GROWTH OVERFISHING

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ABSTRACT

Growth overfishing squanders large parts of the potential rents in fisheries. Many of today's fisheries are characterized by a severely truncated age-distribution, which in addition may have irreversible ecological consequences. Nevertheless, the implications of age-differentiated harvesting for management have received surprisingly little attention in the literature. In the present paper, optimal and non-cooperative exploitation paths for a generic age-distributed resource are derived. We show that, in the case of perfect selectivity, competition between two agents is sufficient to dissipate all rents. Akin to the classical Bertrand competition in prices, each agent has an incentive to target fish at a younger age. That is, the "race to fish" extends to the dimension of age. This observation is crucial also with respect to management: Individual quotas are not able to restore efficiency unless accompanied by gear regulation. Moreover, it turns out that quotas specified in terms of numbers are far superior to those specified in terms of volume or value. (158 words)

Keywords: Fisheries management; age-structured dynamics; gear selectivity; differential games

INTRODUCTION

Fish stocks could play a significant role in providing food security for the world's growing population – if they are properly managed (Smith et al., 2010). Yet, there is probably no other area of environmental economics where the gap between potential and actual performance is as large (Heal, 2007). Even in fisheries whose aggregate biomass is reasonably well managed, growth overfishing is increasingly seen as a serious problem (Hsieh et al., 2006; Beamish, McFarlane, and Benson, 2006; Ottersen, 2008). Due to the size-selective properties of harvesting gears, large fish are over-proportionally removed from the stock. Since older and larger fish are better able to buffer adverse environmental conditions (Ottersen, Hjermann, and Stenseth, 2006), this truncation of the fish stock's age structure can lead to magnified fluctuations of abundance (Anderson et al., 2008). Moreover, if this has evolutionary effects, the increased variability may be irreversible (Stenseth and Rouyer, 2008).

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Growth overfishing is also a substantial economic problem. In fact, it could be much more important than recruitment overfishing.[1] The value of an individual fish grows significantly with age in many, if not most, commercial fisheries. Moreover, recruitment is to a large extent driven by environmental conditions. It is therefore crucial to fully account for the age-structure and the natural growth potential of fish stocks. For example, Diekert et al. (2010) showed that the resource rent in the Barents Sea cod fishery could be more than doubled, simply by changing the mesh size of trawlers.

The detrimental effect of catching fish that are too small is long known to practitioners and scientists (Petersen, 1893). In industrial fisheries, there has probably almost always been some gear regulations, even though they have been largely ad hoc. Biologists are much concerned with the analysis of recruitment for stock assessment and forward-looking advice for total allowable catch. While the importance of accounting for the size-selectivity has clearly been recognized in the economic literature of the 1960s (Turvey, 1964; Smith, 1969), it has received surprisingly little attention thereafter. The process of growth overfishing has not been treated analytically so far.

To describe the mechanisms clearly, we consider age to be a continuous variable[2] and look at the situation in equilibrium. Moreover, as we focus on growth overfishing, we assume that recruitment is exogenous. The other necessary features for our model to work is to describe natural mortality as constant and growth as a non-decreasing process (in other words, fish never starve but face a constant risk of heart failure). Finally, we presume precise targeting in the sense that unwanted fish are not harvested.[3]

This paper is formatted for the proceedings of the IIFET conference in Montpellier. It focuses on the exposition of the case of linear costs and perfect selectivity. The main results generalize to convex costs and different selectivity patterns. These results, as well as the proofs to the propositions in this paper, are available from the author. The current paper continues with a brief look at the related literature. Then the general model is presented and the intuition behind the optimal age-specific harvesting pattern is described. Subsequently, the unregulated- and regulated harvesting pattern in a competitive setting are discussed.

In general, there is a growing interest in using age-differentiated and stage-based models in empirical resource economics. Although the general problem of optimal multicohort harvesting has long been held to be intractable (Clark, 1990), there exists a large mathematical literature. Tahvonen (2009) has recently shown in a discrete setting that the previous pessimism in the economic literature might have been premature. In addition to his pioneering approach in for fisheries, there exists a related literature in forestry economics (see Xabadia and Goetz, 2010 and the references therein). The fundamental difficulty arises from the fact that a state variable which changes not only as it moves through time but also as it moves through age, necessitates the use of partial differential equations of the form: $\frac{\partial x(a,t)}{\partial a} + \frac{\partial x(a,t)}{\partial t} = f(a,t)$. To get a first grip on management issues in face of age-differentiated dynamics, we will assume that things do not change over time, so that we are left with an ordinary differential equation $\frac{\partial x(a)}{\partial a} = f(a)$.

The original analysis applying an equivalent simplification is from Clark, Gordon, and Friedlaender (1973), who follow a single cohort over time. They formulate the problem in a way we name *perfect selectivity*. Accordingly, costs are only incurred when a fish is harvested. Hannesson (1975) is a pioneering numerical study in this spirit. Stollery (1984) has compared optimal and unregulated harvesting in a general age-time distributed setting, though his contribution is largely neglected. The classical exposition on the multicohort problem is from Beverton and Holt (1957). They, and much of the empirical literature dealing with age-structured fisheries, formulate the harvesting technology in a way that we refer to as *knife-edge selectivity*. According to this formulation, selectivity and effort are separable controls and costs are associated with applying effort. Interestingly, Clark (1990) uses one model specification to discuss optimal harvesting and the other to discuss implications for ITQ management.

We show how – irrespective of model formulation – growth overfishing is the result of a situation where every agent has an incentive to target fish at a smaller age than his opponent. The race to fish extends to the dimension of age. With perfect selectivity, non-cooperation between as few as two players dissipates all rents, akin to the classical Bertrand competition in prices. As fishing is a process which removes individuals from a population, but it is the weight and value of these individuals that generates economic profits, it follows quite naturally that an individual transferable quota (ITQ) which restricts the number of fish that are allowed to be harvested is superior to a quota in terms of biomass. The former will increase in value at the same rate at which the individual fish increases in value and will therefore be able to reduce the race to fish, while the latter increases in value only at the rate at which a larger fish is able to fetch a higher price per kg (if this is at all the case). However, as long as it is less costly to harvest fish when they are more abundant, no indirect regulation will be sufficient to achieve the first best. There is a long standing debate on the efficiency and effectiveness of ITQ management (Wilen, 2000). Their inability to restore optimality in face of resource heterogeneity as been discussed i.a. by Boyce (1992); Townsend (1995); Gavaris (1996) and Costello and Deacon (2007). We contribute to this literature by pointing to the effect of different quota specifications and by highlighting the superiority of number-quotas.[4] Yet, no undifferentiated ITQ scheme is sufficient to prevent growth overfishing. Gear regulation will be necessary.

OPTIMAL HARVESTING

Let $x(a)$ be the value of the biomass of the fish stock as a function of age a. The biovalue at a given age a is the number of fish of that age, $n(a)$, multiplied with their individual value, $v(a)$, i.e. $x(a) = n(a) \cdot v(a)$. The value of a fish of given age a is its weight in kg, $w(a)$, multiplied with its price per kg, $p(a)$, i.e. $v(a) = p(a) \cdot w(a)$. Assume that the value of a fish increases with age but at a decreasing rate. The development of the biovalue over age then consists of two parts: (i) the individual gain in value and (ii) the decline in the number of individuals due to natural mortality m and fishing mortality f. Assume that all variables are non-negative and that natural mortality is positive and independent of age. In mathematical terms, the dynamics (over age) are given by:

$$\frac{\partial x(a)}{\partial a} = \left(\frac{\partial v(a)/\partial a}{v(a)} - (m+f) \right) x(a). \tag{1}$$

Denote the relative growth in value of the individual fish by $\varphi(a) = \frac{\partial v(a)/\partial a}{v(a)}$. As long as it exceeds the decay in numbers, the biovalue will increase.[5] It will decrease when mortality exceeds the individual growth rate. Eventually, the value will approach zero. The development of the natural biovalue over age is as shown in Figure 1. For future reference, the biovalue in absence of fishing is denoted by $x_0(a)$ and can be written as $x_0(a) = v(a) \cdot Re^{-ma}$ (where recruitment is exogenous $n(0) = R$ and the solution of $\frac{\partial n(a)}{\partial a} = -mn(a)$ is Re^{-ma}). Denote the age where the unharvested biovalue reaches its maximum by a_{max}. That is, $\varphi(a_{max}) = m$.

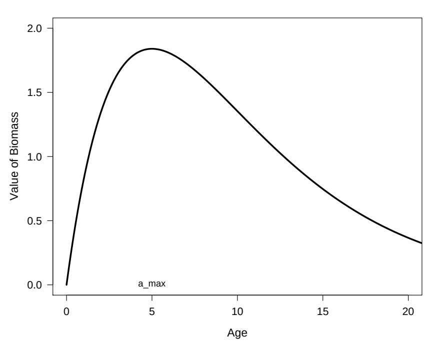


Figure 1: Development of value of biomass in absence of fishing

In principle, bio-economic analysis of a lumped parameter model pertains to the question "how much fish should be harvested". In contrast, age-structured modeling implies two questions: "how many fish should be harvested" and "which fish should be harvested". Depending on the structure of the fishing technology, the formulation of the optimization problem and the resulting harvesting pattern will differ.

Given perfect selectivity, the problem of a hypothetical sole owner that attempts to achieve the social optimum (defined as the maximum sustainable instantaneous profits) is:

$$\begin{aligned} \max \pi(f(a)) &= \int_0^\infty f(a)\cdot x(a) - c(f(a))\,\mathrm{d}a \\ \text{subject to} \quad \frac{\partial x(a)}{\partial a} &= (\varphi(a) - m - f(a))\,x(a). \end{aligned} \tag{2}$$

Let the control region be $f \in [0, f_{max}]$ where f_{max} can be bounded or unbounded. We know from above that the biovalue $x(a)$ will – with or without fishing – eventually approach zero. Therefore it cannot be optimal to apply the control continually as $a \to \infty$, but fishing stops for good at some age A. Similarly, by inspecting the state equation one sees that the natural biovalue grows steeply in the beginning. Therefore it cannot be optimal to harvest very small fish.

The exact harvesting pattern, balancing the length of the fishing interval and the intensity of fishing, will be determined by the costs. On the one hand, the interval should be as short as possible, because one would really only want to have fish of maximum value in one's net: Fish that are too young would still grow in value in the water, and targeting fish that are too old means that at this age, the stock has already lost some of its value. On the other hand, a shorter interval necessitates a higher fishing intensity that could come at exceedingly higher cost. Consider first the case when fishing is costless. Then, evidently, one should harvest each cohort in the instant it has reached its maximum value. When costs are linear, the effect of increasing marginal costs is still absent and the optimal path is characterized by an impulse control at the age of maximum biovalue as well. If costs are strictly convex, a more gradual approach path is optimal and harvesting stretches over some interval. However, fishing is still most intense at the age of maximum biovalue (to get, loosely speaking, most bang per buck).

Proposition 1. *Under perfect selectivity, the optimal extraction pattern is characterized by harvesting with maximum intensity at the age of maximum biovalue and:*

(a) no harvesting at any other age when marginal costs are constant and f_{max} is unbounded (impulse control at a_{max}, see Figure 2a).

(b) harvesting at maximum intensity in the shortest interval around a_{max} and no harvesting elsewhere when marginal costs are constant and f_{max} is bounded.

(c) fishing intensity increases in some interval $[a_0^*, a_{max})$, decreases in some interval $(a_{max}, A]$, and is zero elsewhere when marginal costs are increasing.

COMPETITIVE HARVESTING

How does the harvesting pattern change when we move from the sole-owner solution to the competitive situation of many agents? We will first discuss the unregulated game and show how the ensuing "rule of capture", where the individual agent can claim ownership only by harvesting a fish (Boyce, 1992, p.385), leads to a "race to fish" along the dimension of age: Each agent has an incentive to catch a fish at an earlier age than his competitors. Thereafter, we will discuss how and if a naïve regulation with undifferentiated ITQs or by restricting only effort or gear can remedy this situation. We focus on the linear costs case.

No regulation

Let there be N symmetric agents and denote the fishing mortality from agent i by f^i. The development of the biovalue then reads:

$$\frac{\partial x(a)}{\partial a} = \left(\varphi(a) - m - \sum_i f^i(a)\right) x(a). \tag{3}$$

and profits for player i are:

$$\pi(f^i(a)) = \int_0^A (x(a) - c) f^i(a)\, \mathrm{d}a$$

Proposition 2. *Provided that $\sum_{i \neq j} f^i(a) \geq \varphi(a) - m$ for all j and all a where harvesting is economically viable (i.e. $x(a) \geq c$), the unique Nash equilibrium of the unregulated game under perfect selectivity and linear costs is characterized by a continuous but at no point differentiable interval where $x(a) = c$ (see Figure 2b). Harvesting starts at $a = a_0$, defined by $x_0(a_0) = c$, and continues until $a = a_{max}$. The players make zero profits.*

As a preliminary, define by $g^i(a)$ the fishing intensity necessary from each participating player to keep the biovalue at the level c. That is $\sum_i g^i(a) = \varphi(a) - m$ for all a at which $x(a) = c$. Similarly, define f^i_{max} as the fishing intensity that reduces the biovalue from $x(a) > c$ to $x(a) = c$ as fast as possible. This allows to deal both with the case of bounded and unbounded individual fishing intensity. Theoretically, the bound on f^i could be so low that $\sum_i f^i_{max} < \sum_i g^i(a)$, but we abandon this case until the discussion of gear regulation.

Lemma 1. *The set of Markov-strategies*

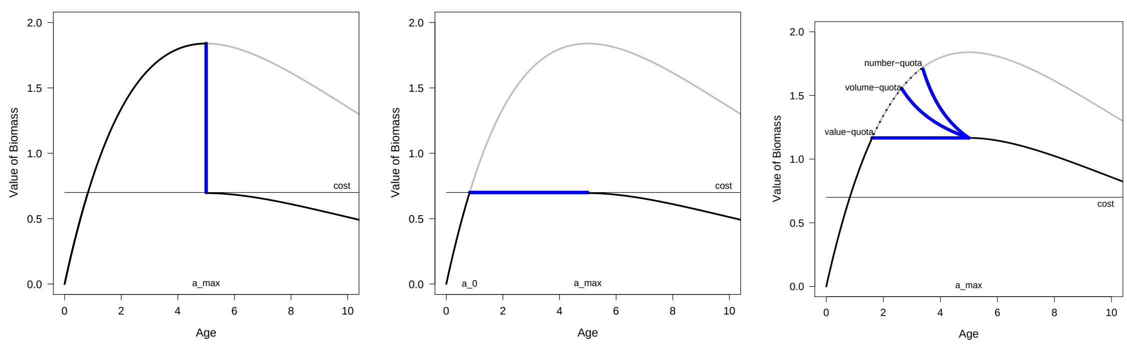
$$f^{i*}(a, x(a)) = \begin{cases} f^i_{max} & \text{if} \quad x(a) \;>\; c \\ g^i(a) & \text{if} \quad x(a) \;=\; c \\ 0 & \text{if} \quad x(a) \;<\; c \end{cases} \tag{4}$$

constitutes a Nash equilibrium.

The intuition behind this result is analogous to the proverbial statement that there are no dollar bills laying on the street, for if there were, someone else would have taken them. For illustration, imagine that $[a_0, a_{max}]$ comprises a number of discrete intervals Δa. Any realization of surplus value in an interval will be exploited instantly by choosing f^i_{max}, leading to a decline in the biovalue. The biovalue will be below c at the start of the next interval, inducing no fishing activity. In the interval after the next, the biovalue will be above c again, hence triggering maximum effort, etc. In the limit as $\Delta a \to 0$, the level of fishing intensity that keeps the biovalue at $x(a) = c$ from a_0 to a_{max} is given by $\sum_i g^i(a)$. Note that the individual g^i is not uniquely determined: there is an infinite number of combinations of individual fishing intensities so that the overall sum $\sum_i g^i(a) = \varphi(a) - m$ for $a \in [a_0, a_{max}]$. What matters is that the path of $x(a)$ is unique.

Note the similarity with the classical Bertrand-price-competition for perfect substitutes: The player shares the obtainable profits when harvesting at same age as his opponents, but obtains the full profits when harvesting at a younger age. This mechanism is at the heart of the "race to fish" along the dimension of age. In contrast to the Bertrand-game of course, the decision is not to pick one price out of an interval, but there are (infinitely) many dates on the interval $[a_0, a_{max}]$ at which the players can harvest. As the biovalue in $[a_0, a_{max}]$ grows again if there is no further fishing, the players will harvest at any point in $[a_0, a_{max}]$: given that the other players harvest at every possible date, abstaining from harvesting at some date will not lead to any improvement in the obtainable biovalue at the other dates.

The result that competition between as few as two agents can lead to total rent dissipation was also obtained in the dynamic lumped-parameter game with linear costs by Clark (1980). The difference is that here the problem is really not excessive effort but that inefficiently small fish are targeted, effectively prohibiting the stock from gaining surplus value. Clark, Gordon, and Friedlaender (1973) obtained singular paths for the optimal control of a single cohort through time with discounting. The optimal extraction pattern (Figure 2a) and the non-cooperative extraction pattern (Figure 2b) are respectively the limiting cases of a zero and an infinite discount rate. The advantage of modeling the entire stock in equilibrium is that it provides a clear and direct link to growth overfishing as the biovalue moves through age.



(a) Social optimum (b) Unregulated game (c) Quota regulation

Figure 2: Harvest patterns under perfect selectivity

Quota regulation

In order to answer how an undifferentiated ITQ system remedies the dire outcome of the non-cooperative game, it is first of all important to recall that there are two processes characterizing the development of an age-differentiated fishery. First, the individual fish are growing in value with age. This implants an incentive to catch fish at a later age. Second, the number of fish is declining with age, increasing the costs of catching one fish of a given age. This implants an incentive to catch fish at an earlier age.

The introduction of individual quotas does not break the second process: the quota price will be independent of age. Let each individual own a quota Q^i, and introduce this as a constraint on a new state variable $y(a)$ with $\partial y/\partial a = f^i(a)q(a)$ and $y(A) \leq Q^i$. The Hamiltonian for agent i in the quota regulated game is then given by:

$$\mathcal{H}^{qt} = [(1-\mu)x(a) - \rho q(a) - c]f^i(a) + \mu x(a)\left(\varphi(a) - m - \sum_{j\neq i} f^j(a)\right) \quad (5)$$

To see that ρ does not depend on age, consider the first-order condition for the adjoint variable ρ: $\frac{\partial \rho^t(a)}{\partial a} = -\frac{\partial \mathcal{H}^{qt}}{\partial y} = 0$. That is, the introduction of quotas will not effectively separate the harvesting decision from the stock development.

As it is evident from the total dissipation of rents under no regulation, competition implies that the individual places no value on the stock development ($\mu = 0$). Maximal fishing intensity is triggered when the biovalue exceeds the cost of harvesting.[6] However, in the quota regulated game, the agent has to take account of the opportunity costs of depleting his quota. It is here that it makes a difference whether the quota is specified in terms of numbers, volume, or value. If the individual is constraint by the number of fish he is allowed to harvest ($q(a) = n(a)$), he has to give up one unit of quota for catching one fish, inserting an incentive to target older and more valuable fish. Hence, such a quota system restores the incentive to take the value growth of the individual fish into account (though it does not change agent i's incentive to harvest before his competitors in order to benefit from the higher abundance at smaller ages). In contrast, if the quota is given in terms of value ($q(a) = x(a) = p(a)w(a)n(a)$), the obtainable value from taking out one unit of quota does obviously not change with age. Hence such a quota system does not implant any incentive to postpone harvesting. A quota which is given in terms of biomass ($q(a) = w(a)n(a)$) represents an intermediate case. It will pick up the value growth stemming from an increase of price with age, but not the value growth which is coming from an increased weight. When the price does not change with age, the effect of a biomass quota is identical to a value quota.

The different effects of the various quota specifications is well illustrated for the linear case when contrasting the conditions that trigger maximum fishing intensity to the corresponding condition for the sole-owner. Maximum fishing intensity is applied when:

$$x(a) > \begin{cases} c & \text{unregulated competitive harvesting} \quad (6a) \\ \dfrac{c}{1-\rho} & \text{quota in terms of value} \quad (6b) \\ \dfrac{c}{1-[\rho/p(a)]} & \text{quota in terms of biomass} \quad (6c) \\ \dfrac{c}{1-[\rho/p(a)w(a)]} & \text{quota in terms of numbers} \quad (6d) \\ \dfrac{c}{1-[\lambda^*/p(a)w(a)n(a)]} & \text{social optimum} \quad (6e) \end{cases}$$

When the quota is given in terms of value, maximum effort is triggered when the natural biovalue surpasses the level $x_0(a_0) = \frac{c}{1-\rho}$. The onset of harvesting is then postponed as this condition is fulfilled at a later age. Since its right-hand-side does not depend on age, the exploitation path is characterized by a straight line as in the unregulated game (only now it is elevated to the level $\frac{c}{1-\rho}$, see Figure 2c). The more the total allowable harvested value is constrained, the higher will be ρ. If on the one hand, the value which is allowed to be harvested under such a regime exceeds the harvested value in the unregulated game, the quota will be worthless ($\rho = 0$). On the other hand, it is clear that there is a finite highest quota price ρ_{max}. As the total allowable catch goes to zero, the onset of harvesting approaches a_{max}. In other words, an undifferentiated value-quota eliminates growth overfishing only if it entirely prohibits harvesting.

A number-quota given in terms of numbers will induce a harvesting pattern which is closest to the optimal one. Along its path, the reduction of every quota unit will yield the same profit, as it picks up the entire value growth of the individual fish. But again, it does not fully eliminate growth overfishing, as it does not completely break the "rule of capture" (Boyce, 1992).

In spite of not restoring efficiency, the superiority of quotas in terms of numbers over conventional biomass quotas could have high policy relevance. To the best of our knowledge, no commercial fishery is managed by such a regime, although this should – in principle – be technically feasible, in particular when fish are aligned individually along the production process, e.g. when headed and gutted. There are however various accounts of bag-limits or other restrictions on numbers in recreational fisheries, where individual handling of fish appears natural.

Gear or effort regulation

A gear restriction to not fish any fish younger than a_{max} eliminates the growth overfishing by definition. Moreover, a gear regulation is able to induce the optimal harvesting pattern. The reason is that, given perfect selectivity, the detrimental effect of non-cooperation is not too much effort, but that the fish are caught too early. A gear regulation will hence effectively solve the stock externality.[7]

In contrast, a regulation of effort alone will achieve very little, though it may improve upon the total rent dissipation under no regulation. An effort regulation has no effect on the "race to fish": The agents would still fish maximally as soon as $x(a) \geq c$, only now, by adequately limiting f^i_{max}, the condition $\sum_{i \neq j} f^i_{max} \geq \varphi(a) - m$ for zero profits in the unregulated Nash Equilibrium would not be fulfilled for small a. Not all economically viable fish could be harvested in the beginning, leading to an initial rise of the surplus biovalue. For older fish, also the limited fishing mortality is sufficient to remove all economically viable fish and the exploitation pattern would then follow the straight line described in Figure 2b.

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ENDNOTES

[1]Recruitment overfishing is defined as harvesting too many fish before they have matured, so that the replenishing potential is restricted, growth overfishing is defined as the excessive harvest of inefficiently small fish. Whereas it is often argued that recruitment overfishing is the less likely but far more severe form of overfishing, it is important to note that growth overfishing, via the link described above, could significantly increase the risk of stock collapse.

[2]Note that fishing is in effect a size selective process. However, the age of a fish has a close relation to the size of a fish, and the former has the advantage that it moves at the same speed as time (i.e. one year later a fish is one year older), greatly simplifying the analysis.

[3]In fact, there is no difference between harvesting and landing in our model and the same result could have been obtained with imprecise harvesting and costless discarding.

[4] Turner (1997) finds that value-quotas are preferable over volume-quotas (number-quotas are not discussed) with respect to quota induced discarding. The contrast is different assumptions on selectivity; he assumes that it is impossible to harvest anything of one class of fish without also harvesting something from another class.

[5]Note that the relative growth in value is very steep for small ages. As $\varphi(a) = \frac{\partial v(a)/\partial a}{v(a)}$ we have for any polynomial $v(a)$ that $\varphi(a) \to \infty$ as $a \to 0$.

[6]Note that in contrast to the classical Bertrand game, where a quantity pre-commitment yields Cournot outcomes (Kreps and Scheinkman, 1983), this is not the case here. The crucial difference is that the agents can harvest at more than one age (equivalent to naming more than one price).

[7]However, in presence of a congestion externality in the sense that the accounting rule for N players harvesting fish of the very same age is that each agent obtains $(\frac{1}{N}x(a_{max}) - c)$, then the individual profits will be inferior to dividing the optimal profits evenly among all incumbents $(\frac{1}{N}[x(a_{max}) - c])$. Gear regulation is then able to reach the optimum optimorum (Turvey, 1964), but if the number of players were endogenous, agents would of course enter the fishery until all rents are dissipated.