



A Model of Quota Prices in a Multispecies Fishery with “Choke” Species and Discarding

Aaron Hatcher¹

Accepted: 11 April 2022 / Published online: 9 May 2022
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Abstract

Using a two-stage optimisation model, we simulate the determination of market-clearing quota lease prices in a multispecies fishery. Assuming fixed proportions technologies, we find that equilibrium quota prices are jointly determined. Price equilibria are sensitive to both the number of quota species and the heterogeneity of the fleet, with corner prices observed where there are a relatively large number of species. Where the fleet is very heterogeneous, quota prices fail to capture all rent as resource rent and inframarginal rents are earned by some vessels. If there is excess demand for quota (for example, as a result of the exhaustion of the quota for a “choke” species) bidding up of the quota price causes all other quota prices to fall. This can result in some vessels starting to earn inframarginal rents even though they are discarding part of the catch. We also use the model to examine the impact of a “deemed value” charge for over-quota landings.

Keywords ITQs · Quota prices · Quota markets · Multispecies fisheries · Discarding

JEL Classification Q22 · Q28

1 Introduction

The use of tradeable catch or landing quotas (often referred to generically as Individual Transferable Quotas or ITQs) is now widespread in fisheries management. In principle, tradeable quotas enable managers to regulate total harvest efficiently, to the extent that markets allocate quota to the most efficient users. Quota markets (including both lease and asset markets¹) usually develop informally, although institutions may be created centrally in order to improve transparency and reduce friction in trading. Willingness to pay for quota in either market should then reflect the additional profits earned from their use, and

¹ See, for example, Newell et al. (2007). Note that in most ITQ systems in-season quota leases are defined in physical quantities while annual ITQs are defined as percentages of the annual TAC (total allowable catch).

✉ Aaron Hatcher
aaron.hatcher@gmx.com

¹ Economics and Finance, Faculty of Business and Law, University of Portsmouth, Richmond Building, Portsmouth PO1 3DE, UK

quota prices can be taken to approximate resource rents in the fishery (see Arnason 1990; Grafton 1995; Squires et al. 1998).

While the basic economics of ITQs is well established in the literature, theoretical analysis is mostly focused on the simplest case of the single species fishery, despite the fact that many, if not most, quota managed fisheries are multispecies. Multispecies fisheries are characterised by jointness in production, so that the range of feasible output compositions is restricted (Squires and Kirkley 1996; Vestergaard 1996; Turner 1997; Singh and Weninger 2009). In other words, different species are caught together, and the ability of fishermen to alter the species mix in the harvest is limited. As a result, in multispecies fisheries market equilibrium quota prices are jointly determined (Campbell 1995; Vestergaard 1999). This interdependence of prices for different species quotas complicates the analysis of quota market equilibria, so that it is difficult to derive generalisable results about the relationship between quota prices and fishery performance, for example, or about the effectiveness with which quota prices capture resource rents in the fishery. The relatively small number of empirical models of quota prices in multispecies fisheries do not find close agreement between observed and predicted prices (Campbell 1995; Squires and Kirkley 1996; Bose et al. 2001) and while econometric analysis of empirical data on quota markets reveals broadly expected relationships overall between quota prices and industry profitability, there is significant noise and price dispersion, at least partly reflecting thin markets and informational issues (e.g., Batstone and Sharp 2003; Dupont et al. 2005; Newell et al. 2005; Holland 2013, 2016; Ropicki and Larkin 2014; Jin et al. 2019).

All else equal, we would clearly expect quota prices in a multispecies fishery to be sensitive to short run quota availability. In many cases this will depend upon fishermen's behaviour in response to regulations concerning the retention or discarding of "over-quota" fish in the catch. The effects of in-season quota supply shortages for relatively abundant species (often referred to as "chokes"), for example, will then depend upon how fishermen respond in terms of discarding as they seek to continue harvesting fish for which quota remains available.² If quota prices are jointly determined, any quota price changes will likely affect all quota prices, so that quota price data for individual species need to be interpreted with caution. Changes in quota prices may also mean changes in the proportion of total fishery rents captured by the value of quota, so that in the short run quota prices may be an unreliable guide to either industry profitability or resource rents.

The aim in this paper is to explore these quota price interrelationships using a simple numerical simulation model in order to focus on the effects of quota supply shortages. To ensure a relatively tractable model, in common with much of the literature simplifying assumptions are made about the vessel harvest function. Firstly, total harvest is assumed to be a *deterministic* function of (short run) fishing effort, here defined as a bundle of variable inputs linked to the number of fishing days. Secondly, for a representative vessel the mix of species in the harvest is assumed to be fixed. Ignoring stochasticity in harvest is a convenient (and common) simplification, and we can think of the harvest as an average for

² Quotas are generally enforced at the point of landing rather than harvesting, due primarily to the difficulty of observing behaviour at sea. Until relatively recently fishermen in Europe were legally required to discard fish for which they had no quota, but from 2019 were required to land *all* fish. Since quotas remain in force under this landing obligation, it has exacerbated the problem of choke species: species for which relatively small national or sectoral quotas are constraining on the ability of fishermen to take up fully their quotas for other species.

a representative vessel. The assumption of fixed proportions in harvesting may arguably be more restrictive, but is used in order to model as simply as possible the real-world problem of chokes and discarding as a result of quotas supplied in different proportions to typical catches.³ Again, we can think of the proportions in which different species are caught as averages for a vessel of a particular type within a given season, but we can also think of them as modelling the harvest proportions which pertain *after* vessels have attempted to match their harvests more closely with quota availability. The important thing is that there are differences in proportions at quota price equilibrium: the harvesting cost implications can then be assumed implicit in the chosen parameter values. In reality vessels can always alter the species mix at the margins, through choice of fishing area and time, adjustments to gear, and so on, but in multispecies fisheries the impacts of a divergence between relative species abundance on the grounds and the relative size of quotas are common and well-documented, and evidence the limited extent to which, in practice, these impacts can be avoided (e.g., Mortensen et al. 2018).

The implications of catch/quota imbalances for discarding in multispecies quota fisheries have been examined by Turner (1997) and Singh and Weninger (2009), assuming deterministic harvest but allowing for costly targeting (weak output disposability). Singh and Weninger (2009) go on to consider the impact of costly targeting and discarding on individual quota prices, but do not explore the joint determination of quota prices for different species nor the impact of short run quota supply shortages (chokes).

To summarise the modelling results, in the simulations we find joint determination of quota prices with quota price equilibria sensitive to the relative numbers of quota species and vessel types in the fishery. The exhaustion of a choke species quota results in a general decrease in the quota prices for all other species, as the choke species quota price is bid up to its price ceiling (the ex-vessel price in the case of costless discarding). With relatively few “free” quota prices, either where there are few quota species or where there are quota prices constrained at their ceilings, we observe the emergence of inframarginal rents as equilibrium quota prices fail to capture all marginal rents as resource rent.

In the next section we develop a simple model of short run vessel behaviour in an ITQ fishery. The following two sections outline the methodology for calculating market equilibrium quota (lease) prices and the optimisation model used to run the numerical simulations. The results of the simulations are discussed in Sect. 5 for a fishery with up to three species and three fishing firms. A baseline scenario has equal numbers of quota species and fishing firms (representing different fishing technologies) with either costless or costly discarding. We then examine scenarios in which there are more species than firms (technologies) as well as fewer species.⁴ We go on to examine the impact of a “deemed value” system where firms can pay an *in lieu* charge to land fish for which they cannot obtain quota. The results are discussed in a concluding section.

³ Allowing for a degree of (costly) targeting greatly complicated the model and initial attempts to incorporate this were abandoned as it became impossible to find stable solutions.

⁴ The number of firms in the model represents the technological variation within the fishery relative to the number of species subject to quotas. In single species fisheries (such as those for pelagic species like herring or mackerel) the number of different fishing technologies may well exceed the number of species. The opposite pattern is likely to be found in highly diverse mixed demersal fisheries such as those in the North Sea, where there are a large number of stocks subject to quotas. The Scottish whitefish fishery, for example, where most vessels are modern stern trawlers of around 15-30m in length, includes over 30 quota stocks.

2 Individual Firm Behaviour

We begin by modelling the behaviour of an individual fishing vessel firm in a multispecies fishery regulated with tradeable quotas. The fishery consists of N such firms, indexed $i = 1, 2, \dots, N$, catching M quota species, indexed $j = 1, 2, \dots, M$.⁵ All firms are assumed to be price takers in all markets. In the short run, each vessel catches species j as a fixed proportion $\beta_{ij} \in [0, 1]$ of its total harvest $H_i(e_i)$, where e_i is an index of fishing effort. Although (in the short run) the β_{ij} are fixed for an individual vessel, they vary across vessels. We will assume compliance with quotas on landing. Omitting the constraints $d_{ij} \leq \beta_{ij}H_i(e_i)$ to avoid clutter, a vessel firm's short run profit maximisation problem is then

$$\max_{e_i, d} \left\{ \sum_j [(p_j - r_j) [\beta_{ij}H_i(e_i) - d_{ij}] - \theta_{ij}d_{ij}] - C_i(e_i) \right\}, \quad (1)$$

where p_j is the ex-vessel price and r_j is the quota lease price for fish of species j , d_{ij} is the quantity of species j which is discarded prior to landing and $C_i(e_i)$ is the cost of fishing effort.⁶ We allow for the possibility of a unit cost $\theta_{ij} \geq 0$ to discarding fish: this could represent a handling cost, for example, or an expected penalty for discarding (if discarding can effectively be observed and sanctioned).

The first order conditions for optimal effort and discards are

$$e_i^* > 0 : \quad \sum_j [p_j - r_j] \beta_{ij} H'_i(e_i) - C'_i(e_i) = 0 \quad (2)$$

and

$$d_{ij}^* > 0 : \quad p_j + \theta_{ij} = r_j, \quad j = 1, 2, \dots, M. \quad (3)$$

The left hand side of condition (2) is simply the marginal net benefit of fishing effort, while condition (3) states that fish will only be discarded if the quota price is equal to (or greater than) the ex-vessel price, plus the cost of discarding (if non-zero). Taken together, conditions (2) and (3) implicitly determine firms' willingness to pay for quota at any quota market equilibrium.

If the level of effort is constrained to some maximum value (e_i^{\max}), then the effort condition becomes

$$\sum_j [p_j - r_j] \beta_{ij} H'_i(e_i) - C'_i(e_i) = \lambda_i^* \geq 0, \quad (4)$$

where λ_i^* is the shadow value of effort at $e_i^* = e_i^{\max}$. In the case of *constant* marginal harvest and cost, we must have a constrained solution. Here, a firm will only earn inframarginal rents if $\lambda_i^* > 0$: if $\lambda_i^* = 0$, all profit is resource rent (captured by the quota lease prices). If we assume, for modelling purposes, that vessels of a particular type have constant average harvest rates and costs per fishing day (with all other costs fixed or quasi-fixed) then we can write (4) as

⁵ Each vessel firm can represent a number of identical firms in the fishery. Heterogeneity across firms in their harvest and cost functions reflects the technological heterogeneity in the fishery.

⁶ The cost function is assumed to be at least weakly convex. We also assume that in the short run there are no significant stock effects on harvest rates.

$$\sum_j [p_j - r_j] \beta_{ij} h_i - c_i = \lambda_i \geq 0, \quad (5)$$

where h_i and c_i are daily harvest and cost respectively. With this simplification, whether or not a vessel earns inframarginal rents ($\lambda_i > 0$) depends only on quota prices.

3 Quota Prices

While individual firms see quota prices as exogenous, conditions (2) and (3) determine individual quota demands and hence industry *inverse* quota demands (quota market lease prices). If discarding is costless, condition (3) implies that ex-vessel prices form quota price ceilings (\hat{r}_j), since no firm will pay more than the ex-vessel price for quota. If $\theta_{ij} > 0$, however, then the quota price ceiling is raised above p_j , since a firm will be willing to pay up to $p_j + \theta_{ij}$ to land legally, rather than to discard, the marginal catch of species j . If $r_j = p_j + \theta_{ij}$, we assume, the firm is just indifferent between landing and discarding fish.⁷

If, at a quota market equilibrium, there is excess supply of quota for a particular species, we would, *a priori*, expect the quota price for that species to be zero. If, on the other hand, there is excess demand for quota (so that any fish caught of that species must be either discarded or landed without quota) the corollary to (3) is that the quota price is bid up to its respective price ceiling. Following Singh and Weninger (2009), we therefore expect a quota (lease) market equilibrium to consist of a set of endogenous quota prices $r_j \in [0, \hat{r}_j]$, such that each firm's fishing effort and quota demands satisfy Eq. (2).

Given the foregoing, however, *interior* quota prices ($0 < r_j < \hat{r}_j$) imply that quota supplies must neither exceed demand (in which case the quota price would be zero) nor must demand exceed supply (in which case the quota price is bid up to its price ceiling). In order to model a quota market equilibrium in which we have interior quota prices for most species (as is commonly observed in practice), we therefore need quota supplies such that the quota market *just* clears for those species. While quota price ceilings may be observed for some species (choke species in particular), zero quota prices are rarely observed. Typically, most quotas are traded at positive prices which are less than the ex-vessel prices for the fish. This implies that quotas are not oversupplied to the in-season quota lease markets that typically operate as firms adjust their quotas to their catches and landings in real time, even though some season quotas⁸ may never be fully utilised.

The intuition for a model of quota lease prices is then as follows. We assume that at the start of a season all quota is owned by fishing firms who then trade quota between themselves.⁹ We further assume that no firm holds quotas in *exactly* the proportions in which they harvest fish of different species, ensuring that there is an active quota lease market during the season. Lastly, we assume that quota is only placed on the market when lease prices are positive, so that supply never exceeds demand (although demand may exceed

⁷ Similar arguments apply if firms were required to land over-quota fish (instead of discarding, but not for sale) incurring a charge equal to θ_{ij} (assuming that discarding is either effectively prohibited or incurs an expected unit cost greater than θ_{ij}). Here, if $r_j = p_j + \theta_{ij}$, a firm is indifferent between landing fish with quota or without quota.

⁸ The total quota for a fishing season is often the Total Allowable Catch (TAC) although in multinational fisheries (as in Europe) the TAC may then be divided into national quotas.

⁹ With "grandfathered" quota allocations, this is typically the case for tradeable quota systems.

supply, if a season quota or TAC is exhausted). Thus quota prices are (weakly) positive¹⁰ and competition for quota results in marginal firms revealing their maximum willingness to pay according to Eq. (3). Assuming one quota lease market for each species, we therefore look for uniform quota prices which exhaust gains to trade, given the existing fleet size (which, in the short run, we assume to be fixed).

4 Quota Market Model

The quota market simulation model consists of a two-stage optimisation model. In the first stage, we find the effort levels and the quota allocation across firms which maximise the total (current) value of the fishery, subject to quota availability. In the second stage, we find the set of uniform quota prices that maximises the flow of resource rent in the fishery. In essence, quota prices are found by backwards induction: we begin with the equilibrium number of firms, fishing effort and quota allocation, and then find the set of quota prices which satisfy the conditions necessary for that equilibrium to exist.

We assume linear harvest and cost functions (constant daily harvest rates and vessel operating costs) which simplifies the individual effort condition to (5), where the effort limit applied for all firms ($e_i^{\max} = E$) corresponds to the elapsed length of the fishing season (in days). The discard condition is simplified to

$$p_j + \theta = r_j, \quad j = 1, 2, \dots, M, \quad (6)$$

dropping the individual firm and species subscripts on the discard cost. By progressively varying the effort limit for all firms, we can then find the quota price equilibrium at different stages of TAC uptake during a season. As a TAC is exhausted, a quota price ceiling is imposed by the model, according to (6), and firms discard fish of that species (or land without quota).¹¹

In the second stage of the model, we find maximal values for the r_j that satisfy condition (5) for all N firms, subject to the constraints $r_j \leq p_j + \theta$, with strict equality imposed where a TAC is exhausted, in accordance with condition (6). Formally, the quota pricing problem in the model is defined as the *minimisation* problem

$$\begin{aligned} \min_r \left\{ \sum_i \left[\sum_j [p_j - r_j] \beta_{ij} h_i - c_i \right] \right\}, \\ \text{s.t.} \quad \sum_j [p_j - r_j] \beta_{ij} h_i - c_i = \lambda_i \geq 0, \forall i; \quad r_j \leq p_j + \theta, \forall j. \end{aligned} \quad (7)$$

This maximises the flow of resource rent in the fishery at $e_i^* = E, \forall i$, assuming uniform quota prices. The maximisation of resource rents determines which (if any) of the λ_i are positive and hence which firms earn inframarginal rents. One of the implications of a linear model is that quota prices and rents only change as TACs are exhausted (assuming all firms remain active).

¹⁰ We cannot exclude the possibility of a market equilibrium in which the quota price for one or more species is equal to zero, even though there is no excess supply.

¹¹ These disposal options are equivalent in the model.

Provided we have heterogeneity across firms, the first set of constraints in (7) form a system of N independent linear equations in M variables: the r_j . However, we can interpret the λ_i as slack variables in a set of N inequality constraints of the form

$$\sum_j [p_j - r_j] \beta_{ij} h_i \geq c_i, \quad i = 1, 2, \dots, N, \quad (8)$$

so that the total number of variables in the problem increases to $M + N$. The maximum number of constraints in the problem is also $M + N$: N constraints derived from conditions (5), together with M quota price ceilings. Anticipating the numerical simulation results described in the next section, we can then characterise any solution to the quota pricing problem with the equality

$$M' + N' = M'' + N,$$

where $M' \leq M$ is the number of *positive* quota prices, $N' < N$ is the number of positive shadow prices (λ_i) and $M'' < M$ is the number of *binding* quota price ceilings. Possible solutions are as follows.

- (i) $M = N$. If the number of species TACs (M) is the same as the number of different vessel types (technologies) in the fishery (N) then at equilibrium we can have a set of positive, interior, quota prices with no vessels earning inframarginal rents.¹² If one or more of the quota price ceilings becomes binding, as TACs are exhausted, then one or more of the λ_i will become positive and these vessels will then be earning inframarginal rents.
- (ii) $M > N$. If the number of species TACs is greater than the number of different vessels in the fishery, then one or more of the quota prices will either be constrained at its price ceiling (even if the TAC is not exhausted), or equal to zero. We cannot have an equilibrium in which *all* quota prices are both positive and interior. If a species TAC is exhausted, so that an additional quota price becomes constrained at its price ceiling, this will result in vessels earning inframarginal rents only where the total number of vessel types plus binding quota price ceilings becomes greater than the number of species TACs.
- (iii) $M < N$. If the number of species TACs is *less* than the number of different vessel types, then we expect interior quota prices, but one or more of the λ_i will be positive and these vessels will be earning inframarginal rents. If a species TAC is then exhausted, so that the quota price is constrained at its price ceiling, this will increase the number of vessel types earning inframarginal rents.

In summary, in the absence of chokes and discarding the condition for observing a full set of interior quota prices is $M \leq N$, while the condition for quota prices capturing all rents (i.e., no inframarginal rents) is $M \geq N$. Rents to inframarginal vessels emerge when $M < N$.

¹² Again, we cannot rule out a quota market equilibrium in which one or more of the quota prices is equal to zero. Neither can we exclude an equilibrium in which one or more of the quota prices is constrained at its price ceiling (even if the TAC is not exhausted). In either case, one or more of the λ_i will then be positive.

Table 1 Parameter values used in the models

	Vessel A	Vessel B	Vessel C	
Daily cost	34	30 (-12%)	28 (-18%)	(Relative to Vessel A)
Daily harvest	20	22 (+10%)	18 (-10%)	
Species 1	45%	20%	30%	Catch composition in three species models
Species 2	25%	35%	10%	
Species 3	30%	45%	60%	
Species 1	–	–	–	Catch composition in two species models
Species 2	25%	35%	40%	
Species 3	75%	65%	60%	

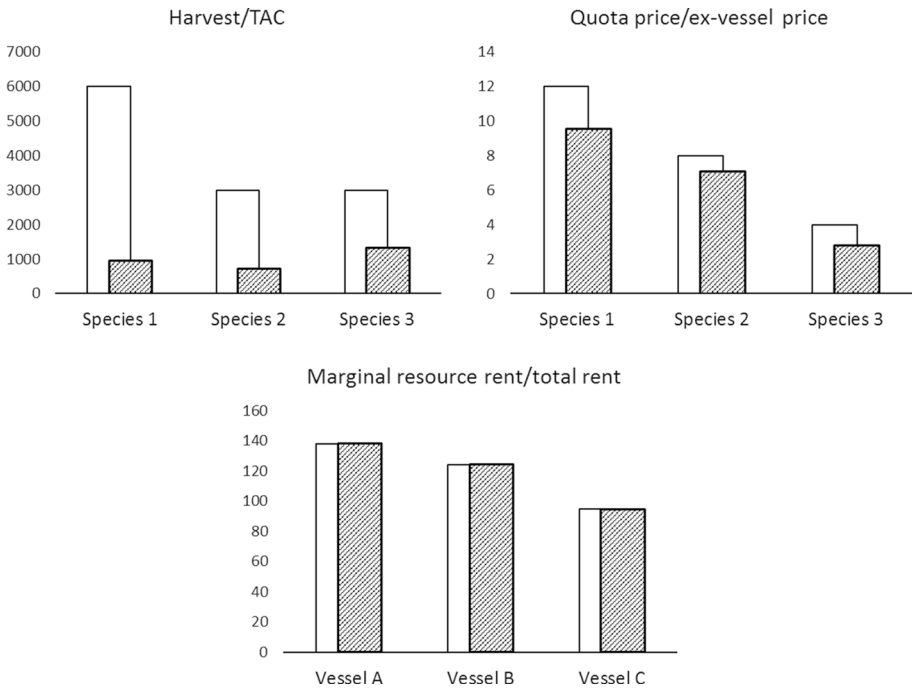


Fig. 1 Baseline model, $E = 50$ days

5 Numerical Results

The simulation model is set up initially with three fishing vessel firms and three quota species. Parameter values were chosen so that the three vessels represented three distinct technologies (different harvest and cost functions; different species catch compositions) and the baseline model illustrated a fishery in which all three vessels remained active at the end of the 250-day season even after two of the three species TACs were exhausted. Ex-vessel prices were set at 12, 8 and 4 for Species 1, 2 and 3 respectively. The other parameter values are shown in Table 1 above (the units are not defined but

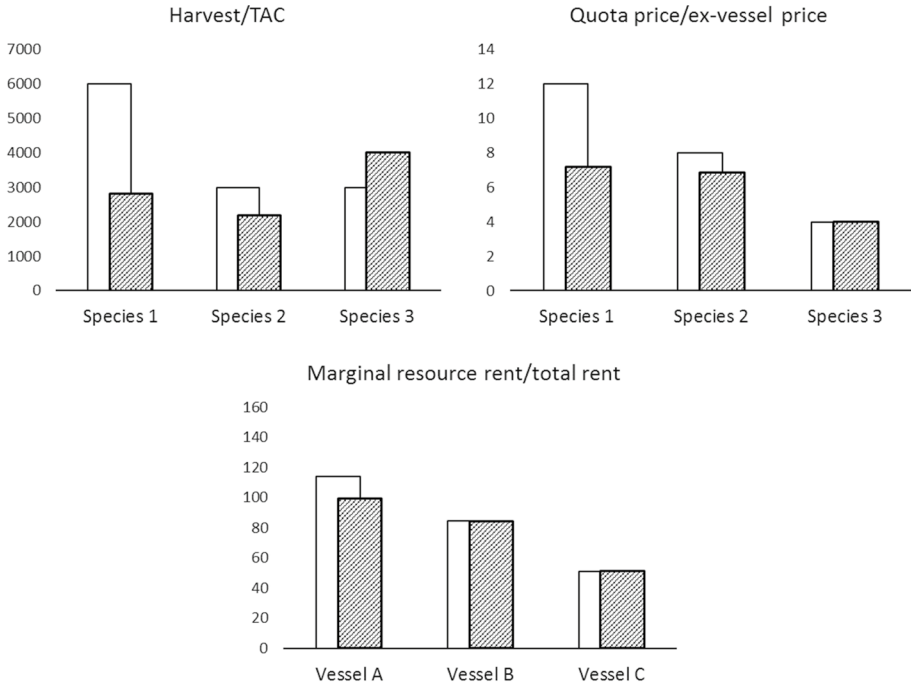


Fig. 2 Baseline model, $E = 150$ days

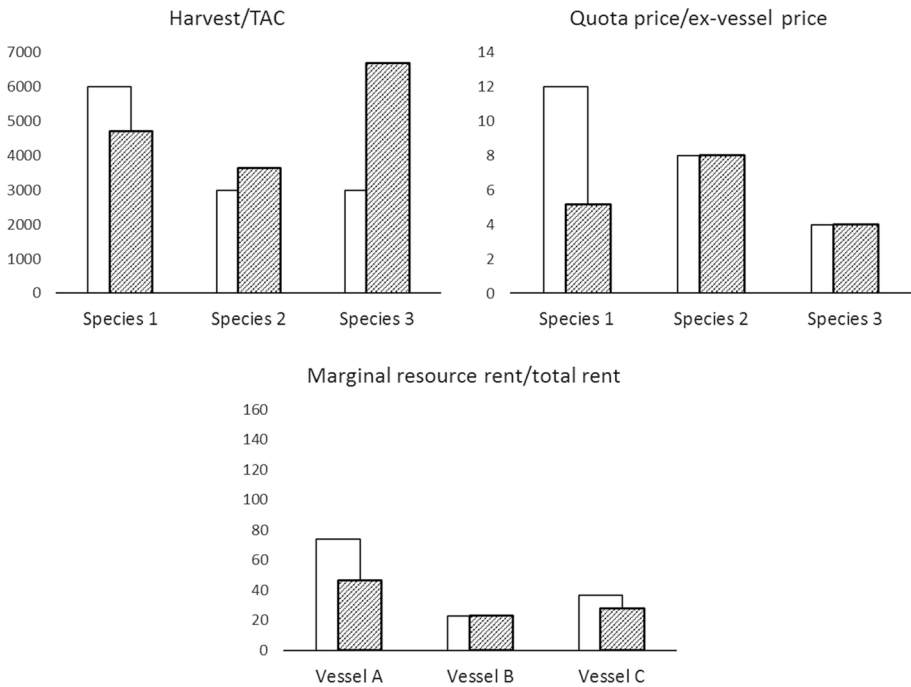


Fig. 3 Baseline model, $E = 250$ days

could be, for example, in £100 and 100 tonnes). The optimisation model was built and run in Microsoft Excel using Analytic Solver (Frontline Systems Inc.).

5.1 Baseline Model: Two Choke Species; Costless Discarding

The baseline model has two “choke” species: one species TAC which is exhausted after 112 days and another which is exhausted after 206 days. Figures 1, 2, 3 show the results of the simulation at $E = 50$, 150 and 250 days (where $e_i^* = E$ for each vessel). In each case, the top left panel shows the total uptake (shaded column) of each TAC. The top right panels show the market equilibrium quota price (shaded) in relation to the ex-vessel (dockside) price for each species, while in the bottom panels the shaded columns show that part of each vessel’s marginal (daily) net harvest value (“total rent”) which is captured as resource rent (payments to quota).

At $E = 50$ (Fig. 1), all the TACs are only partly taken up and we have interior quota prices for all three species. With free quota lease prices for three species and three heterogeneous vessels, the uniform quota prices capture all the daily surplus generated in the fishery: no vessel earns any inframarginal rent. At $E = 150$ (Fig. 2), however, the TAC for Species 3 has been exhausted and all fish of this species are discarded. The quota price for Species 3 has been bid up to the ex-vessel price and the quota prices for the other two species are lower as a result. Although the daily value of harvest is reduced for all three vessels, Vessel A is now earning inframarginal rents. At $E = 250$ (Fig. 3) the TACs for both Species 3 and Species 2 are exhausted and the quota prices for these species have been bid up to the ex-vessel price. Since vessels are now landing only fish of Species 1, daily harvest values are reduced further, as is the quota price for Species 1. Now Vessels A and C are earning inframarginal rents, while Vessel B, the marginal vessel in this fishery, continues to earn only resource rent.

5.2 Costly Discarding

If discarding is costly, the quota price ceiling for species j is raised to $p_j + \theta$, where θ is the unit cost of discarding fish (for simplicity, assumed to be constant across both species and vessels).¹³ The effect of costly discarding when a choke species TAC is exhausted is illustrated in Figs. 4, 5. At $E = 150$, (Fig. 4) Species 3 is discarded and its quota price is raised to above the ex-vessel price due to the cost of discarding. The quota prices for Species 1 and 2 are then reduced by more than is the case in Fig. 2 (the baseline case). Marginal harvest values are reduced for all vessels (due to the cost of discarding) but the inframarginal rents earned by Vessel A are increased due to the reduction in the quota prices for Species 1 and 2. At $E = 250$, (Fig. 5) only Species 1 is landed but its quota price is significantly reduced compared to the baseline case (Fig. 3). Because of discarding costs, marginal harvest values are reduced for all vessels but the inframarginal rents earned by Vessels A and C are increased.

¹³ Again, θ could also represent a unit discard penalty, if this were a practical proposition, or a penalty payable for over-quota landings (assuming that discarding could be prevented, or was more costly, and that such landings could not then be sold).

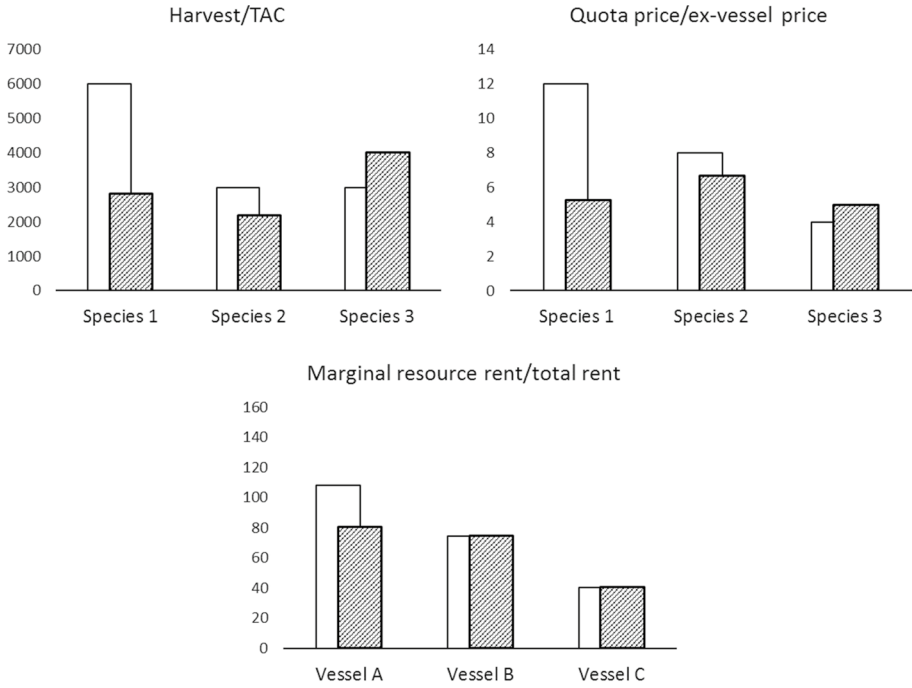


Fig. 4 Costly discarding, $E = 150$ days

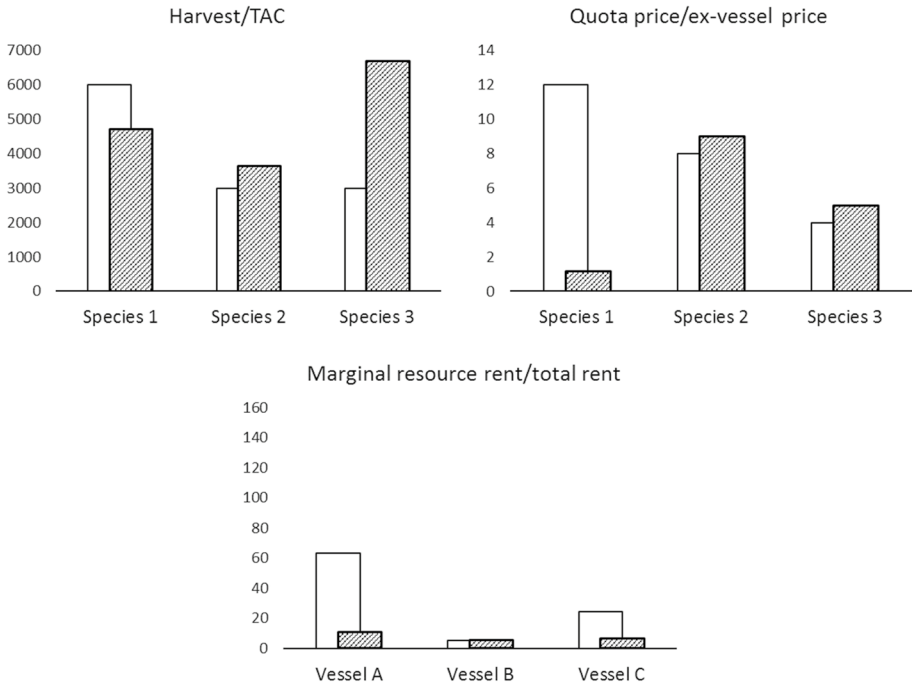


Fig. 5 Costly discarding, $E = 250$ days

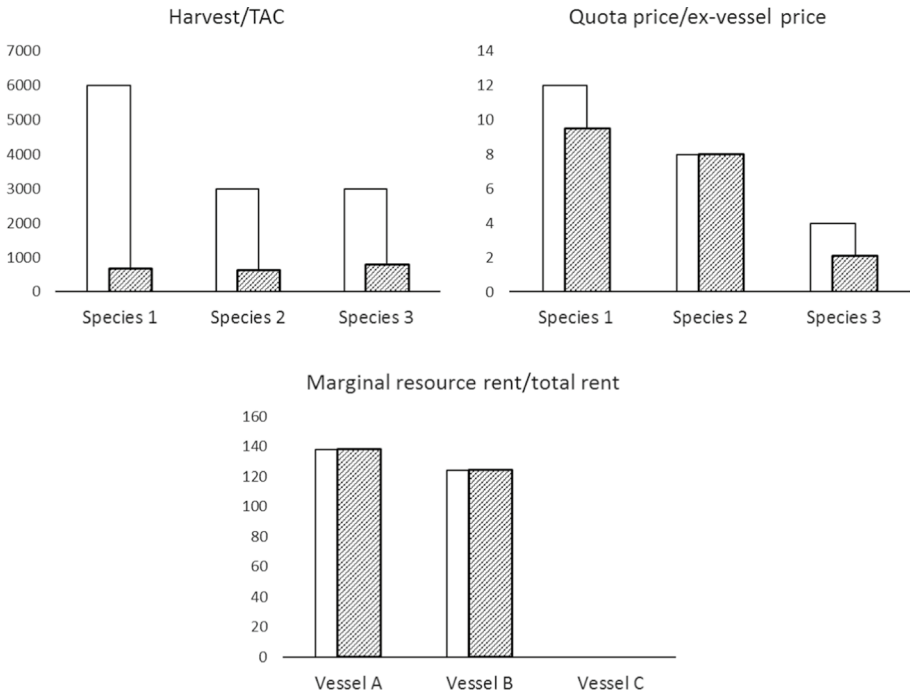


Fig. 6 Three species, two vessels, $E = 50$ days

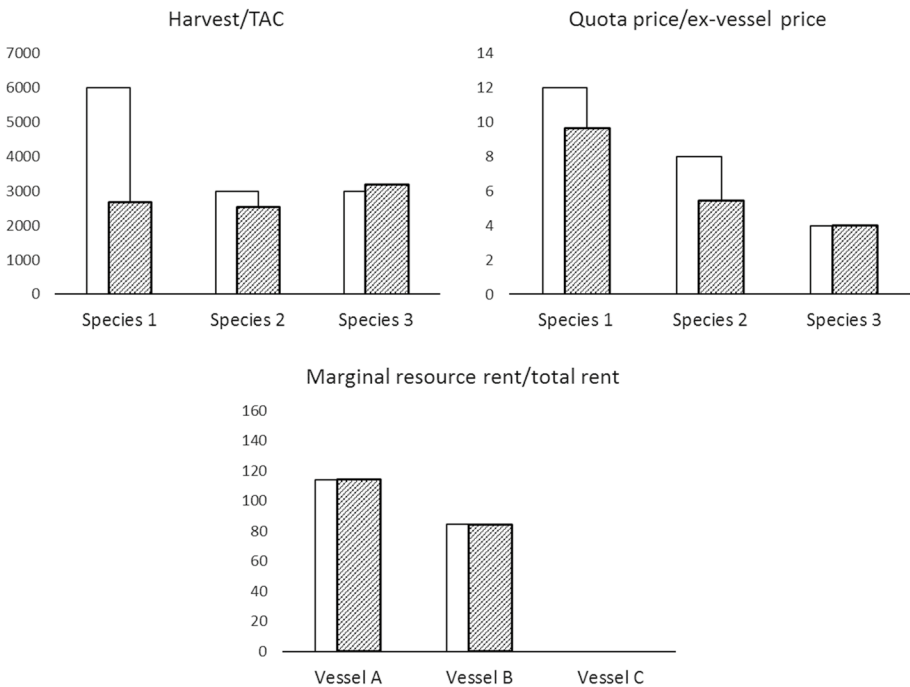


Fig. 7 Three species, two vessels, $E = 200$ days

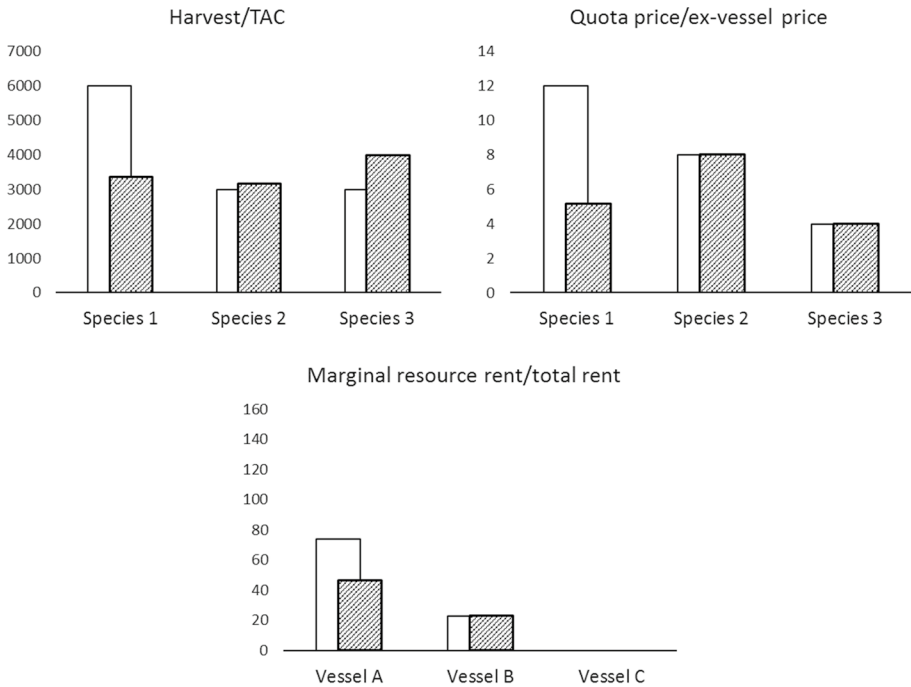


Fig. 8 Three species, two vessels, $E = 250$ days

5.3 Greater Harvest Diversity: More Species than Vessel Types

In this scenario we have three quota species but only two vessels (A and B). Figures 6, 7, 8 show the results of the simulation at $E = 50, 200$ and 250 days. At $E = 50$ days (Fig. 6), the quota price equilibrium has interior prices for only two species, while the quota price for Species 2 is constrained at the ex-vessel price (even though the TAC is only partly taken up). Neither of the two vessels is earning inframarginal rents, however. At $E = 200$ days (Fig. 7), when the TAC for Species 3 is exhausted, the quota price for Species 3 is now constrained at the ex-vessel price and the other two quota prices are interior. Both vessels continue to earn only resource rents. At 250 days (Fig. 8), when two of the three TACs are exhausted and there is only one (significantly reduced) interior quota price, Vessel A is now earning inframarginal rents.

5.4 Greater Vessel Heterogeneity: Fewer Species than Vessel Types

Figures 9, 10 illustrate results for three vessels and two species (Species 2 and 3) at $E = 50$ and 150 days. At $E = 50$ days (Fig. 9), with neither TAC exhausted, we have interior quota prices for both species while one of the three vessels (Vessel B) is earning inframarginal rent. At $E = 150$ days (Fig. 10), the TAC for Species 3 is exhausted and its quota price is bid up to the ex-vessel price. Now two vessels are earning inframarginal rents, with the quota price for Species 2 reduced in line with the reduced marginal harvest values.

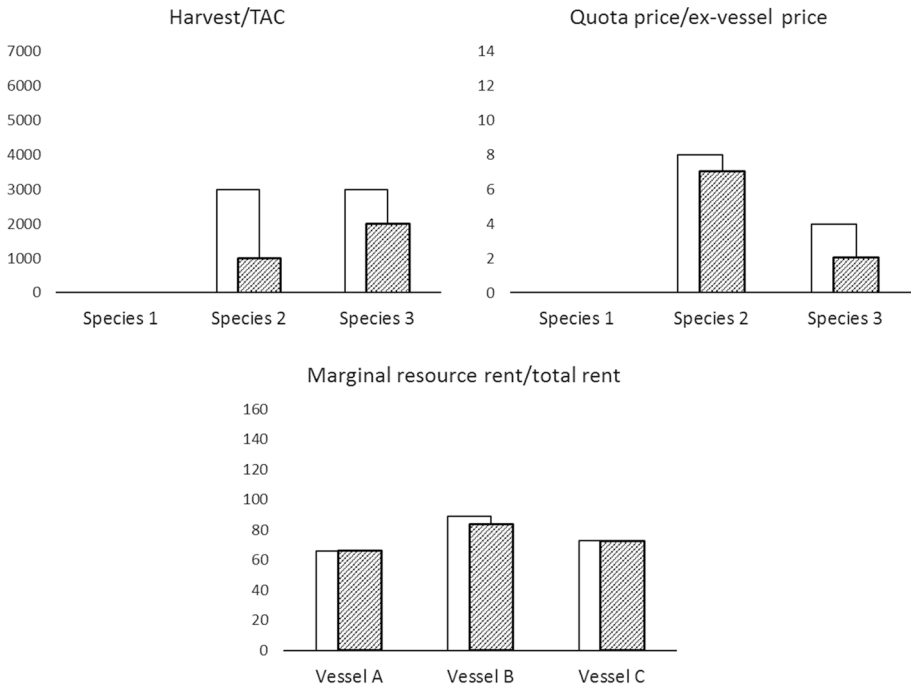


Fig. 9 Two species, three vessels, $E = 50$ days

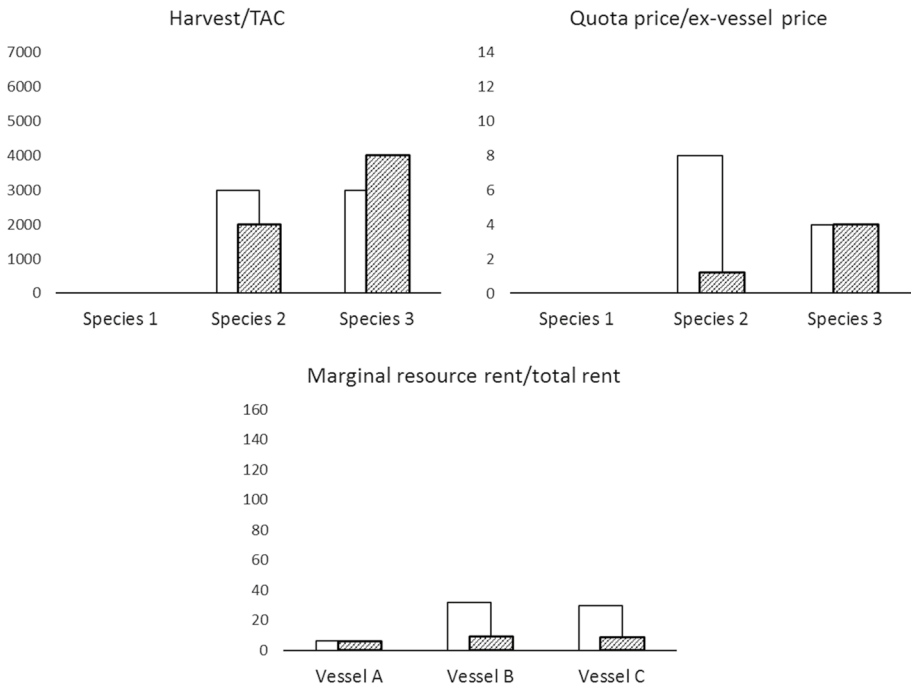


Fig. 10 Two species, three vessels, $E = 100$ days

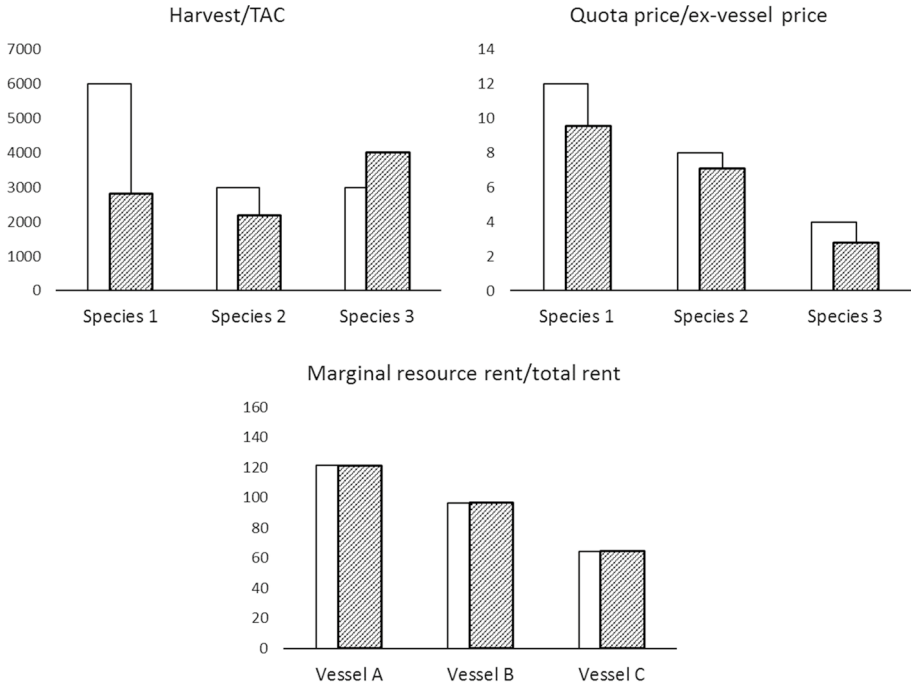


Fig. 11 Deemed values (“true” values), $E = 150$ days

5.5 Price Control: A Deemed Value system

Under a “deemed value” system, vessels are able to land (for sale) fish for which they do not hold quota provided they pay a charge *in lieu*, intended to reflect the market value of quota.¹⁴ In principle, the magnitude of the charge should be such that there is no incentive to pay the charge rather than to lease quota if quota is available. At the same time, the charge should not be set at such a high level that vessels choose to discard fish instead of landing it.

In order to model the impact of a deemed value system on the quota market equilibrium, we modify the objective function in Eq. (1) to¹⁵

$$\max_{e,d,l} \left\{ \sum_j \left[[p_j - r_j] [\beta_{ij} H_i(e_i) - d_{ij}] - \theta d_{ij} - [v_j - r_j] l_{ij} \right] - C_i(e_i) \right\}, \quad (9)$$

where v_j is the deemed value unit charge levied on l_{ij} over-quota landings of species j . In order for any l_{ij} to be positive (implying $d_{ij} = 0$), we simply need to ensure that $v_j - p_j < \theta$ (guaranteed if $p_j > v_j$ and $\theta \geq 0$) so that vessels land, rather than discard, fish for which they do not hold quota. It is then straightforward to show that the quota price ceiling for species j is equal to v_j , provided $v_j < p_j$.

¹⁴ See, for example, Squires et al. (1998), Sanchirico et al. (2006).

¹⁵ Again, the constraints on d and l are not shown in order to avoid clutter.

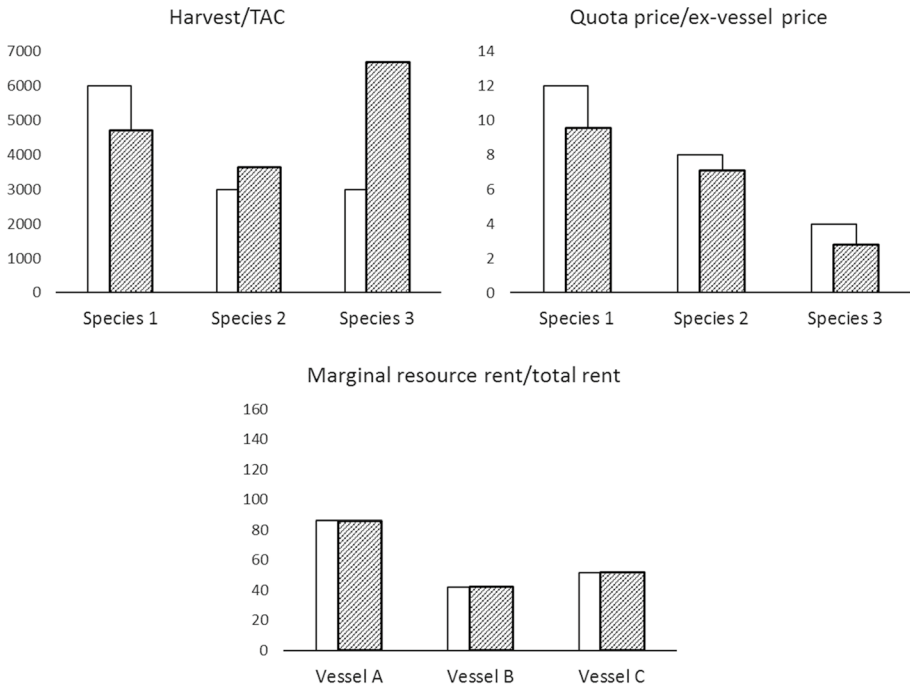


Fig. 12 Deemed values (“true” values), $E = 250$ days

The impact of a deemed value system is illustrated firstly in Figs. 11, 12 for the case where the deemed values *exactly* match the interior quota prices observed for the baseline model at $E = 50$ (Fig. 1). With deemed values applied, at $E = 150$ (Fig. 11) the quota prices are unchanged by the exhaustion of the TAC for Species 3. Compared with the baseline case depicted in Fig. 2, marginal harvest values are increased for all three vessels due to the revenues (net of deemed value payments) from fish which would otherwise have been discarded, but now no vessel is earning any inframarginal rent. The explanation for this stems from the fact that compared with the results shown in Fig. 1, marginal harvest values are only reduced due to the deemed value payments for landing Species 3 without quota. Since here the deemed values exactly match the quota prices in Fig. 1, the reduction in marginal harvest values exactly matches the reduction in marginal resource rent and hence no inframarginal rents emerge. At $E = 250$ (Fig. 12), with the TACs exceeded for Species 2 and 3, the quota prices remain the same but marginal harvest values are reduced further due to the deemed value payments for Species 2 as well as Species 3. By the same reasoning as before, no inframarginal rents are earned by any vessel.

In Figs. 13, 14, 15, the deemed values are set “too low” at 50% of the ex-vessel price. Since the deemed values form quota price ceilings, quota prices remain fixed at these levels at $E = 50$, 150 and 250 days. All vessels earn inframarginal rents as a result, and these are not reduced as TACs are exhausted. In contrast, total rents and resource rents are reduced

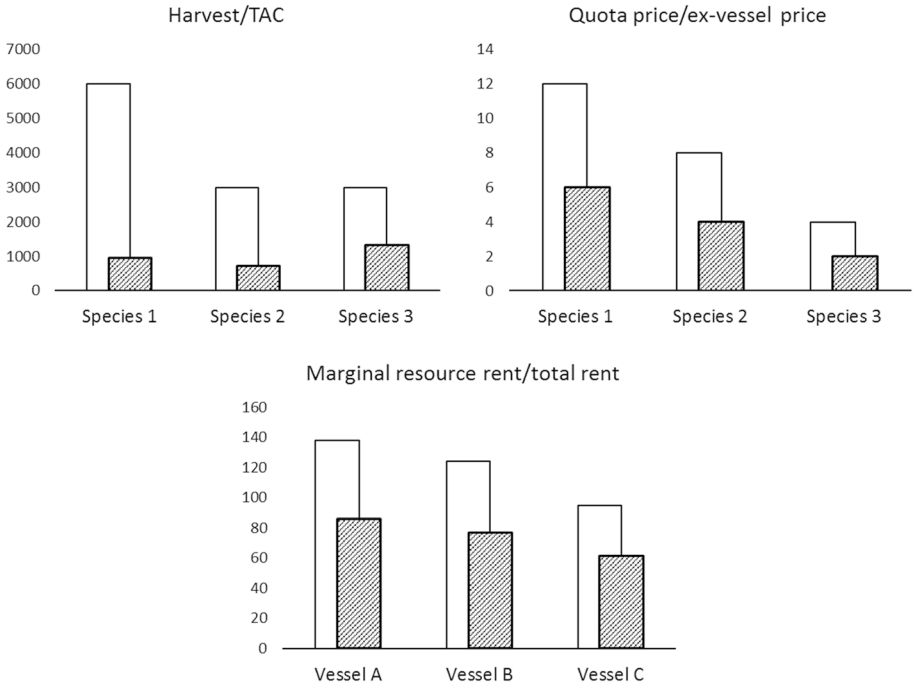


Fig. 13 Deemed values (50% ex-vessel price), $E = 50$ days

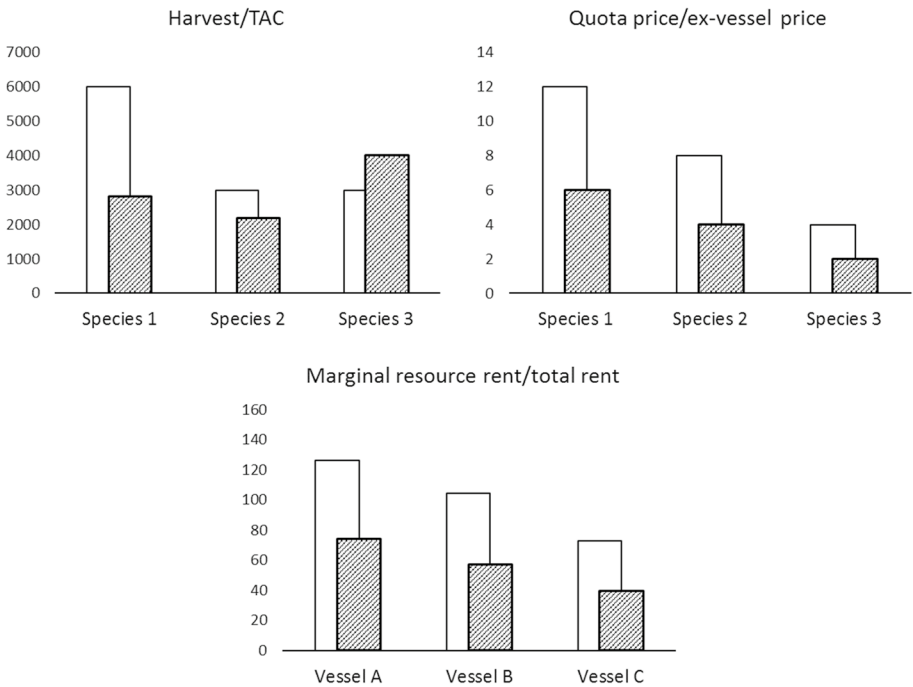


Fig. 14 Deemed values (50% ex-vessel price), $E = 150$ days

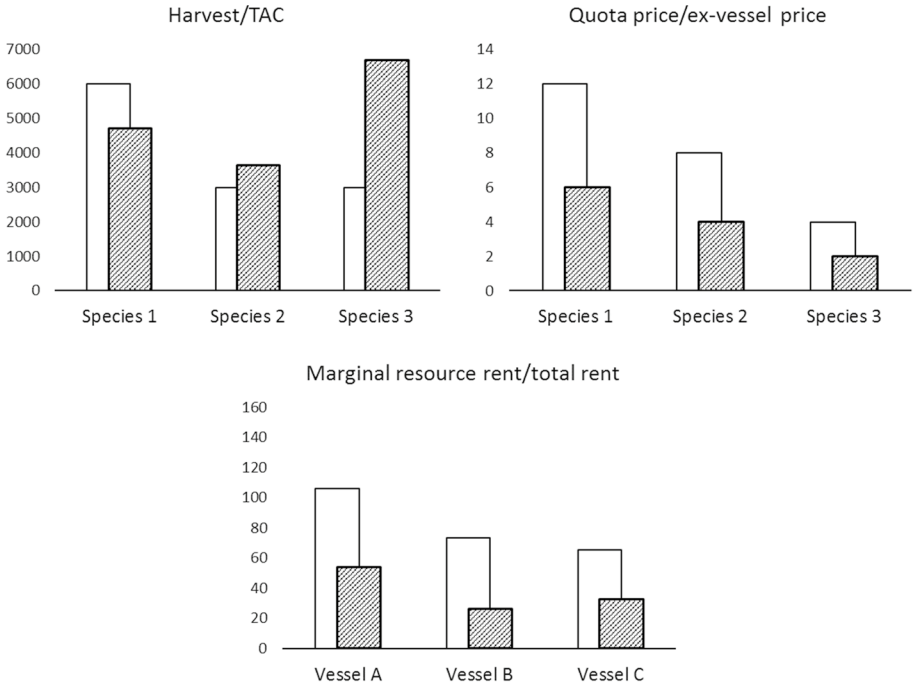


Fig. 15 Deemed values (50% ex-vessel price), $E = 250$ days

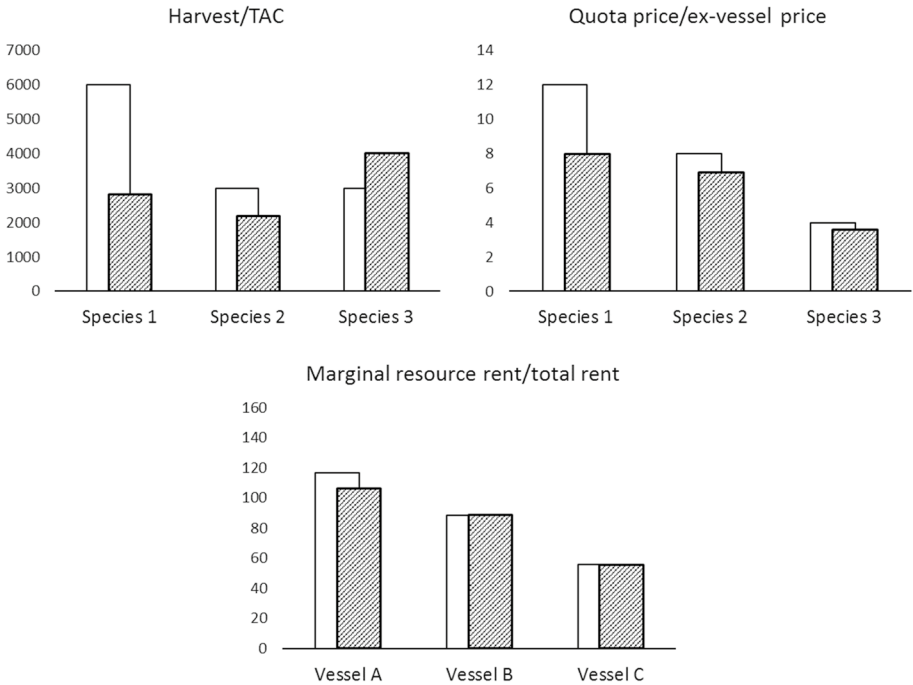


Fig. 16 Deemed values (90% ex-vessel price), $E = 150$ days

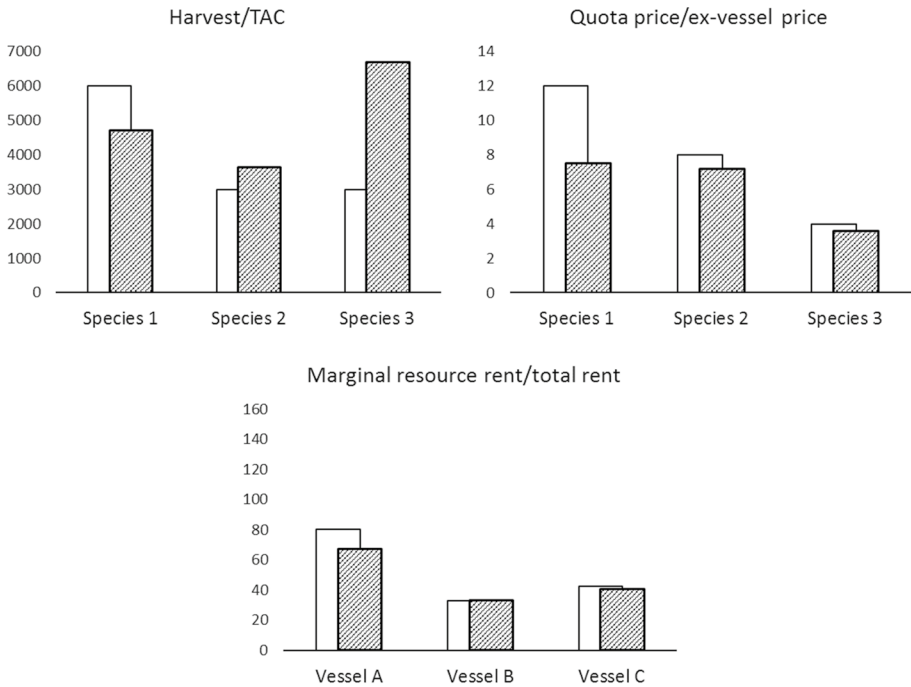


Fig. 17 Deemed values (90% ex-vessel price), $E = 250$ days

as vessels pay deemed value charges on higher levels of over-quota landings.¹⁶ In Figs. 16, 17 we illustrate a scenario in which the deemed values are set “too high” at 90% of the ex-vessel price. This does not affect the outcome at $E = 50$ days, and has little impact at 150 days (Fig. 16) compared with the baseline case (Fig. 2), but at $E = 250$ days (Fig. 17) there is a significant reduction in the inframarginal rents earned by Vessels A and C, due primarily to the higher quota price for Species 1 (still being landed with quota).

6 Conclusions

The results of the simulation model illustrate both the joint determination of quota (lease) prices and the dependence of quota price equilibria upon fleet heterogeneity and the diversity of species in the fishery. A complete set of *interior* quota prices (where, as we might expect *a priori*, quota prices are positive but below the ex-vessel price) is only possible where the number of quota species (M in the model) is matched or exceeded by the number of different vessel types or harvesting technologies (N). If the number of quota species exceeds fleet heterogeneity, then we can expect price corners to emerge: quota prices which are either equal to zero or are at their maximum possible values (which are the ex-vessel

¹⁶ Deemed value charges do not count as resource rent in the model, since they are not payments to quota. Depending on policy, they may, however, accrue to managers on behalf of society, which the value of quota may not.

prices, assuming costless discarding). Here, however, such corner prices may indicate neither excess quota supply nor excess quota demand.¹⁷

Given our assumptions about the quota market (in particular uniform prices) this reflects the problem of finding market-clearing prices in a set of simultaneous markets: essentially a general equilibrium problem. This, in turn, depends upon the production jointness typical of multispecies fisheries (and exemplified by the fixed proportions technology assumed in the model). All quota prices are thus jointly determined: the marginal willingness to pay for quota for one species in the catch always depends on the cost of quota for all the other species in the catch. While, intuitively, it might not appear possible for corner prices to exist in equilibrium in the absence of excess quota demand or supply, this is not inconsistent with the behavioural assumptions underlying the market model. A zero quota price would be a disincentive to place quota on the market. A reduced supply of quota would then bid the quota price up to above zero, but this would necessitate an adjustment to all other quota prices, producing a set of quota prices which is not an equilibrium. A quota price equal to the ex-vessel price, for a species for which the TAC is not exhausted, would cause vessels to be indifferent between landing and discarding fish of that species. All else equal, any increase in discards would reduce the demand for quota and hence lower the quota price; but again, this implies a different set of quota prices which is not an equilibrium.

While corner prices can be observed even in the absence of excess quota demand or supply, discarding due to excess quota demand (chokes) will force quota prices to a corner: the price ceiling. Only if this increases the total number of quota prices at their ceiling in equilibrium do we expect inframarginal rents to emerge. Otherwise, the appearance of inframarginal rents, as market-clearing quota prices fail to capture all the marginal value of harvests as resource rent, only occurs where the number of quota species in the fishery is smaller than the number of different vessel technologies. This is not unexpected -- we would normally associate inframarginal rents with fleet heterogeneity -- but note the significance here of the relative number of quota species. Inframarginal rents in the model emerge where, in essence, there are simply too few quota prices to fully solve the general equilibrium problem. The exhaustion of one or more species TACs while vessels in the fishery are still active, and the bidding up of the corresponding quota prices to their price ceilings, has the same effect in reducing the number of quota prices that can adjust in equilibrium. Thus we have the possibility, as we have seen, that the exhaustion of quotas for choke species can result in some vessels earning inframarginal rents or increasing the inframarginal rents that they are already earning. By contrast, where the number of quota species is large compared to the number of different vessel types in the fishery, no vessels will be earning inframarginal rents and the existence of choke species may not change this. The rent effects of chokes and discarding in the fishery therefore depend upon both fleet heterogeneity and species diversity. In all cases the quota price increase for the choke species results in a reduction in the quota price for all other species; the emergence of inframarginal rents is more likely where there are relatively few species and a relatively diverse fleet.

The modelling of a “deemed value” policy, intended to discourage quota-induced discarding and unrecorded (“black”) landings, shows the impact of the level at which the landing charge is set upon the quota price equilibrium. The immediate effect is that deemed

¹⁷ In Fig. 6 we saw an example of quota price at its ceiling value in the absence of excess demand. In other runs of the simulation model with different parameter values (not reported) zero quota prices were observed in equilibrium.

values form quota price ceilings (provided they are not set above the ex-vessel price). If the deemed value charge levels are lower than quota prices would otherwise be (set, perhaps, as a percentage of ex-vessel prices) quota prices may be sufficiently depressed to allow *all* vessels to earn inframarginal rents and these quota prices may then be unresponsive to chokes and discarding. Charges set at a high level relative to ex-vessel prices, on the other hand, have only marginal effects on quota price equilibria and inframarginal rents in the model. From a policy perspective, the level of the deemed value charge is not critical for discouraging discards: if there is excess demand the quota price will never exceed the deemed value charge so that vessels will always have an incentive to land rather than discard over-quota fish (provided the charge is less than the ex-vessel price). Charges set at a very low level will, however, reduce the extent to which resource rents are captured by quota prices, leaving a greater proportion of total fishery rents with firms. Note that a deemed value policy, on its own, cannot prevent over-quota *catches*.

The principal simplifying assumptions of the model, notably those of constant marginal harvests/costs and fixed (output) proportions, could be seen to restrict the general applicability of the model's findings. The emergence of inframarginal rents in the model, for example, depends upon the inability of firms to make adjustments at the margins, so that marginal rents are not dissipated or captured by quota prices. While this may be an unrealistic assumption, in reality the ability of firms to make marginal adjustments to harvest rates and catch compositions in the short run is generally rather limited, so that arguably here we are simply looking at the extreme case. Note, however, that the problem of finding a set of interior quota prices in equilibrium actually increases as the heterogeneity of firms' marginal harvest rates and costs reduces.

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