OPTIMAL TIMING OF HARVEST OF TWO FISH SPECIES WITH MULTIPLE GEARTYPES

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Abstract

In this paper a bioeconomic model is developed for a commercial fishery with multiple gear types in the case of two independent fish species. Where most bioeconomic fishery models focus on either multiple gear types or multiple species (mostly predator-prey relationships) this model combines both aspects for four gear types and two independent fish species. The objective of the paper is to find the optimal allocation of four gear types per period to obtain the highest net benefits while harvesting at a sustainable rate. This is done by developing a discrete time LP-model for a sole owner fishery, given a Total Allowable Catch for the two fish species. The model is applied to the Chippewas of Nawash First Nation commercial fishery in Lake Huron and Georgian Bay (Ontario, Canada). Sensitivity analyses are performed on price changes as well as on the average harvest levels per boat.

keywords: efficient renewable resource management, sustainable fishery, multiple species model, multiple gear types, LP-model

1. Introduction

Fishery management problems often include combinations of economic problems which economic models have dealt with one at a time. Since Gordon (1954) developed the first bioeconomic fishery model, bioeconomic models have generally focused on one specific aspect of a fishery. The models are mostly simplified single-species models applied to one specific fishery. Finding optimal fishery management strategies, in particular open access versus regulated fisheries, has received ample attention in fishery models (e.g. Eggert, 1998; Bjørndal, 1988; Clark ,1980). Milliman *et al*. (1992) and Cook and McGaw (1996) developed bioeconomic models for fish stocks harvested by two or more different user groups or fleets. Recent developments in bioeconomic analysis and fisheries management have shown the need to expand the analysis to multispecies fisheries and management (Eggert, 1998 and Clark, 1990). In empirical studies, several models are developed for multispecies fisheries. Most of the multispecies modelling is concerned with interdependent species systems (e.g. Hannesson, 1983 and Eggert, 1998). Polovina (1989) has developed a model that can be used either for multispecies or multiarea applications. Only few bioeconomic models combine several aspects in one model (e.g. Aguero and Gonzalez, 1996). Literature outlining fishery models with multiple geartypes within one fleet and applications have not been found. Some literature exists on multiple geartype fishery problems (e.g. Hannesson, 1993; FAO, 1992).

The problem analysed in this paper is an example of a real world fishery problem, namely the commercial fishery of the Chippewas of Nawash First Nations in the Bruce Peninsula in Ontario, Canada. This fishery is characterised by catching two fish species given a Total Allowable Catch (TAC) and limited gear. The problem can be defined as follows: how to allocate the available gear over the year in a fishery for multiple species to obtain the highest net benefits, while harvesting at a sustainable rate.

The problem outlined above is of an economic nature. If the problem is not acknowledged (i.e. the property rights are not defined) and each fisherman catches as much fish as he wants to, an economic sub-optimal situation exists and there will be a possibility of overharvesting (see Bulte, 1997; Clark, 1990; Conrad and Clark, 1987; Bjørndal and Conrad,1987; Dasgupta, 1982). Overfishing can be defined as both biological over fishing, i.e. effort exceeds the so-called Maximum Sustained Yield Effort, and economic over fishing, which occurs when marginal costs exceed marginal revenue (Bulte, 1997). Perman *et al.* (1996) explain that in a bioeconomic open access equilibrium, which implies perfect competition, the total (and not the marginal) costs equal the total revenues at the same point where the resource stock is constant through time. Heijman (1991) shows that perfect competition in the case of a renewable resource, like a fishery, is not an efficient market form. Bulte (1997) states that the fundamental problem of open access fishery is that fishermen have no incentive to take into account the shadow price of the resource. To avoid both types of over fishing the property rights of the fishery have to be not only clearly defined, but also enforceable (Perman *et al*., 1996). Perman *et al.*(1996) and Conrad and Clark (1987) demonstrate that regulation of a fishery might be economically desirable. In Hartwick and Olewiler (1986) and Conrad (1995) the following regulation alternatives can be found: (1) closed seasons which limit harvesting during spawning periods, (2) gear restrictions, (3) limited entry to the fishing grounds, (4) catch quotas, that might or might not be transferable, (5) taxes on catch or input that are equal the shadow prices and (6) establishing ownership by forming co-operatives. However, discussing the characteristics of the different types of resource management is beyond the scope of this study. In this study, a given level of the TAC for the two fish species is used as an exogenous factor to prevent for over fishing. Therefore, the problem dealt with is not to find a sustainable level for the TAC, but rather to determine how to spread the TAC over the year, given the available gear and the price variations.

In this study a model is developed to determine which boats should catch how much of each species, by season, to maximise profits without depleting the fish stocks. The fishery analysed in this paper is assumed to be managed by a sole owner. Although the fish species regarded in this study are neither ecologically or technically interrelated, one could speak of a multiple species model in a way that the fish stocks in this study are managed by the same sole owner, who has to choose how much of each two species is to be caught. The total net benefits of the fishery as a whole are regarded. In most fishery models the profits to individual fishermen are maximised. The nature of the fishery regarded here is such that the benefits are distributed within the group of fishermen.

2. Background of the economic problem

In this section the historical context, the biological characteristics and the production technologies, as well as the price and cost structure of the Nawash fishery are presented. These factors are all of importance since they affect the way the bioeconomic model is defined.

Long before the Europeans came to North America, First Nations fished in Lake Huron and Georgia Bay and traded fish with other First Nations for goods. In economic terms this was clearly a commercial fishery. The management of native fishery differs from most western fisheries in a way that the band as a whole is both the manager and the beneficiary of the fishery. Whereas in western fisheries the government makes the laws and therefore affects the behaviour of the individual fishermen, but is not the direct beneficiary. In 1836 a treaty was signed between the Queen of England and the Chippewas of Nawash First Nations, that allowed the latter to retain ownership of a seven mile zone of water around the Bruce Peninsula (Ontario, Canada) - i.e. they became the owners of the resource. However, when Canada became one country, constitutional laws were passed that assigned the management of the resources to the provincial governments. The Ontario Ministry of Natural Resources (OMNR) considers itself as the owner of all fisheries in Ontario and has set individual quotas for the main species in Lake Huron and Georgian Bay for both native and non-native fisherman. In 1993 judge Fairgrieve declared that the Treaty of 1836 must be recognised by the province of Ontario and that the Chippewas of Nawash have a treaty right to the commercial fishery to provide for their livelihood. From 1996 the OMNR and the Chippewas of Nawash have a conflict of interest about the ownership and management of the fishery. Although issues have not yet been solved between the two parties, in this study the Chippewas of Nawash First Nations will be considered the sole owner of the commercial fishery in a view that the band as a whole makes decisions for the total commercial fishery.

In this paper we take into account the two main fish species of the Bruce Peninsula commercial fishery, namely Whitefish (*Coregonus clupeaformis*) and Chub, or Bloater, (*C. Hoyi*). Some differences exist between the geographic abundance of the fish species. Whitefish can be caught both near shore and offshore, while chub can only be caught in the deeper rough waters of Lake Huron and Georgian Bay. Different boat and net types are used to catch the different species. This will be discussed later in more detail. No interactions, e.g. a predator-prey relationship, exist between whitefish and chub and therefore the definition of multiple species we use in this paper is restricted to the catch of more than one fish species in the same fishery.

Seasonality occurs in the abundance of the fish. There are two peaks for the nearshore catch of whitefish in June-July and in November-December; offshore these peaks are followed by prolonged peaks. The peak for chub is in December-January. The catch rates for chub are not as variable as they are for whitefish, since there is less seasonal migration. The harvest in pounds of chub is less than the harvest of whitefish (Crawford, 1996). The data available for this study are harvest data for the years 1995 to 1998.

Two different boat types are used to catch the fish, namely punts and tugs. Chub lives in the deeper offshore waters and can therefore only be caught by tugs, since these boats are able to navigate in the rougher offshore waters. However, the tugs can go near shore as well and can therefore catch both whitefish and chub. The tugs have a mechanical winch, which assists in taking in the nets. The small punts are lighter and the nets have to be pulled in manually. They can only be used near shore for the catch of whitefish. The nets that have to be used for the catch of whitefish and chub differ and are therefore not exchangeable. However, the type is the same for both species, namely gillnets. Both this and the fact that tugs operate with a four or five men crew, while the punts only need two men, results in different cost structures for both fisheries, which will be discussed later.

Combining the different boat types and net types results in a number of different gear types. As explained above, the punt owners are restricted to whitefish harvesting. In this paper, the combination of whitefish nets and punts will be defined as gear type A. For tug owners, three different gear types can be distinguished, depending on the nets the boat owner possesses. Gear type B includes tug owners who only have chub nets. Tug owners who possess both whitefish and chub nets can choose whether they want to catch whitefish or chub. We define gear type D for tug owners who choose to catch chub and gear type E for those catching whitefish. Note that gear type B and D are both tugs catching chub. In Table 2.1 the gear types are clearly represented. Note that gear type C, which would be punts catching chub, does not exist. The reason for this is that chub is a fish that lives offshore, while punts are restricted to near shore waters because of their smaller size and are therefore not suitable for the catch of chub.

Table 2.1 Characteristics of the gear types used in the Bruce Peninsula Fishery.

Gear type	Net type	Boat type	Choice
A	Whitefish	Punt	No
B	Chub	Tug	No
D	Chub	Tug	Yes
E	Whitefish	Tug	Yes

The difference for the catch of the two species by boat size and net type results in different cost structures for the fisheries. Punts are operated by a two men crew and they have less operation costs than the tugs. The purchase costs of punts are also less. However, some restraints exist for the use of punts within the fishery. The nets have to be pulled in manually and the amount of net is therefore limited to 100-150 yards[1]. Although tugs do not have the restrictions that result from their size like punts do, their bigger size implies substantially higher costs. For example, fuel combustion is much higher, since tugs weigh a lot more and have to travel a longer distance. The costs of repairs and maintenance are higher as well. Hence, "the minimum amount of fish required to just cover the operating costs of the tugs is significantly more than the quantity of fish required to cover the operating costs of the small boats" (Rollins and Ivy, 1998, p. 9). In this study, only the costs directly linked to the fishing effort are included. Comprehension of costs like fishery assessment costs and costs of fish plant operations are beyond the scope of this study.

The prices of fish are an important factor in the decision-making process of the fishery. The prices of the different fish species may vary over the year "due to supply effects caused by seasonal migrations of the stock and demand-side market conditions" (Rollins and Ivy, 1998, p 31). Due to the spawning run in November, the prices of whitefish are low in this period, while in February the prices are higher. Although the prices do have an influence on the decisions made regarding the fishery, the

Bruce Peninsula fishery is too small to be able to influence the prices. The Band is considered a price taker. Because of the fine quality of the whitefish caught on the Georgian Bay side of the Bruce Peninsula, the prices for whitefish are most of the time higher than the average prices in the same period (Crawford, 1998).

As mentioned before, the fishery described in this study is assumed to be managed by a sole owner. This indicates that the Band Council, the management body of the Nawash, represent the interest of all the fishermen. Assuming this implies that both in the short term and long term no market inefficiencies occur. This assumption may be somewhat idealised, but any potential deviations from this ideal are beyond the scope of this study. However, in reality, the conditions exist for self-management by the group of the fishery as a "common" property resource. As follows from the above, the net earnings from the fishery do not go the individual fishermen, but to the band as a whole. They are distributed within the group of fishermen. The distributional aspect is not taken into account in this study.

The fishing grounds surrounding the Bruce-Peninsula are divided in several management zones. For each of these zones a TAC is set. In this study however, these management zones are not taken into account. The analysis is performed for the Bruce Peninsula fishery as a whole.

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[1] 1 yard = 0.9144 meter

3. The model

In this section a bioeconomic model is developed. Population dynamics are not explicitly included in the model, but are assumed to be reflected in the harvest levels per boat and given levels of the TAC's for the different fish species. The purpose of the fishery is to obtain the highest net benefits without depleting the fish stock. This is done by allocating both the available vessels and the TAC (Total Allowable Catch) over the periods. The time horizon in the model is one year that is divided in six two-month periods. January and February form the first period, March and April the second and so on. The model is developed for a sole owner fishery, which supplies only a small part of the total market for the fish species. Therefore, the decision-maker is considered a price taker. The demand-side of the fishery is therefore not included in this study. As a consequence, the prices of fish and the seasonal differences in prices are exogenous factors that vary by period.

Most fishery models use logistic growth functions in which harvest levels, as well as natural growth and mortality rates are included, to derive the optimal (sustainable) stock and harvest levels (see e.g. Conrad and Clark, 1987; Bjørndal, 1988; Hannesson, 1983 and Wilen, 1985). In the model developed in this study, the maximum sustainable stock level is reflected in a Total Allowable Catch (TAC). Rollins and Ivy (1998, p38) say the following about the level of a TAC: "The purpose of a TAC is to ensure a constant yield of fishing effort is maintained annually. To this end, if the TAC is selected correctly, then the stock of fish is such that a steady state level of harvest prevails. This suggests a constant return to fishing effort employed. However, if a TAC is set too high, then the growth rate of the stock diminishes over time to the extend that there are less fish available each year.[2] Under these circumstances cost of fishing effort would rise. If the TAC were set too low, then the growth rate of the fish stock is actually increasing to the extend that per unit costs of fishing effort would be decreasing with the number of fish caught."

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[2] Obviously, this only holds if the TAC is fully used.

As mentioned before, the main objective of this sole owner fishery is to maximise the total net benefits for a year while harvesting at a sustainable level. The purpose is therefore to find the optimal allocation of the available gear types given a certain TAC. The total net benefits function for the fishery as a whole for one year is given by

$$TNB = \sum_{p=1}^{N} \frac{NB_p}{(1+r)^p} \qquad (p = 1, \dots, N) \qquad (1)$$

where TNB denotes the total discounted net benefits over the year and NB_p are the net benefits obtained in period p. The time preference rate r is assumed to be constant over time. The net benefits per period (NB_p) are defined by the gross benefits of catching fish minus the total costs per period summed over the two fish species. This is expressed in Eq. (2):

$$NB_p = \sum_{s=1}^{M} (P_{sp} * H_{sp}) - TC_p \, . \qquad (s = 1, \dots, M) \qquad (2)$$

It is shown that the gross benefits are determined by the amount of fish of species s harvested in period p, H_{sp}, multiplied by the price of fish species s in period p, P_{sp}. In fact, H_{sp} reflects the amount of fish harvested in period p, as a part of the Total Allowable Catch (TAC) for a whole year. The total costs of the fishery in period p, TC_p consist of fixed and variable costs for the fishery. The variable costs depend on the number of boats per gear type j harvesting fish in period p, N_{jp}, multiplied by the variable costs per period of putting one boat into service, VC_{jp}. The fixed costs FC_{jp} only depend on the available number of boats per gear type j (N_{jp}^{MAX}) and do not vary between periods. The total costs of the fishery can be expressed as follows:

$$TC_p = \left[\sum_{j=1}^{K} \left(VC_{jp} * N_{jp} + FC_{jp} * N_{jp}^{MAX} \right) \right] \qquad (j = 1, \dots, K) \qquad (3)$$

The costs per fish species are depending on the gear type that is used. Recall that a gear type is a certain combination of boat and nets and that one fish species can be caught by more than one gear type.

The relationship between the fish stock and harvest is reflected in given levels of harvest per gear type for the different periods. In reality, given levels of harvest per gear type do not exist. Harvest is then determined by the changes in fish stock, which can be described in a biological growth function. The assumption of given harvest levels in this model creates the possibility of obtaining an optimal solution for the problem.

To achieve the highest net benefits, the number of boats of each gear type to be put into service (N_{jp}) must be determined. Also, the TAC's for the two species must be allocated over the periods. From the above, two constraints follow. First, certain levels of TAC for the two fish species are provided. Therefore, the owner of the fishery must decide how much fish of each species can be caught in each period to not harvest more than the TAC for one year. This constraint can be described with the function

$$\sum_{p=1}^{P} H_{sp} \leq TAC_s . \qquad (4)$$

Equation (4) shows that sum of the amount of fish species caught in period p (H_{sp}) can not be greater that the TAC for the species in question, TAC_s. Since there is only a limited number of boats of each geartype available, additional constraints of the following form have to be added to the model:

$$N_{jp} \leq N_{jp}^{MAX} \qquad (5)$$

where N_{jp}^{MAX} denotes the maximum available number of boats of gear type j in period p.

4. Variants of the model and data

The model developed in the previous section has been applied to the commercial fishery of the Chippewas of Nawash First Nations in the waters around the Bruce Peninsula in Ontario, Canada. The data used as input in the model are harvest data from the Nawash Fishery Assessment Program for the years of 1995 through 1998. The cost and price data we used are derived from the data on the cost structure of the Nawash fishery and the price lists as described in Rollins and Ivy (1998). Two fish species are considered in the application, namely whitefish and chub. The fish are caught with four different gear types as described in section 2.

First, the basic model is described. After that the results of the basic model are analysed and sensitivity analyses are performed on the prices and harvest levels of whitefish and chub[3]. Table 4.1 gives an overview of the different variants of the model.

Table 4.1 Description of the analysed variants.

Variant	Description
Variant 1	Basic model
Variant 2	Lower prices
Variant 3	Higher prices
Variant 4	Lower harvest levels
Variant 5	Higher harvest levels

In the basic model, from now on referred to as Variant 1, the time preference rate for one year is set at 6%. This rate approximates the bank rates for the years of 1995 through 1998 as provided by IMF (1999). The time preference rate of 6% for one year is divided over six two-month periods, which results in a time preference rate of 1% per period. The prices used in Variant 1 are based on the data

[3] Sensitivity analysis is not performed on the time preference rate and the TAC. Since the optimization period is one year (divided into 6 periods) and the time preference rate is 1% per period (corresponding to 6% per year) discounting has only a minor effect on the net benefits, the timing of the harvest and the allocation of the geartypes over the periods. Further, the TAC appears not to be a binding constraint in all the variants.

Rollins and Ivy (1998) provided in their report[4]. The prices are based on data for the period August 1, 1996 to July 10, 1997. In this study, the monthly prices are averaged to derive prices for each two-month period. In the basic model average prices are used. The harvest levels per boat for the different gear types are determined by taking the average per period of the harvest data from the Assessment Program for the years of 1995 through 1998. Table 4.2 summarises the assumptions on prices and harvest levels for Variant 1.

Table 4.2 Assumptions on prices and harvest levels in Variant 1.

Period	Price per lb. whitefish (CAD $)	Price per lb. of chub (CAD $)	Harvest level A (lbs.)	Harvest level B (lbs.)	Harvest Level D (lbs.)	Harvest level E (lbs.)
1.January-February	1.36	1.50	498	150	150	700
2. March-April	1.20	1.50	511	100	100	1,200
3. May June	1.49	1.50	1,498	900	900	2,400
4. July-August	2.31	1.50	1,929	1,200	1,200	3,000
5. September-October	1.60	1.50	4,328	3,000	3,000	6,000
6. November-December	1.08	1.50	10,504	6,500	6,500	16,000

The Nawash are considered price takers in this study. The prices in the model are based on price data for one year. One could expect the model to be sensitive to changes in prices. The Variants 2 and 3 describe two extreme situations with respectively lower and higher prices for both whitefish and chub. For the lower prices in Variant 2 the lowest price of the two monthly prices per period is taken from the available data. And analogue to this the high prices in Variant 3 are the highest monthly prices per period.

[4] Rollins and Ivy (1998) revised weekly prices for different market class sizes into a list with average prices per month for whitefish and annual chub prices per pound for 5 size classes. No seasonal variation occurs in the abundance of chub. As a consequence, prices of chub are stable through the year.

In all variants the available gear consists of twelve punts and six tugs, of which 4 have both whitefish and chub nets. The latter implies that the sum of the boats of gear type D and E put into service cannot be greater than 4.

Variants 4 and 5 analyses situations in which the harvest levels per boat per period are changed. In Variant 4 the harvest level for the four gear types considered are lowered whereas in Variant 5 the harvest levels are increased. Both high and low levels are determined by taking respectively the highest and lowest levels of the harvest profile for four years, as can be derived from the Assessment data.

The costs of the fishery can be divided in variable and fixed costs for both punts and tugs. Variable costs only occur when a boat is put into service, while fixed costs also exists when a boat is not used in a certain period. The variable costs for punts, gear type A, are CAD$ 2277 per period. The variable costs consist of fuel, grease and oil, detergents, tables, parts and maintenance, repairs, etc. The fixed costs for one punt are CAD$ 1377, which include costs of the boat, nets, net and fish boxes and gear. Since tugs are bigger boats and have to navigate in rougher offshore waters, both the fixed and the variable costs for tugs are substantially higher than for punts. The variable costs are CAD$ 3491 and the fixed costs are CAD$ 5352 per tug per period. These costs are based on the data for the total Bruce Peninsula fishery, as gathered by Rollins and Ivy (1998).

5. Results

In Table 5.1 the results of Variant l are shown. The variables determined by the model are the number of boats of the four gear types that are put into service in the various periods and the discounted net benefits per period. The results for Variant 1 show that gear type A is only used in periods four, five and six. In these periods the gross benefits are high enough to cover at least the variable costs. From the data it can be computed that the gross benefits per vessel of gear type A should be at least CAD$ 3,654 to cover the variable costs in one period. For tugs this would be CAD$ 8,843. For period one it implies that given the prices per pound of whitefish, the harvest per punt per period has to be CAD$ 3,654/ CAD$ 1,365 = 2,677 lbs. to break even the variable costs. The actual harvest level per vessel is only 498 lbs. in this period. This explains why gear type is not used in periods one to three. The negative shadow price for gear type A in period one supports this.

Table 5.1 Results of Variant 1 (prices are in CAD$, the harvest levels per vessel are in pounds)

A. Results: number of boats put into service per gear type and their shadow prices.

Period	Number of A	Shadow Price	Number of B	Shadow Price	Number of D	Shadow Price	Number of E	Shadow price
Available boats	12		2		4		4	
1.January-February	0	-1598	2	615	0	0	4	2292
2. March-April	0	-1647	0	0	0	0	4	2909
3. May June	0	-36	2	3422	0	0	4	11592
4. July-August	12	2115	2	11517	0	0	4	6733
5. September-October	12	4466	2	4758	0	0	4	32464
6. November-December	12	8677	0	0	0	0	4	25686
Total shadow prices		11977		20312		0		81676

B. Results: total harvest and shadow prices, number of boats used and discounted benefits per period.

Period	Harvest of whitefish (lbs.)	Shadow Price	Harvest of chub (lbs.)	Shadow Price	Total tugs used	Total punts used	Discounted Net benefits (CAD $)
1.January-February	18,748	0	5,474	0	6	0	-35,780
2. March-April	21,432	0	0	-0.966	4	0	-36,520
3. May June	50,320	0	9,310	0	6	0	19,224
4. July-August	61,752	0	20,476	0	6	12	74,206
5. September-October	157,500	0	11,256	0	6	12	165,260
6. November-December	238,440	0	0	-0.281	4	12	160,600
Totals per year	548,190		46,516		6	12	346,990
TAC per year	1,266,638		1,323,166				

Fixed costs exist for all available boats in all gear types. The total fixed costs of the fishery per period are calculated as 12 * CAD$ 1,377 + 6 * CAD$ 5,352 = CAD$ 48,636. This means that when no boat is put into service, the negative net benefits for one period are -/- CAD$ 48,636. Putting a boat into service results in additional variable costs. The choice whether to use a boat depends on the possibility to cover at least the variable costs.

The same reasoning for the use of gear type A holds for the periods 2 and 3. In the periods four, five and six the gross benefits exceed the total costs and all available vessels are put into service. To obtain positive net benefits for the whole year, the benefits from the last three periods do not only have to cover (at least a part of) the overall costs made by boats of gear type A for these periods, but also the fixed costs for the periods one to three.

The gear types B, D and E are all tugs and have the same cost profile, but the fish species harvested are not the same. The choice of a gear type therefore depends on the prices of the fish species and harvest per boat. In period one, the two vessels of gear type B are used. Recall that this is the maximum available number of boats for this gear type. The shadow price indicates that having an additional tug of gear type B into use (that is not available in the fishery at the moment) would increase the net benefits with CAD$ 615.[5] Since the gear types B and D are both tugs harvesting chub, one could expect the use of additional boats of gear type D. This is not what happens, though. The gear types D and E are defined as tugs with both whitefish and chub nets that therefore have a choice to catch either species. In the results can be seen that in all periods is chosen to put into service all four boats available for the gear types D and E to harvest whitefish (i.e. gear type E). Although the price per pound of whitefish in that period is lower than the price of chub, the higher harvest per boat for whitefish explains the choice for gear type E. Remarkable is that in the periods two and six, no tugs of gear type B and D are used. This can be explained with the same reasoning as used before for the periods one, two and three for gear type A. The negative discounted net benefits in the first two periods are offset by the profits from the last four periods. The total discounted net benefits for Variant 1 equal CAD $346,992.[6]

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[5] However, this shadow price overestimates the increase in net benefits since the fixed costs of a extra boat are not taken into account.

[6] The results of all the variants should be compared with average existing net benefits of about CAD $300.000 per year.

Sensitivity analyses are performed on changes in the prices of the two fish species (Variant 2 and 3) and the harvest levels per boat (Variant 4 and 5). Table 5.2 and 5.3 respectively show the number of boats put into service and the net benefits per period of the different variants.[7]

Table 5.2 Number of boats put into service in the different variants.

Gear type	Period	Variant 1	Variant2	Variant 3	Variant 4	Variant 5
A	1	0	0	0	0	0
	2	0	0	0	0	0
	3	0	0	0	0	12
	4	12	0	12	12	12
	5	12	12	12	12	12
	6	12	12	12	12	12
B	1	2	0	2	0	2
	2	0	0	0	0	2
	3	2	2	2	0	2
	4	2	2	2	0	2
	5	2	2	2	0	2
	6	0	0	2	0	2
D	1	0	0	0	0	0
	2	0	0	0	0	0
	3	0	0	0	0	0
	4	0	0	4	0	4
	5	0	0	0	0	0
	6	0	0	0	0	0
E	1	4	4	4	4	4
	2	4	4	4	4	4
	3	4	4	4	4	4
	4	4	4	0	4	0
	5	4	4	4	4	4
	6	4	4	4	4	4

The results indicate that price changes do have an influence on the number of boats used. In the case of a price decrease, in Variant 2, the number of boats of gear type A used in the fourth period falls to zero as opposed to twelve boats in the basic model. In this period it is not possible for a punt owner to break even the variable costs. The low prices have a similar effect on the use of gear type B in period one. Due to the fact that in Variant 2 compared to Variant 1, twelve punts less are used in period four, the harvest of whitefish in that period decreases. Both this and the fact that the overall prices of fish are lower, cause a fall in the discounted net benefits per period. As a consequence, the total net benefits in the case of lower prices fall to CAD$ 206,904. In the case of higher prices in Variant 3 the only change in the allocation of the gear types is that in period four, the tug owners with both

[7] Detailed results of the various models are given in Appendix I.

whitefish nets and chub nets decide to catch chub (gear type D) rather than whitefish (gear type E). This can be explained by the significantly higher prices for whitefish as opposed to chub prices. As a result of the higher prices, the net benefits are CAD$ 400,753 which is remarkably higher than in Variant 1.

Table 5.3 Discounted Net Benefits per period for the different variants (in CAD$).

Period	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
1	-35,780	-30,350	-10,940	-44,580	-22,910
2	-36,520	-23,150	-17,210	-47,250	-14,420
3	19,224	-11,120	18,991	6,635	96,794
4	74,206	-6,805	64,011	-4,771	181,460
5	165,260	109,800	142,020	58,116	290,420
6	160,600	168,540	203,880	122,150	287,400
Total	346,990	206,915	400,752	90,300	818,744

In the Variants 4 and 5 the harvest levels per boat, which are exogenous variables in the model, have changed to respectively higher and lower levels of harvest. In Variant 4 the lower harvest levels result in no chub caught in all periods. The harvest levels of chub (gear type B and D) are so low, that it is not beneficial for the owners to go out and fish for chub. Putting an additional tug of these gear types into service would in all periods lower the net benefits. The negative shadow prices for tugs support this conclusion. As a result, the four tugs with a choice are fully used as gear type E. The benefits of the fishery in this Variant have to come from whitefish harvest only, while the fixed costs remain for all gear types. Therefore the total discounted net benefits are lower than in Variant 1 at a level of CAD$ 90,297.

In Variant 5, where the harvest per vessel is higher than in Variant 1, the total harvest of both whitefish and chub are considerably higher. As compared to Variant 1 additional boats are only put into service in periods when at least the variable costs are covered.

On the basis of the results of the various models it is very well possible to advise the manager of the fishery described here, what gear type would have to be bought in case one would invest in an additional boat. The extend to which a gear type is a constraint in the model can be derived from the level of the shadow prices. From Table 5.1 can be seen that gear type E is used in almost all periods in all model variations. In Table 4.3 for model 1 and in Appendix 1 for the other models, the number of gear type E and the accompanying shadow prices are shown. When shadow prices for the different gear types are summed over the periods, one can conclude that the annual shadow prices of gear type E are highest in all variants. Based on this it can be concluded that investing in an additional boat of gear type E, which is a tug harvesting whitefish, would be most profitable.

5. Conclusions and recommendations

The purpose of this study was to find the optimal allocation of the available gear, differentiated by gear type and period, to obtain the highest net benefits while harvesting at a sustainable rate. In this study, a discrete-time linear fishery model was developed. The model was applied to the Bruce Peninsula fishery. In view of the average net benefits of CAD$ 300.000 per year it can also be concluded that the fishing behaviour under consideration is fairly efficient.

The model results indicate that the TAC's for both fish species is not binding. Even though the TAC's are not fully used, not all boats are utilised in each period. This points out that in this model besides the expected ecological reasons also economical grounds exist to not fully use the TAC's. The reason for this can be found in the price levels as well as the levels of harvest per boat that are used as an input in the model. Based on the shadow prices for the gear types, it can be concluded that investments in a new boat can best be made in gear type E, e.g. tugs with whitefish nets.

The results of the sensitivity analyses indicate the model is sensitive to changes in prices and harvest levels. The price data used in the application are data for only one year. Since prices do have an influence of the allocation of the gear types, it is desirable to have more information on the variability of the price levels throughout the years. The model only provides a good indication for the use of the different gear types if the pattern of prices of whitefish and chub throughout the years is constant. As was to be expected, the analysis performed with lower harvest levels and lower prices lead to lower discounted net benefits.

In this study a static model is developed for a time horizon of one year. There are several ways to expand this model. One option is to expand the model to a dynamic version. The waters surrounding the Bruce Peninsula hold a complex ecosystem. When more information on the biological aspects of the fishery is available biological growth functions for the different species can be constructed. As a result of that, the harvest levels that are given in the current model can be determined by dynamic cost-effort functions and the optimal levels for the TAC per species per year can be determined. The purpose of the model can then be extended to maximising the total net benefits of the fishery as well as finding the bioeconomically optimal (steady-state) harvest levels and the optimal path to approach the steady–state solution. Bulte *et al.* (1998) performed both a static and a dynamic analysis for the Northeast Atlantic mink whales. They conclude that approximating a dynamic model by annual series of static models would result in a failure of the static model to account for the impact of current harvesting on future benefits and costs. In a dynamic version of the model developed in this study, differences in time preference rates can be expected to have greater impact on the allocation of the gear types.

In reality the fishing grounds surrounding the Bruce-Peninsula are divided in several management zones. An additional way to expand the model would be to include these management zones. The model would have to be changed in such a way that TAC's are set for the different zones, which in turn would put an additional restriction on the allocation of the available gear.

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