing and storage facilities. After the TAC is exhausted, fishing vessels are idle.

This paper describes a new institutional approach to resolving the problems of TAC fisheries. It is called the Virtual Population method. To illustrate it, a case study of the Atlantic Herring fishery of the United States is used. Reduced competition can decrease the incentive for input stuffing and lead to increased product quality and to higher prices for the fish. It can also lead to fewer gear conflicts and safer working conditions. If a VPU expects market gluts this year, it can postpone its harvest since the deferred harvest carries over to the next year which also increases own resource growth. Reduced competition leads to less processing and storage capacity. Reduced competition can also decrease incidental catch and habitat degradation and this would affect the increase in stock abundance also.

The case study presumes that the VPUs seek to optimize own present value of profits conditional on anticipated catches of others. For the numerical simulation with considerations of relevant constraints a Mathematical Programming (MP) is used. MP is at its best in constructing

"What if…" scenarios involving non-trivial structural changes. A social planner or sole owner's optimization problems can be analyzed with a much simplified version of the MP model. A sole owner problem is a special case in which there is only one VPU. Such an owner has clearly defined exclusive use rights and no uncertainties caused by harvests of others. However, with multiple VPUs a VPU has expectations for the behavior of fishermen outside his virtual population unit. Using an MP model within the Atlantic herring fishery we test with multiple VPUs. Conceptually, the result is a Nash Equilibrium (NE), but the results appear better than the standard NE and only slightly inferior to the sole owner solution.

SOLE OWNERSHIP AND VIRTUAL POPULATION

Exclusive access to a portion of a population is delegated to the care of fishermen or groups. A "Virtual Population (VP)" is shadow of real population. As with abstract accounting humans learned to create an artificial firm on paper to measure and monitor the flow of funds through the real firm, a VP is an accounting unit which can be scaled arbitrarily. A VPU (individual, port, region etc) is delegated sole right to manage its own VP. The VPUs' incentive structure is based not on the behavior of everyone and but on 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 over all fishermen in the real fishery under unregulated open access or a conventional quota management system. If one fisherman reduces his harvest, then the increased stock at later time periods does not belong only to the contributing fisherman; it is shared with all other fishermen including fishermen who deplete their VPs. In this case other fishermen can benefit from the increased stock size without paying any additional costs. There is an incentive for other fishermen to free ride and this dilutes individual fishermen's conservation incentive. However, for a particular VPU, growth due to its conservation decisions is allocated to its own VP. A virtual population provides better defined use rights than traditional fishery management systems. VPs are similar to flexible Individual Quotas on a portion of a stock and a virtual population with transferability has at least as good features for management as do ITQs. A VPU may allow limited transferability; a portion of a VPU may be traded and reassigned in a similar way to other property or more likely transfers may be restricted to internal transfers under transfer rules and procedures decided by the VPU membership.

Virtual populations may have even better potential than ITQs for management because:

- End of period carryovers are handled easily because each VPU decides how to handle it. There is no necessary quota per se but harvesting too much this year means a smaller VP next year; less this year means more next.
- In connection with the expected influence of substitutes and complements to target fish, VPUs can make their own harvest decisions in order to get the best price for their harvests.
- As with Community Development Quotas, distributional issues may be lessened by moving away from individual allocations.
- Supplementary management measures can better reflect regional or individual knowledge of fishers.
- Progress does not require a uniform set of management measures.
- Issues of spatial and temporal distribution of real stocks may be diminished.
- Punitive measures, such as temporary shut-downs for violation of safe minimum standards are focused on the VPU which commits the violation.

Since there is no carry over under management with ITQs, fishermen have an incentive to sell or lease when the quota is greater than their fishing capacity or when fishermen have personal reasons not to catch the quota amount for that fishing year. Under ITQ, there is no incentive to harvest less than the maximum allowed. However, own carryover is automatic under VPU management and a VPU's investment in conservation will increase own VP size at later time periods. This flexibility is advantageous in a world of uncertainties with respect to markets and personal issues. Management using virtual population is partially decentralized and the harvest decisions are handled largely at a local level. A VPU can plan and adjust own harvests as long as its decision does not seriously deplete own VPU.

ATLANTIC HERRING FISHERY

The Atlantic herring is one of the most important pelagic species in the Gulf of Maine and throughout the North Atlantic. Many species of fish, bird, and marine mammal rely on herring as a source of food. In terms of commercial values the Herring fishery is relatively small compared to other Northeast fisheries, but is important as the major lobster bait in the region. The New England lobster fishery is the one of the largest fisheries in the New England and the landings of American lobster accounted for 43 percent of the landed value in New England fisheries in 2000. The lobster fishery is heavily dependent on a supply of fresh bait and herring is the major lobster bait used in the New England area (Cho, 2001). Maine led in landings of lobster for the 19th consecutive year and more than 80 percent of the lobster bait was herring for this area in 2001.

Management of the U.S. Northwest Atlantic sea herring stocks beyond territorial waters commenced in 1972 and the fishery was regulated by the International Commission for the Northwest Atlantic Fisheries (ICNAF) until its role in the Northeast was substituted by Fishery Conservation and Management Act adopted by Congress in 1976 (NEFMC, original FMP). Additional details appear in the Cho's dissertation. They are suppressed in this paper in the interests of brevity.

The total allowable catch is distributed to Management Areas 1A, 1B, 2, and 3 on an annual (January through December fishing year) basis. The individual area TACs are designed to allow flexibility in the harvest of herring while protecting individual spawning components.

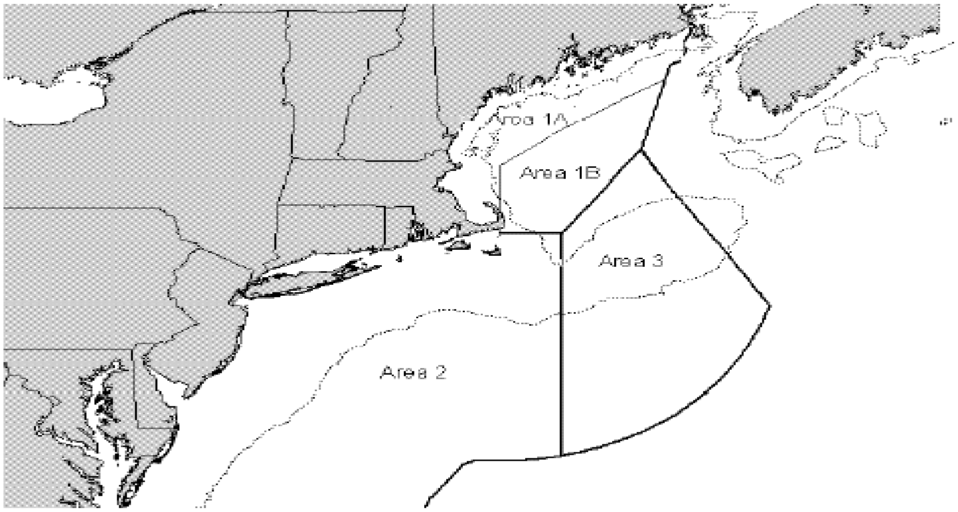

Figure 1. Atlantic herring management areas

According to the landings data herring fishery was dominated first by purse seine, then by single mid-water trawling after about 1981. Currently single and pair mid-water trawls dominate the fishery. There has been change of the landing areas. Management Area 1A has been the dominant landing area, but in recent years there has been an in crease in landing from Georges Bank partly due to the change from purse seines to mid-water trawls since purse seines tent to be less effective in deeper water (SAFE 2002).

Herring prices are in general divided into 2 price categories by the market; domestic and export market. Compared with Norwegian herring U.S. herring has lower fat content and this is one of the reason why the U.S. herring export market is limited, but the price is still higher than domestic market price. There are two major domestic markets for sardine; canneries and bait market for lobster fishery. There are fewer active fishing vessels than many other fisheries and it might be easier to transit to a rights based management regime such as ITQ or virtual population. Given the widespread abhorrence of ITQs in New England, VPs and 1-3 VPUs might be an attractive alternative.

BIOECONOMIC MODEL Using VPs

Cost and revenue functions

The objective of the ith VPU is to maximize the present value of own profits subject to constraints on gear type, market access, fishing areas and stock growth. Total costs include fixed costs and variable costs. Cost of operating one standard fishing vessel for one day is denoted as c. For the variable cost of harvesting we assumed that

$$\text{Cost per unit effort} = cE \qquad \text{(Eq. 1)}$$

where c is a constant unit costs of an effort, E. Variable costs include fuel, supplies, crew wages etc. Variable costs for an ith VPU vary according to the efforts. Fixed costs for VPUs include the initial cost for buying vessel and insurance. Therefore, the total cost function is

$$\text{Total cost} = c{*}Total\ effort + fc \qquad \text{(Eq. 2)}$$

fc is a fixed cost. After taking into account salvage value of fishing vessels and acquisition cost of entering new fishing, total cost function for the ith VPU extends as follows.

Total cost = c*total effort - salvage value (=disinvestments) + acquisition cost of new vessels + initial fixed cost for buying vessel at year 1 (Eq. 3)

Furthermore, there are two major types of fishing vessels in this fishery, purse seine and mid-water trawl. Since purse seiners fish only in management area 1, the average cost is lower than the one by mid-water trawlers.[2] Mid-water trawlers with on board refrigerated seawater capability are well suited to harvest in any areas for either domestic or export markets. Purse seines do not have salt water freezer and herring caught only in Area 1A is sold for export market. Considering these two major types of fishing vessels total cost is

$$\begin{aligned}\text{Total cost} = {} & (c_m TE_m - salvage\,value_m + acquisition\cos t_m) + (c_g TE_g - salvage\,value_g \\ & + acquisition\cos t_g)\end{aligned} \qquad \text{(Eq. 4)}$$

where TE_m is the total effort of a mid-water trawler
C_m is the variable cost for the unit effort for a mid-water trawler
Salvage value$_\mathrm{m}$ is the salvage value for a mid-water trawler
Acuisition cost$_\mathrm{g}$ is the cost for buying a mi-water trawler
TE_g is the total effort of a purse seine vessel
C_g is the variable cost for the unit effort of a purse seine vessel

Salvage value$_g$ is the salvage value for a purse seine vessel
Acquisition cost$_g$ is the cost for buying a purse-seine

Total revenue for an ith VPU is equal to price, *p*, multiplied by harvest quantity, h^i. Under the management using VP, price increase is expected due to the less competition and higher fish quality than under open access. However, ex-vessel price is assumed fixed over time in this study. Total revenue for the ith VPU is

$$TR_i = p * h^i \qquad \text{(Eq. 5)}$$

Individual VPUs can have own harvest strategy and price is the same for the unit harvest. We assumed landings are equal to harvests. Price for herring depends on the sale in different markets.

Growth function and harvest

Superscript T implies total and superscript i implies an individual VPU. Subscript t is a time period. G_0 is the aggregate initial growth rate at the aggregate initial virtual population size, Xv_0^T.[3] The total initial virtual population size, Xv_0^T is set equal to the total real population size, X_0^T. G_t is the aggregate growth rate at time period t and the change of aggregate growth rate at time t, ΔG_t is the difference between G_t and G_0. G_t increases as the total virtual population, Xv_t^T, increases when the total virtual population, Xv_t^T, is smaller than the half of the carrying capacity.

$$G_0 = r * Xv_0^T * (1 - Xv_0^T / K) \qquad \text{(Eq. 6)}$$
$$G_t = r * Xv_t^T (1 - Xv_t^T / K) \qquad \text{(Eq. 7)}$$
$$\Delta G_t = G_t - G_0 \qquad \text{(Eq. 8)}$$

Where:

K	Carrying capacity
r	Intrinsic growth rate for the stock
Xv_0^T	Total initial virtual population
Xv_0^i	ith VPU's share of the total initial virtual population.

ΔG_t increases as the growth rate at time t, G_t, increases compared to the initial growth rate G_0. The initial VP for a VPU is the share (α_0^i) of the total initial virtual population.

Virtual populations vary over time according to the harvest decisions by the individual VPUs, and the contributions of each to the aggregate change in growth rate at the current time period compared to the initial growth rate.[4] The increase in the own virtual population is reallocated only to the VPU that increases own VP.

A sole owner's stock changes as follows:

$$X_{t+1}^i = X_t^i + G_t^i - H_t^i \qquad \text{(Eq. 9)}$$

Under idealized sole ownership the putative owner has sole access to a fraction (a partition) of the real stock, X_t^i and own growth rate function, G_t^i. Growth of a VP includes the growth rate change imputed to individual VPU. In our model a VPU's growth rate, G_t^i, is:

$$G_t^i = \alpha_0^i G_0 + \Delta G_t \; {\Delta X v_t^i}/{\Delta X v_t^T} \qquad \text{(Eq. 10)}$$

where:

α_0^i = ith share of the initial total virtual population

$\Delta Xv_t^i = Xv_t^i - Xv_0^i$ the difference between the individual initial VPU and individual VPU at time period t.

$\Delta Xv_t^T = Xv_t^T - Xv_0^T$ the difference between the total initial VPU and total VPU at time period t.

These definitions of ΔXv_t^i and ΔXv_t^T are analytically more convenient than the more conventional expressions involving first order differences. The growth function is non-linear and cannot be easily scaled in a consistent way to preserve $\sum_i G_t^i \equiv G_t^T$ since $\sum_i rXv_t^i (1 - Xv_t^i / K) \neq rXv_t^T (1 - Xv_t^T / K)$.

In our model individual growth of VPU, G_t^i, is calculated using (Eq. 10).[5] Therefore VP size at the next time period is

$$Xv_{t+1}^i = Xv_t^i + \alpha_0^i G_0 - H_t^i + \Delta G_t * {\Delta X v_t^i}/{\Delta X v_t^T} \qquad \text{(Eq. 11)}$$

$\Delta Xv_t^i / \Delta Xv_t^T$ in (Eq. 11) measures the cumulative contribution of ith VPU to the total cumulative virtual growth change. The multiplication of this ratio by ΔG_t (Eq. 11) measures the contribution to the cumulative total growth change compared to the initial growth rate. Individual contribution to the growth rate increases or decreases own virtual population for the next period. This sharply penalizes a VPU if the VPU depletes its own VP below the initially assigned or reference stock size.

Harvest is a function of fishing mortality and total virtual population. Harvest for individual VPU holder is

$$h_t^i = qE_t^i Xv_t^T \qquad \text{(Eq. 12)}$$

where the q is a catchability coefficient, E_t^i is fishing effort and Xv_t^T is total population at time t. Catchability coefficient q is constant and positive. Fishing efforts are Days at sea (DAS) by fishing vessels and there are constraints on maximum DAS per year or per month by fishing area. The upper limit on annual Days at sea is 146 days and the monthly limit is 24 days.

Objective function

As one of constraints for this fishery the MP model includes vessel dynamics. The number of vessels increase or decrease in accordance with the profits fishermen make and vessel decay factor. The transition equation is:

$$NV_{t+1} = (1 - decayv) * NV_t + Nzero + Acquire_t - Salvage_t \qquad \text{(Eq. 13)}$$

where :

NV_t = number of vessels at time t

$Nzero$ = initial number of vessels

$decayv$ = complement of the depreciation (decay) rate

$Acquire_t$ = number of new vessels purchased

$Salvage_t$ = number of vessels sold (salvaged)

Vessel acquisition and salvage prices differ according to the gear type, but it is assumed salvage price is 50 percent of the acquisition price regardless of the gear type. *Acquire* is the number of new vessels entering the herring fishery, *Salvage* is the number of old vessels to be salvaged.

The objective of the ith VPU is to maximize present value of profits with constraints described in the previous chapters. A discrete time mathematical programming using GAMS[6] seeks optimal values for variables set in the program. The profit function for an individual VPU is

$$\begin{aligned} \mathrm{Pr}\,ofits(\pi^i) &= \mathrm{p} * \mathrm{h} - [(c_m TE_m - salvage\ value_m + acquisition \cos t_m) + \\ &(c_g TE_g - salvage\ value_g + acquisition \cos t_g)] \end{aligned} \qquad \text{(Eq. 14)}$$

Subject to

$$\begin{aligned}
&H_t^i = qE_t^i Xv_t^T \\
&Xv_{t+1}^i = Xv_t^i + \alpha_0^i G_0 - H_t^i + \Delta G_t * {}^{\Delta Xv_t^i}\!/_{\Delta Xv_t^T} \\
&Xv_t^T \le K \\
&NV_t^i = (1 - decay) * NV_{t-1}^i + Nzero_{t-1}^i - Salvage_{t-1}^i \\
&H \cos t_t^i = Vop \cos t_t * E_t^i - Asratio * Salvage_t^i + Vacp \cos t * Acquire_t^i \\
&Revenue_t^i = EVP * H_t^i \\
&Xv_0^i = PSS(VPU) * Fishzero \\
&X \min{}_t^i = SMS * PSS(VPU) * Fishzero \\
&Nv_t \le Nv_{\max} \\
&0 \le h_t \le h_{\max}
\end{aligned}$$

EVP is ex-vessel price of herring and is determined by the market where the landed herring is sold; domestic market and export market. Export is allowed for purse seiners only in Area 1 and mid-water trawlers in all Areas. *Fishzero* is the initial total population and is assigned to VPUs according to the initial endowment rate, *PSS*. Minimum size of VPU is restricted by safe minimum stock size, *SMS*. E_t^i is total effort for each VPU.

MODEL ANALYSIS

We test two different models; sole owner model with two cooperative VPUs and non-cooperative optimization model via an iterative process. Sole owner model has two homogeneous VPUs; VPU1 and VPU2.[7] Optimal solution is obtained by maximizing the sum of present value of two cooperative VPUs. They have identical cost and revenue structure. Each VPU has 7 purse seines and 5 mid-water trawls respectively. They are allowed to all fishing areas 1, 2 and 3. They do not compete each other and try to maximize the sum of profit, not own profit.

The discounted present value of net revenue for this model is

$$\text{Max NR} = \sum_i \sum_t d_t \pi_t^i \qquad \text{(Eq. 15)}$$

where π_t^i is the profit for i^th^ VPU and d_t is a discount factor.

Non-cooperative optimization model has also two homogeneous VPUs. However each of them try to maximize own profit, not the sum of profit.

$$\text{Max NR} = \sum_t d_t \pi_t^i \qquad \text{(Eq. 16)}$$

The MP model in this study uses iterative conditional optimization. The ith VPU maximizes its present value of net benefits conditional on its anticipation of other VPU's harvests. At the next iteration, the anticipated harvests are replaced by the sum of conditionally optimum harvests for other VPUs. At the end of each iteration the absolute deviations between anticipated and conditionally optimal harvests are calculated and summed. The loop is repeated until the total sum of errors is acceptably small.

The following figure 2 shows harvests path over time. The paths increase temporally, because we chose low initial biomass. Since VPUs in the sole owner model are cooperative they produce homogeneous harvests for each and this is the half of the aggregate annual harvest. Aggregate harvests by non-cooperating VPUs are greater than those of the sole owner model.

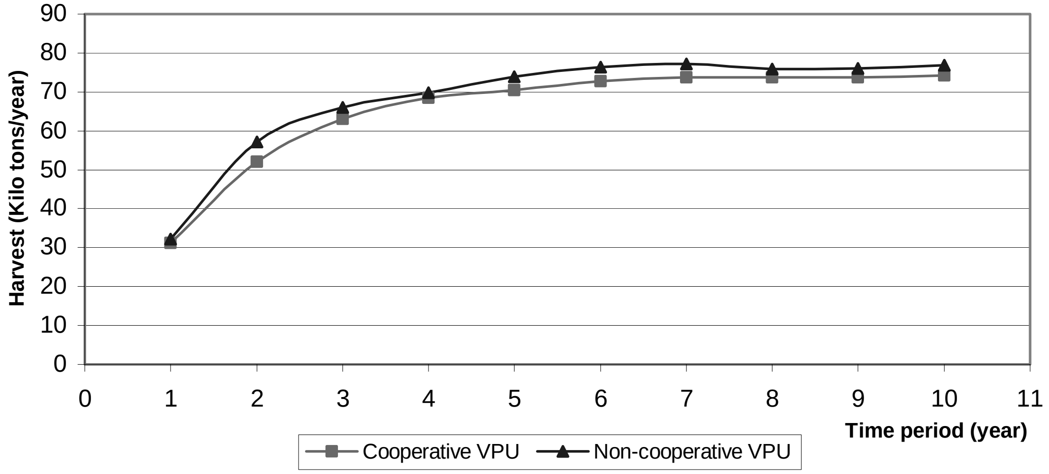

Figure 2. Optimal harvest path

They compete for own profit maximization and try to catch more, but the overall harvests are not far away from the sole owner's optimal harvest pattern. Catch per unit effort is qXv_t^T and this increase as the aggregate VP increases.

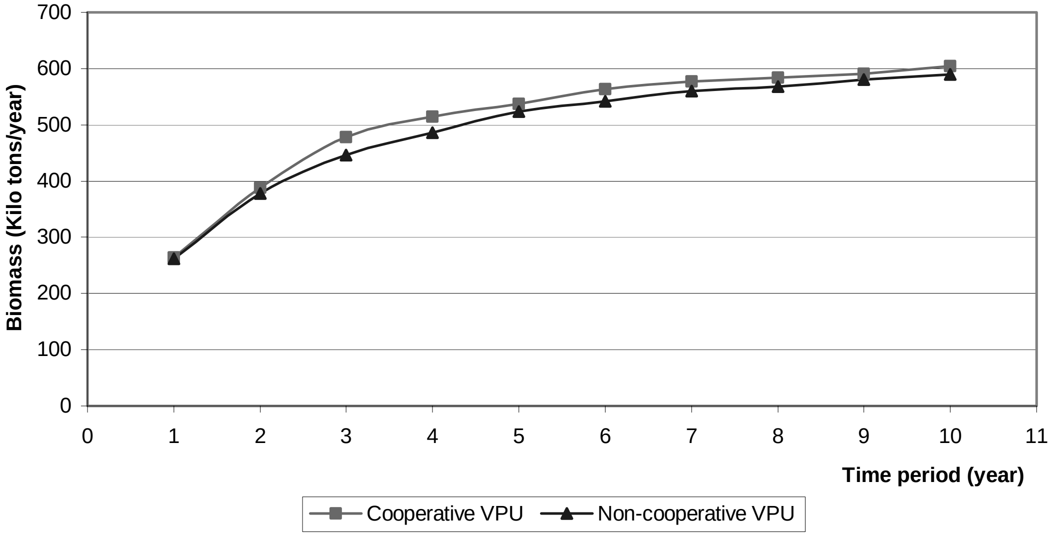

Figure 3. Optimal biomass path

Figure 3 shows the optimal biomass trajectories for the cooperative and non-cooperative Nash equilibria. It is apparent that the cooperative solution produces a trajectory that is slightly higher, but not by much.

Figure 4 contains a plot of the normalized objective function for the Nash equilibrium as a function of iteration count. It also shows the normalized cooperative solution which is constant when plotted against iteration count. It is evident that Nash equilibrium is approached quite quickly and that it is approximately 98 percent of the cooperating objective function. The slight oscillations indicate that the convergence is less than perfect and cycles around a point of attraction.

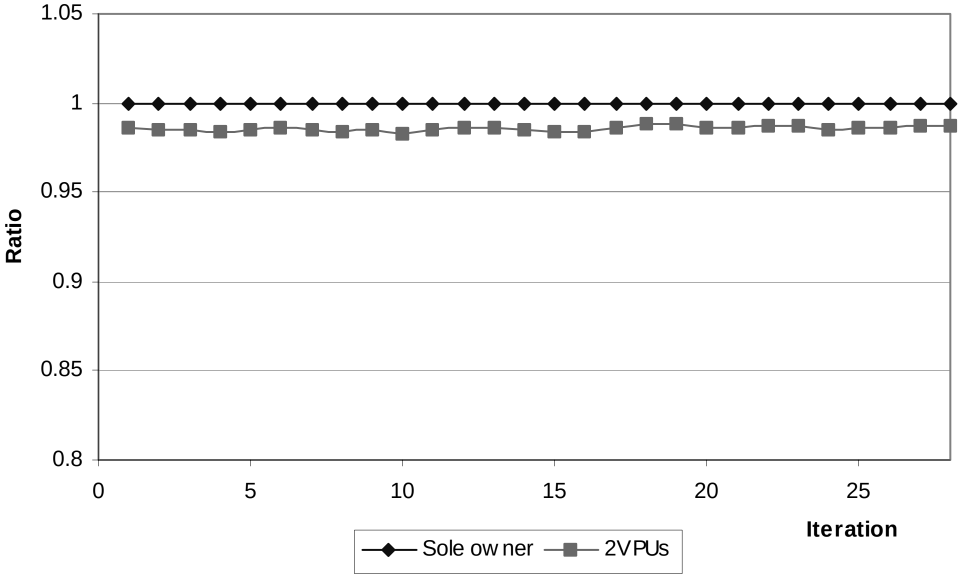

Figure 4. Relative profits

CONCLUDING REMARKS

Optimal fishery management under a VPU regime has been tested using an MP model. We tested the performance of VPUs using both cooperative and non-cooperative variants. Profits realized by two non-cooperative VPUs are not significantly less than the sum of profits for cooperative VPUs. Many articles show that non-cooperative players exploit resources competitively and decrease the available resource very rapidly. However our study shows two VPUs in a Nash equilibrium do not deplete the stock. They harvest more and their VPs are slightly smaller than VPs in the cooperative solution, but they also follow closely the cooperative optimal path. In our study VPUs try to increase the initial stock size by reducing effort immediately. After the VPs increase they increase their harvests. There is a strong penalty system in a VP system if a VPU decreases its stock below the reference stock size (Xv_*^i). Until a depleting VPU restores its stock to the initial level it is severely penalized, which makes a VPU behave conservatively. Conversely, if short term economic consideration favor temporary depletion, followed by compensatory conservation, a VPU can do so.[8]

REFERENCES

Cho, Jung-Hee, 2001, Optimal exploitation of Atlantic herring stocks in USA, University of Rhode Island.

Gavaris, Stratis, 1996, Population stewardship rights: decentralized management through explicit accounting of the value of uncaught fish, *Can. J. Fish. Aquat.* Sci.53, pp. 1683 - 1691.

Gordon, H. Scott, 1954, The economic theory of a common-property resource: The fishery, *Journal of Political Economy*.

NMFS, 2004, Web document http://www.nmfs.noaa.gov/bycatch.htm

NEFMC, 2002, Atlantic Herring Stock Assessment and Fishery Evaluation Report.

Endnotes

1. The authors are Ph.D candidate and Professor, respectively, in the Department of Environmental and Natural Resource Economics, University of Rhode Island, Kingston, RI USA. 02881-0218

2. Mid-water trawlers fish in all management areas.

3. For precision, we should use G_* and Xv_*^T where the * denotes a policy reference value for growth and biomass. We assume Xv_*^T and Xv_0^T are both less than Xv_{msy}^T. Same economy notation is achieved by our assumption $Xv_*^T = Xv_0^T$. However, this is not a necessary assumption. If $Xv_0^T > Xv_{mey}^T$, we should not assume $Xv_*^T = Xv_0^T$ because that would force unnecessarily rigid conservation.

4. This rule may seem unnecessarily complicated but in fact it leads to numerical calculations that are much simpler than some other rules which sound simpler.

5. Gavaris did not cover this point since he was not using a surplus production model. In effect a VPU receives two initial allocations:

(1) $\alpha_0^i G_0$

(2) $\alpha_0^i X_0^T$

After initial time a VPU continues to receive the "initial endowment" of growth ($\alpha_0^i G_0$) plus a fraction of aggregate growth change, $G_t - G_0$. The fraction received depends on own cumulative conservation success to aggregate conservation success.

6. GAMS is an acronym for General Algebraic Modeling System. It is a high level language which is compiled and is compatible with all the major solvers. It can also be used as a stand alone simulation language.

7. In the real world such homogeneity is unlikely and the MP model does not require it. We wanted results which are not contaminated by real world differences of little interest to our readers.

8. Recall, from the foot note 3, that for simplicity we have been assuming $Xv_0^i = Xv_*^i$ and $Xv_*^T \leq Xv_{msy}^T$.

APPENDIX

Coefficients used in the context

Initial VPU; 200 kilo tons for each VPU

Carrying capacity K; 1375 kilo tons

Intrinsic growth rate; 0.93

Cost per unit effort for purse seines; 12 kilo dollars/DAS
for mid-water trawl; 17 kilo dollars/DAS
Acquisition cost for a purse seine; 1100 kilo dollars
for mid-water trawl; 1600 kilo dollars
Acquisition: salvage price ratio; 0.5
Ex-vessel price for domestic markets is $220/ ton

for export market is $320/ton

Initial fleet size; 7 purse seines and 5 mid-water trawls for each VPU