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Planning for changing productivity and catchability in the Maine lobster fishery

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A B S T R A C T

Catches and biomass in the Maine lobster fishery have been at record levels in recent years despite sustained high exploitation rates. The fishery is almost completely based on lobsters just molting to legal size each year and thus is vulnerable to changes in environmental or ecological conditions that reduce recruitment. I use a bioeconomic model of the fishery that incorporates an empirically estimated vessel-level production function to evaluate how a reduction in recruitment might affect profitability and optimal effort levels relative to recent years. While large reductions in effort would almost certainly be required to maintain fishery profitability, the degree of effort reduction and the optimal seasonal distribution of effort and catch are sensitive to the time series of data used to estimate the production function. Because of the unidirectional upward trend in recruitment and catches, it is unclear whether changes in the production function are due to technological innovation or ecological change. However, the answer has important implications for the level of effort the fishery may be able to profitably support in the future.

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1. Introduction

American lobster (*Homarus americanus*) is the most valuable fishery in the northeastern United States and by far the most valuable fishery in Maine. Landings in Maine, which now account for over 80% of US commercial landings of American lobster, have grown dramatically over the last two decades with record landings of over 34,000 metric tons 2009 (Fig. 1). Although the gross value of the fishery is high, the profitability of the fishery is low (Thunberg, 2007) and is decreasing with increases in fuel and bait prices and recent declines in ex-vessel price. The fishery supports a large number of lobstermen and many coastal communities that are heavily dependent on the fishery and have few alternative sources of income and employment to offset a decline in productivity and profitability of the fishery.

Lobster that have just molted to legal size form the vast majority of catch, and the biomass of legal size lobster is fished down to about 20% of its annual peak (after the summer molt) each year. Recruitment to the fishery has been at record levels in recent years enabling annual catches in the last decade to average nearly three times the mean catches between 1950 and 1990. Minimum and maximum size limits and prohibitions on taking berried females help to ensure conservation of the brood stock but this does not fully explain the increases in productivity of the stock the last few decades.

There are a variety of explanations for the increased productivity and abundance of the Gulf of Maine lobster stock. A reduction in predation resulting from the decline of groundfish in the Gulf of Maine has been suggested as one of the causes of the increase in abundance, but this does not seem to provide a sufficient explanation (Steneck and Wilson, 2001). A reduction in predators may also have resulted in an indirect increase in stock productivity by expanding the suitable habitat for lobster and thereby expanding carrying capacity. Anecdotal evidence suggests that the fishery has expanded into areas where lobsters were not previously fished (Fogarty and Gendron, 2004). Another potential contributor to increased growth is the large amount of herring bait used in the fishery, much of which is consumed by lobsters that subsequently leave the trap or are returned to the water because they are undersized (Saila et al., 2002; Grabowski et al., 2010). Grabowski et al. (2010) note that trap density has increased fourfold over the last two decades and as much as 75,000 metric tons of herring bait was used in the fishery annually in recent years. All of these factors have likely contributed to the increase in lobster abundance and landings, but there is increasing evidence that recruitment to the fishery and subsequent landings are strongly driven by levels of settlement of post larvae which may be largely a function of environmental conditions including water temperature, currents and winds that affect the survival of larvae and post larvae and their dispersion and settlement (Drinkwater et al., 1996; Incze et al., 2006; Steneck and Wilson, 2001; Wahle et al., 2004).

Whatever the cause for the increased productivity of the stock, the fishery is highly vulnerable to a reduction in recruitment to the fishery (i.e. the size of the cohort molting to legal size each year)

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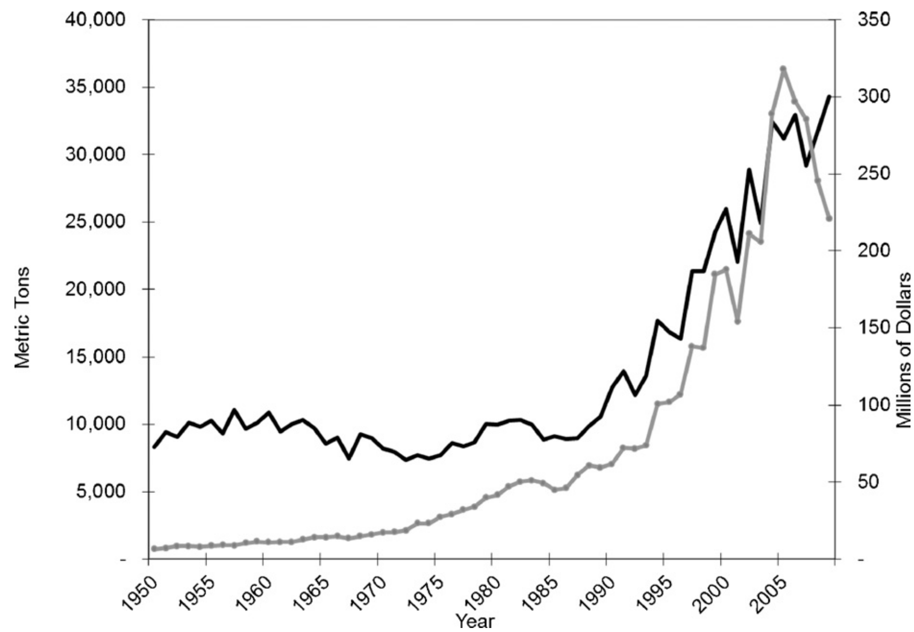

Fig. 1. Maine lobster landings (black line) and landed value (grey line with circles) from 1950 to 2009.
Source: http://www.maine.gov/dmr/commercialfishing/historicaldata.htm.

which is affected by lagged larval settlement and juvenile growth and survival. While it is difficult to guess when and to what degree a reduction in recruitment might occur, it is important to consider the reductions in fleet size and effort levels that may be required to keep the fishery economically viable and how the overall profitability of the fishery may be affected. It is widely accepted by managers, and also by the majority of license holders, that there is already excess effort in the fishery. A survey of Maine lobster license holders by the Maine Department of Marine Resources in 2008 found that 56% of respondents saw the need to reduce the number of traps being fished in their area and 51% favored an across the board cut in the trap limit (http://www.maine.gov/dmr/rm/lobster/effortquest7-17-08.pdf). Reductions in recruitment and catch will intensify the need for effort reductions. However, thousands of lobstermen, their families and communities are dependent on the fishery, and large reductions in effort are likely to be difficult to achieve, particularly in the short run. Recent studies suggest that estimates of post larvae settlement may be useful in predicting recruitment to the fishery 5–8 years later (Incze et al., 2006; Wahle et al., 2004). Knowledge of how reductions in recruitment will affect economically viable fleet size and effort levels, along with advance warning of recruitment declines may help facilitate long range planning for the fishery and the communities that depend on it.

I construct a bioeconomic model of the fishery that I use to evaluate how revenues, costs, and net income to fishermen may change with different effort levels and seasonal exploitation patterns and different levels of recruitment to the fishery. The model suggests that large reductions in effort will be required just to keep the fishery economically viable let alone maximize profit. However, the level of effort reductions required and predicted impacts on profits are sensitive to the time series of data used to estimate the production function embedded in the model.

2. Methods

I construct a numerical bioeconomic model that embeds an empirically estimated monthly demand model and a vessel-level daily production function that determines the catch, revenue, cost and profits associated with alternative monthly effort levels given specified biomass and input prices. Modeling the intra-annual distribution of catch and effort is critical because fishery landings are highly concentrated in the late summer and fall and the distribution of catch and effort over the year greatly impacts the total effort required to take a given level of catch as well as the harvest costs and the value of the catch. The monthly model captures seasonal changes in catchability, congestion effects that reduce catch rates when effort levels are high, effects of changes in fishable biomass on catch rates, and the impact that monthly landings have on price. I use the model to estimate the monthly effort levels and soak times that would maximize either net revenues or economic profit given recent biomass and recruitment levels, and for a scenario in which biomass and recruitment levels fall to the levels observed in the late 1980s prior to the expansion of the fishery.

2.1. Production function

A production function is estimated using individual level data on retained catch and effort collected through a port sampling survey that has been running since 1966.[1] The survey collects data on retained catch, traps hauled, and average soak times from a randomly selected sample of lobstermen each month. Since 2001, bait use is also recorded. I use a translog specification to model daily retained catch as

$$\ln(q) = \sum_{m=1}^{12}\alpha_m d_m + \sum_{k=1}^{K}\beta_k \ \ln(x_k) + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K}\gamma_{kl} \ \ln(x_k)\ \ln(x_l) + \varepsilon \quad (1)$$

where q is the retained catch in pounds from one observed trip (typically one day of fishing); d_m are dummy variables representing the month fishing took place; x_k are the values of the explanatory variables which include: number of traps hauled that trip, the average soak time, average kilograms of bait per trap, the estimated total

[1] The port sampling data was provided by Carl Wilson from the Maine Department of Marine Resources. This program collects catch and effort data directly from lobstermen as they land their catch. It began in August 1966 and is still in operation. Ten lobster buying locations (dealers buying directly from the fishermen) are selected at random each month, April through December. http://www.maine.gov/dmr/rm/lobster/research.htm#P.

Table 1
Production functions of individual daily lobster landings in Maine estimated with alternative time series of data.

Variable name	*Post 2000* data		*Long Run*		*Pre 1994* data	
	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value
May	–	n.a.	0.46	0.00	0.41	0.00
June	–	n.a.	–	n.a.	–	n.a.
July	0.46	0.00	0.63	0.00	0.55	0.00
August	0.70	0.00	0.90	0.00	0.82	0.00
September	0.80	0.00	0.96	0.00	0.94	0.00
October	0.91	0.00	1.00	0.00	0.88	0.00
November	0.93	0.00	0.92	0.00	0.81	0.00
December	0.77	0.00	0.58	0.00	0.43	0.00
Log(trip hauls)	0.57	0.00	(0.84)	0.04	–	n.a.
Log(soak time)	4.01	0.00	1.84	0.00	2.14	0.01
Log(hauls in Maine)	2.65	0.00	3.11	0.00	6.37	0.00
Log(biomass[i])	(2.33)	0.00	(2.93)	0.00	(5.75)	0.00
Log(trip hauls)$\hat{2}$	0.06	0.00	0.04	0.00	0.06	0.00
Log(soak time)$\hat{2}$	(0.22)	0.00	(0.17)	0.00	(0.18)	0.00
Log(hauls in Maine)$\hat{2}$	(0.08)	0.00	(0.11)	0.00	(0.22)	0.00
Log(biomass)$\hat{2}$	0.09	0.00	0.08	0.00	0.18	0.00
Log(biomass) * Log(soak time)	–	n.a.	–	n.a.	0.15	0.03
Log(biomass) * Log(hauls in Maine)	–	n.a.	–	n.a.	–	n.a.
Log(biomass) * Log(trip hauls)	–	n.a.	0.08	0.00	–	n.a.
Log(trip hauls) * Log(hauls in Maine)	–	n.a.	–	n.a.	0.02	0.03
Log(trip hauls) * Log(soak time)	–	n.a.	0.06	0.01	–	n.a.
Log(hauls in Maine) * Log(soak days)	(0.22)	0.00	(0.09)	0.00	(0.27)	0.00
Log(biomass) * Log(August biomass)	(0.03)	0.00	0.01	0.00	–	n.a.
Log(soak time) * Log(bait per trap)	0.13	0.01	–	n.a.	–	n.a.
Log(bait per trap)	0.29	0.00	–	n.a.	–	n.a.
R-square for model	0.62		0.60			

(i) Note that biomass and bait per trap are in pounds. (ii) *P*-values for variables left out of a particular model are marked n.a. for not applicable.

number of traps hauled in Maine that month, and the legal-size biomass of lobster as estimated by the current stock assessment model (ASMFC, 2009). α_m, β_k and γ_{kl} are the estimated parameters of the production function. The monthly dummy variables capture recurrent seasonal shifts in lobster catchability (independent of recruited biomass) that apparently relate to the migratory, feeding and molting patterns of lobster.

I estimate production functions with different time series of data to explore whether and how the function has changed over time. Parsimonious final models were selected using likelihood ratio tests to eliminate insignificant variables. I include bait use in the production function model estimated with only *Post 2000* data but cannot do so with earlier times series where bait use was not recorded. The production function I use in the simulations of current conditions is estimated with data from 2001 to 2009 when data on bait use was collected. I refer to this production function henceforth as the "*Post 2000*" production function. To simulate catch in a future fishery with lower recruitment and biomass, I use production functions estimated with longer or older time series of data. A production function estimated with the full 1982–2009 time series is referred to henceforth as the "*Long Run*" production function. A production function estimated with data from 1982 to 1993, is referred to henceforth as the "*Pre 1994*" production function.

2.2. Demand model

Ex-vessel prices are sensitive to monthly landings, so determining the optimal levels and seasonal distribution of effort requires modeling how prices are affected by the seasonal distribution of landings as well as total landings. I estimate a monthly inverse demand function for the Maine fishery using landings and revenue data from 1990 to 2007. I use a log–log specification to model monthly average ex-vessel lobster prices in Maine, $price_t$, as a function of monthly landings in Maine, *lbs*, US quarterly per capita personal income, *USpci*, the US-Canadian exchange rate, *Canex*, and the percentage change in US gross domestic product from the prior year, $\Delta USgdp$. Using a dummy variable, d_{post94}, to designate observations after 1994, I model a structural shift in the market after 1994 at which time both the slope and intercept of the demand functions are allowed to shift. I also correct for first order autocorrelation with $\rho\varepsilon_{t-1}$.

$$\begin{aligned}\ln(price_t) = {} & \alpha_0 + \alpha_1 d_{post94} + \beta_1 \ln(lbs) + \beta_2 d_{post94} \ln(lbs) \\ & + \beta_3 \ln(USpci) + \beta_4 \ln(Canex) + \beta_5 \ln(\Delta USgdp) \\ & + \varepsilon_t + \rho\varepsilon_{t-1} \end{aligned} \qquad (2)$$

I do not model supply and demand simultaneously because supply appears to be exogenously determined by lobster availability and the time of year rather than price. The fact that catches, and apparently effort, have increased in recent years as price declined provides support for that assumption. Though Canadian and perhaps Massachusetts lobster landings might be expected to be important predictors of lobster price in Maine, these variables prove to be insignificant and are therefore left out of the demand model. The Canadian exchange rate is a factor because much of the Maine lobster is exported to Canada for processing; however, Maine lobster (at the ex-vessel market level) does not appear to compete in the same market with Canadian lobster, perhaps because the imported Maine lobster is being processed into frozen product rather than being sold live.

2.3. Bioeconomic model

The bioeconomic model predicts monthly and annual catches, revenues, costs and profits given monthly effort levels (hauls per trip, soak time, trips per month, number of vessels), specified starting biomass level and monthly recruitment to the fishery, and specified economic conditions (which affect price). Appendix 1 provides a mathematical description of the model. Effectively the model attempts to simulate the catches, revenues, costs and profits that would have occurred in a specific past year with a different level and seasonal distribution of effort. July biomass and monthly recruitment to the fishery are set at the assessed levels for

Table 2
Elasticity at data means of catch per trip to monthly total trap hauls in Maine, monthly fishable biomass, and bait per trap and with data at August 1988 levels.

Variable	Production function		
	Post 2000	All data	*Pre 1994*
Elasticities at data means			
Total trap hauls in Maine	(0.31)	(0.58)	(0.71)
Monthly biomass	0.44	0.72	0.72
Bait per trap	0.50	n.a.	n.a.
Elasticities at August 1988 data levels			
Total trap hauls in Maine	(0.18)	(0.55)	(0.76)
Monthly biomass	0.37	0.68	0.79
Bait per trap	0.45	n.a.	n.a.

Table 3
Inverse demand function for Maine lobster ex-vessel price. $R^2 = 0.84$.

Variable	Coefficient	Standard error
Intercept	6.814	0.493
Post 1994 dummy variable	(0.694)	0.270
Log(pounds landed in ME)	(0.180)	0.016
Log(pounds landed in ME) * post 1994 dummy variable	0.055	0.019
Log(US per capita personal income)	0.827	0.117
Log(Canadian exchange rate $C per $US)	(0.478)	0.149
Log(annual change GDP)	0.094	0.032
ρ (1st order autocorrelation)	0.547	0.057

either July 2006–June 2007 (to evaluate optimal effort and profit for the "current" fishery) or at estimated levels from July 1988 to June 1989 (to evaluate optimal effort and profits for a fishery with reduced productivity). Monthly biomass for the subsequent months is then determined by subtracting the modeled catch and adding the observed "recruitment" to the fishery for that month. The "recruitment" to the fishery is the observed change in biomass estimated by interpolating the quarterly biomass estimates based on the current stock assessment model (ASMFC, 2009) and adding the observed catch from that period (see Eq. (A5) in Appendix 1). Although I attempt to replicate the observed recruitment for the period being modeled I fix the economic conditions at 2006–2007 levels for all simulations. The rationale is to explore how optimal effort and profit would be affected if the fish stock and recruitment reverted to some prior observed level (e.g. July–June of 2006–2007 or 1988–1989) while economic conditions remain representative of current conditions. I use 2006–2007 economic conditions rather than more recent conditions that have prevailed since the downturn in the US economy so predictions are more relevant to a time when the US economy is exhibiting "normal" economic growth rather than in recession which depresses prices.

The control variables for the optimization are the number of vessels fishing each month and the average soak time per trap each month. The number of trap hauls per vessel per fishing day is set at 250.[2] The number of fishing days per month is then determined by the soak time, the trap hauls per day and the total number of traps in the water per individual which is fixed at 800 traps (the current regulatory limit). The optimization model maximizes the objective (either net revenues or economic profits) subject to a constraint that total annual catch does not exceed the observed level in the year for which starting biomass and recruitment are replicated (i.e. as if that were the regulated total allowable catch set by regulators). Net revenues are defined as gross revenues less costs of fuel and bait. Economic profit is calculated by subtracting fixed costs, crew share and the opportunity cost of the captain's labor from net revenue.

The model optimizes effort and catch over a one-year period, running July through June since the new recruits (called shedders) on which the fishery is mostly based typically begin molting to legal size and thus into the fishery some time in July. The model starts with the biomass of legal size lobster that was estimated to have been available to the fishery in July according to the stock assessment model for the year for which starting biomass and recruitment are being replicated.

The net growth of fishable biomass, independent of fishing, each month is then calculated by subtracting the subsequent month assessed biomass from the prior month biomass and adding the observed catch (i.e. growth in September is equal to September biomass minus October biomass plus September catch). This can be thought of as the surplus production of fishable biomass. The biomass in the simulation model is then adjusted each month by adding the net growth of fishable biomass and subtracting the simulated catch. Effectively, monthly recruitment to the fishery and natural mortality are assumed to remain the same as estimated by the assessment and biomass is adjusted from the observed/assessed historical levels to reflect the difference between the historical and simulated catch.

Vessels are modeled as homogeneous due to a lack of cost data to differentiate costs by scale of vessel or operation. I use estimates of average fuel use per trap haul from a 2007 survey of Maine lobstermen done by John Driscoll (personal communication, May 27, 2009), bait use is specified as a linear function of soak time estimated from the port sampling survey, and estimates of fixed costs are drawn from a fixed cost survey carried out by the National Marine Fisheries Service (https://fish.nefsc.noaa.gov/fvcs/). Fixed costs are assumed to be $35,000 per vessel – the average fixed costs for lobster vessels under 40 feet which includes the majority of vessels in the Maine lobster fishery. These fixed costs include annual costs such as mooring fees, haul-out, maintenance, insurance, etc., but they do not include depreciation or the opportunity cost of capital tied up in the vessel. Total fixed costs are determined by multiplying the fixed costs per vessel by the maximum number of vessels fishing during the year (i.e. the fixed costs are incurred for a vessel whether or not it fishes the entire year). The bait and fuel prices used are representative of prices in the last few years. Crew share is calculated as 20% of revenues after subtracting fuel and bait costs. This is the common method of crew remuneration for operations with a single sternman which are the majority of the active fleet. I set the opportunity cost of the captain's time (when calculating economic profit) at $15 per hour which was the median hourly wage in Maine in 2009. This is probably a low estimate of opportunity cost given that many captains are highly experienced and skilled fishermen; however, most do not have post high school educations and, in many areas, there are few job opportunities other than lobstering (GMRI, 2008).

Catch per vessel fishing day is determined by the selected production function given the specified effort levels and the simulated biomass. Price is determined endogenously by the demand model which uses the simulated catch and the actual observed US-Canadian exchange rate, US quarterly per capital personal income, and the percentage change in US gross domestic product from the prior year to determine the ex-vessel price.

3. Results

3.1. Production function results

As the production function models show catchability is considerably higher in the late summer and fall (controlling for fishable biomass and other factors) (Table 1). The total numbers of traps

[2] The number of traps hauled by individual per day varies widely from under 50 to as many as 400, but 250 is a common objective. Most lobstermen tend to try to haul about the same number of traps each day though they may adjust soak time and the number of days fished per month during the year.

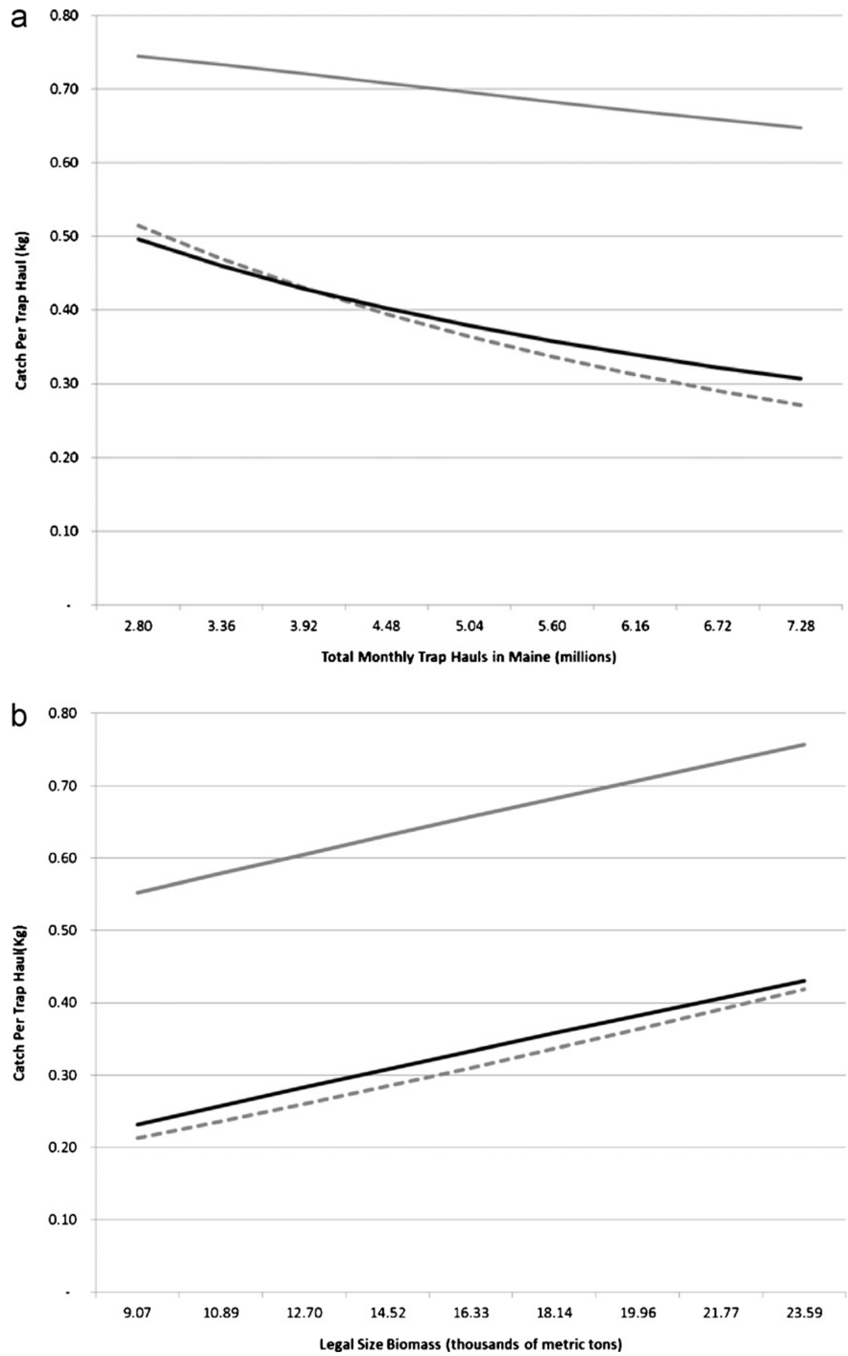

Fig. 2. Comparisons of simulated catch per trap haul as a function of (a) total monthly trap hauls and (b) biomass (*ceteris paribus* with other variable set at August 1988 levels) with *Long Run* (black line), *Post 2000* (grey line), and *Pre 1994* (dotted grey line) production functions.

hauled in Maine is included as a proxy for congestion. There is anecdotal and experimental evidence that there is a substantial congestion effect in the fishery (whereby the catch per trap is reduced by competition amongst traps in heavily fished areas – e.g. Wilson, 2007) and the significance of the monthly total trap haul variable confirms that (Table 1).

The production function estimated with only this more recent data is systematically different from the function fit with the full 1982–2009 time series, the "*Long Run*" production function, or the production function estimated with data from 1982 to 1993, the "*Pre 1994*" production function (Table 1). The *Post 2000* production function best reflects the current fishery and how it would be affected by changes in seasonal effort distribution in the short to medium term. However, in the long-run, if the lobster biomass declines to the levels in the 1980s or 1990s, the *Long Run* production function or the *Pre 1994* production function may be more applicable.

With a translog specification, the interpretation of the individual model coefficients is not straight forward because of the interaction terms. However, it is illustrative to compare the elasticities of catch with changes in biomass and total effort in Maine (a proxy for congestion). Both have an important impact on the optimal annual and seasonal levels of effort and catch. The values in Table 2 show the percent change in catch with a one percent change in the variable of interest (e.g. total trap hauls in Maine, biomass and bait per trap) with other variables held constant at data means or at August

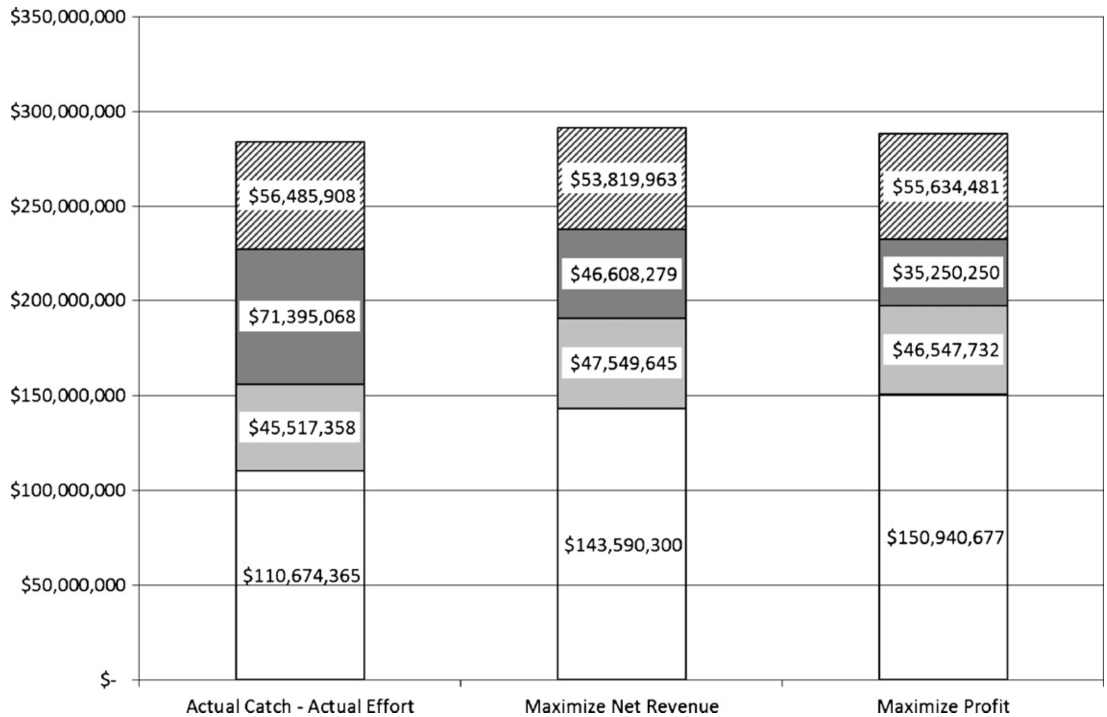

Fig. 3. Breakdown of total annual revenues into owner-operator profit (white), crew share (light grey), fixed costs (dark grey) and variable costs (diagonal stripes) from simulations with varying objectives with 2006–2007 recruitment and 2006–2007 economic conditions using the *Post 2000* production function.

1988 levels. Since elasticities are not constant and mean data levels differ substantially amongst the three data sets used to model production, comparing elasticities at the same base data levels (e.g. at August 1988 levels) arguably gives a more clear comparison of the different production functions than elasticities at data means. Fig. 2 illustrates graphically how catch per trap haul varies with total Maine trap hauls and biomass (with other variables held constant at August 1988 levels). All three production functions show congestion effects (e.g. elasticity is negative for total trap hauls in Maine) but the absolute value of the elasticity with the *Post 2000* model is smaller suggesting a weaker congestion effect (Table 2 and Fig. 2). Elasticity of catch to monthly biomass is positive but less than one for all models suggesting catch rates decline as biomass is fished down but less than proportionately (Fig. 2). However, the elasticity is smaller for the *Post 2000* model suggesting catch rates are less affected by a decrease in biomass. These results suggest that the current fishery is able to absorb greater levels of effort with smaller congestion effects and more able to maintain catch rates as biomass declines during the season and over years. Only the *Post 2000* model includes bait per trap, but this model indicates an elasticity of 0.5 at mean data levels and 0.45 at August 1988 data levels. This suggests that increasing bait use would likely increase revenue per trap haul more than the cost of the increased bait at current bait and lobster prices; however, this result is likely to hold over only a limited range of increase in bait use.

All three production functions show that catchability is substantially higher in the fall and lower in the winter independent of fishable biomass; however, the seasonal peak in catchability appears to have moved from September in the *Pre 1994* production function to October in the *Long Run* production function to November in the *Post 2000* production function. Finally, as Fig. 2 shows, the *Post 2000* production function generally predicts higher catch per trap haul given the same levels of biomass and effort. I also estimate a production function with *Post 2000* data that did not include bait to investigate whether differences with production functions based on different time series of data are a result of including bait use in the model. The *Post 2000* model without bait has a poorer fit to the data but the systematic differences relative to the production functions with earlier or longer time series are similar or amplified – i.e. the elasticity of catch to changes in biomass and total effort are much smaller in absolute value than for the *Long Run* and *Pre 1994* production functions.

The reasons for the differences in the *Post 2000* and the *Long Run* and *Pre 1994* production functions are unclear, but anecdotal evidence suggests that the fishery has expanded spatially as the abundance of lobster has increased so that it can effectively absorb more effort with less congestion. Lobstermen may also be following the lobster more as they migrate offshore in the late fall keeping catch rates higher. Higher overall catch rates may have enabled fishing at times and places that would not have been economically viable in the past. Unfortunately there is insufficient spatial data on the fishery to explore these hypotheses rigorously. It is also possible that technological improvements such as GPS and improved sonar have increased the average catchability of lobster and thus catch rates for a given level of effort and biomass.

3.2. Demand analysis results

A quite parsimonious demand model provides an excellent fit to the data explaining 84% of the variance with all of the explanatory variables significant at the 1% level (Table 3). As expected monthly prices are inversely correlated with monthly Maine landings. The intercept is higher but the elasticity is greater after 1994 reflecting an increased share of product being exported to Canada for processing. It appears that since the lobster is not going into the live market (but rather is processed into frozen product) the price is lower but more product can be absorbed with less impact on price. As expected, prices generally increase with per capita income but are also sensitive to economic growth. When the change in GDP from the prior year is higher, prices are relatively higher reflecting

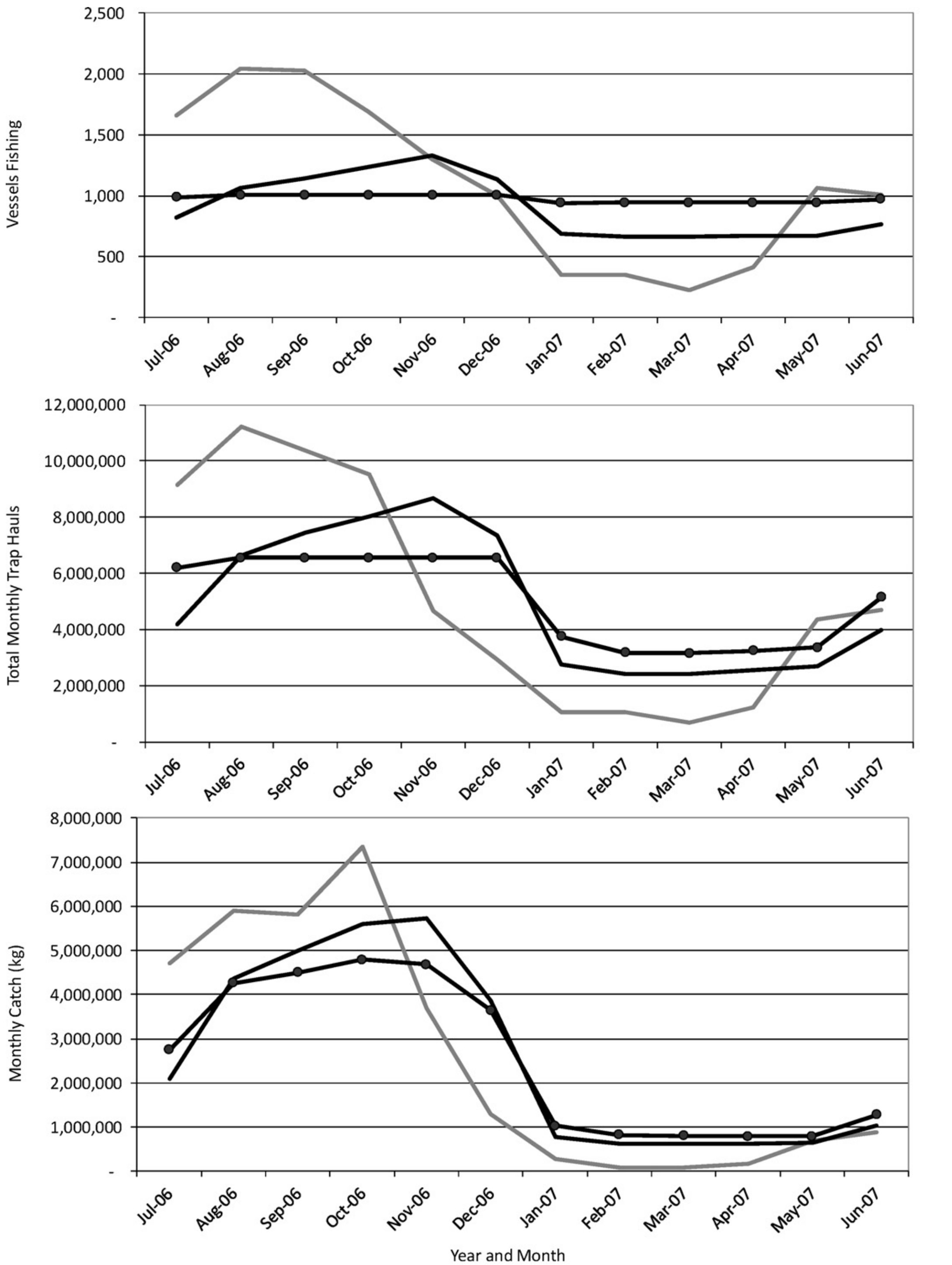

Fig. 4. Actual (grey line), net revenue maximizing (black line) and profit maximizing (black line with circles) fleet size, effort and catch trajectories with 2006–2007 recruitment and 2006–2007 economic conditions using the *Post 2000* production function.

the fact that lobster is a luxury good and demand tends to fall in an economic downturn.

3.3. Bioeconomic model results 2006–2007 conditions

I begin by evaluating how effort and profit and the seasonal distribution of catch in 2006–2007 compare to the net revenue maximizing and profit maximizing levels. The model suggests that the profits accruing to owner-operators (all Maine lobstering is done by owner-operators) could have been increased by nearly 30% with effort set to maximize net revenues and by 36% with profit maximizing effort (Fig. 3). There are some gains in average price resulting from shifting some production into the winter and thus smoothing production, but the increase in profits under the profit maximization scenario results primarily from decreased fixed costs associated with decreasing the fleet size.

Both net revenues maximization and profit maximization substantially decrease the fleet size and move some effort from the late summer and fall into the winter and spring (Fig. 4). The fleet sizes (i.e. peak number of vessels fishing in any month) that maximize net revenue and profits are 65% and 49% of the estimated 2006–2007 fleet size respectively. However, total annual trap hauls remain

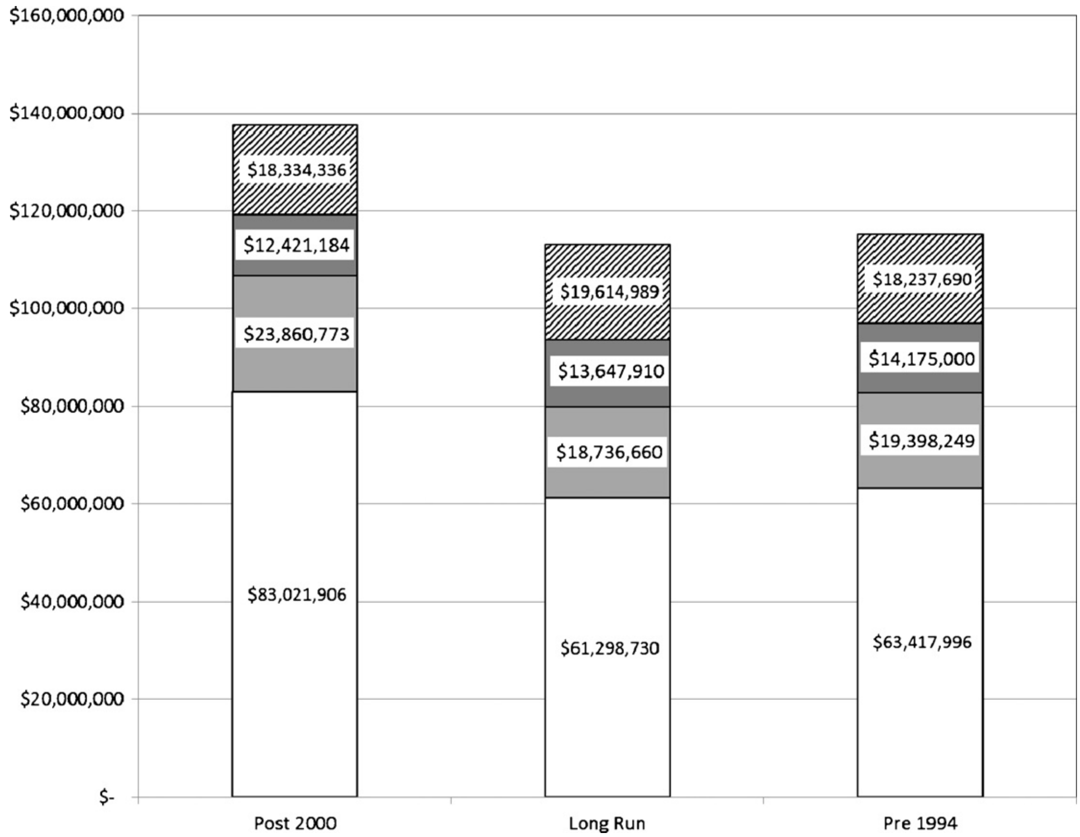

Fig. 5. Breakdown of total annual revenues into owner-operator profit (white), crew share (light grey), fixed costs (dark grey) and variable costs (diagonal stripes) from simulations with alternative production functions, 1988–1989 recruitment, 2006–2007 economic conditions and a management objective of economic profit maximization.

close to the observed level regardless of the management objective. With profit maximization the number of vessels fishing remains relatively constant over the year though total trap hauls decline in the winter as soak times increase. In both scenarios, catch remains fairly concentrated in the late summer and fall because catchability is higher. Catch rates are higher in the fall both because of higher underlying catchability and because biomass (which is comprised mostly of lobster that molted to legal size in late summer) has not been fished down as much as it has later in the year.

The profit maximizing number of vessels fishing each month is quite sensitive to fixed cost assumptions. Information on fixed cost is limited and does not enable us to model the true heterogeneity of the fleet. It is likely that many of the vessels that are smaller and fish only in the summer and fall may have lower fixed costs than the vessels that fish most of the year. A survey of lobstermen in 2006 found that 17% of active lobstermen had earned some revenue from other fisheries the prior year which could defray some of their fixed costs (GMRI, 2008). Though the survey did not clarify the sources of additional fishing revenue, it is likely that they include groundfish, shrimp and scallops fished primarily in the winter when lobster fishing is less profitable. If fixed costs are lower for a fraction of the fleet that fishes only in the summer and fall, the optimal catch and effort trajectory may be closer to the net revenue maximization scenario than the profit maximization scenario which is driven by fixed costs. This is an important question to resolve because the current number of participants in the fishery is far greater than the optimal number suggested by this analysis, and reducing participation is likely to meet strong opposition for social and political reasons – particularly in the “downeast” (northeastern) part of the state and in the islands where many communities are heavily dependent on the lobster fishery and there are few other sources of employment. As noted above, fixed costs do not include the opportunity cost of capital tied up in the boats so may cause the model to underestimate the savings associated with reducing the fleet size and therefore overestimate the optimal long-run fleet size (thus countering the potential bias that may be caused if fixed costs for part-time vessels are overestimated).

3.4. Bioeconomic model results 1988–1989 biological conditions

Next I model the fleet size and monthly effort and catch that maximize net revenues or economic profits assuming recruitment and biomass estimated from July 1988 to June 1989 but with the 2006–2007 economic conditions. I compare predictions using models that embed production functions estimated with different time series of data (i.e. the *Post 2000*, *Long Run* and *Pre 1994* production functions) to evaluate the sensitivity of results to the years of data used in estimating the production function.

The production function used has a substantial effect on simulated profit and on the optimal effort and distribution of effort and catch over the year. Under profit maximization the models with the *Long Run* or *Pre 1994* production functions respectively predict owner-operator profit equal to only 74% and 76% of the level predicted by the *Post 2000* production function model (Fig. 5). Profit maximization for the *Long Run* and *Pre 1994* models suggests optimal catches and revenues substantially lower that the profit maximizing levels identified when the *Post 2000* production function is used. This is because catch per trap haul is considerably lower with the *Long Run* and *Pre 1994* production functions (given the same level of biomass and effort) and because catch per trap haul is reduced more by the decrease in biomass as the stock is fished down during the year and by increases in total effort (Fig. 6). While similar catches are taken in the summer it is not profitable to take as

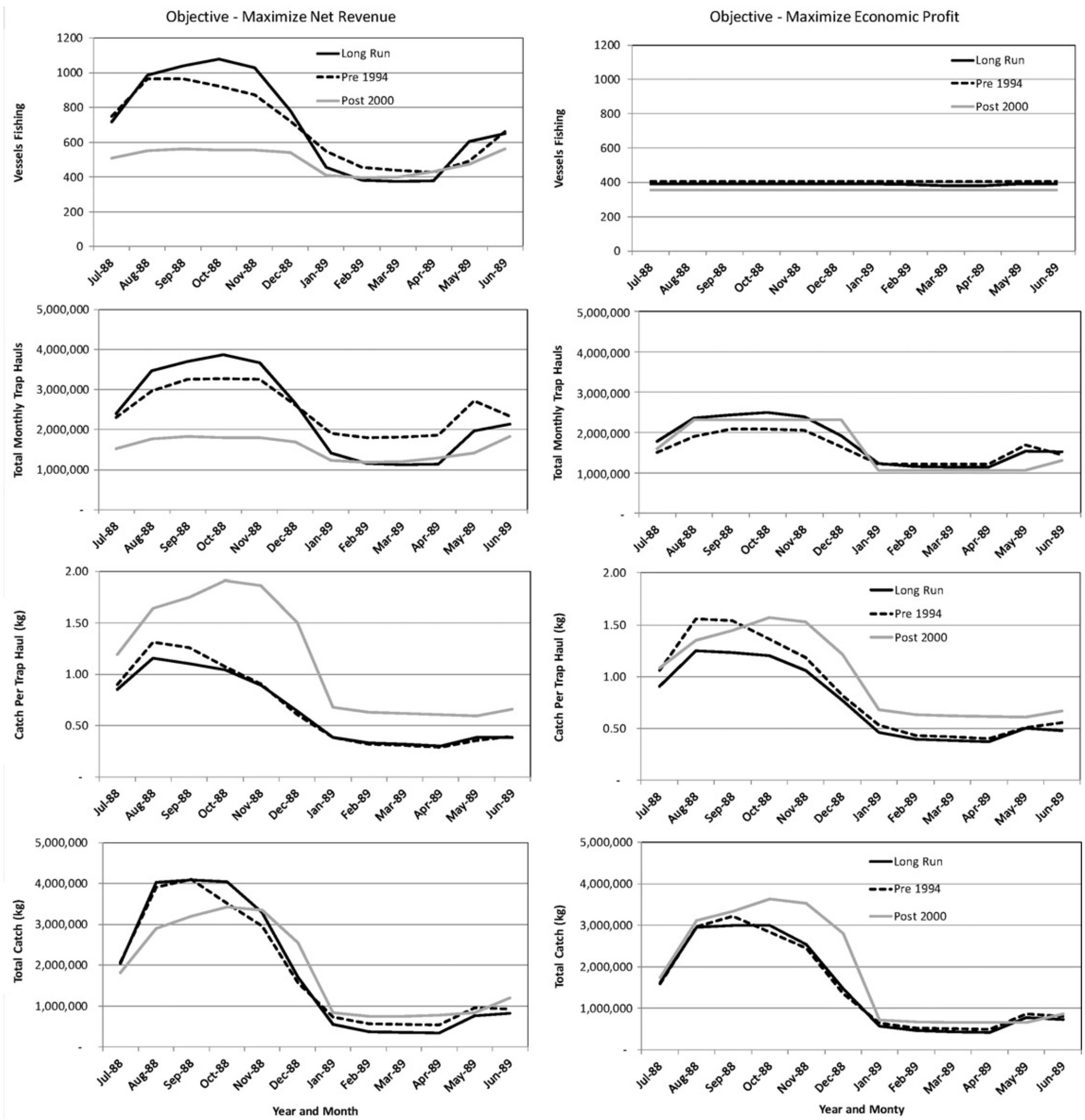

Fig. 6. Monthly catch per trap haul, fleet size, catch per trap and catch trajectories from simulations with *Long Run* (black line), *Post 2000* (grey line), and *Pre 1994* (dotted grey line) production functions for alternative production function time series with 1988–1989 recruitment and 2006–2007 economic conditions and alternative management objectives.

much catch in the fall as would be done if the production function remained like the *Post 2000* one.

Regardless of the production function used, the profit maximizing fleet size, assuming 1988–1989 starting biomass and recruitment, is less than half the profit maximizing flee size assuming 2006–2007 biological conditions and less than a quarter of the estimated 2006–2007 fleet size. The profit maximizing fleet size is estimated to be slightly higher with the *Long Run* and *Pre 1994* production function models but remains fairly constant over the year with all three models. Profit maximizing total annual trap hauls are only about one-third the 2006–2007 historical level.

With a management goal of net revenue maximization (assuming 1988–1989 starting biomass and recruitment), total annual catch is the same for the three models (constrained by the model at the 1988–1989 catch) though revenues are slightly higher with the *Post 2000* production function model due to catches being distributed more evenly over the year (Fig. 6). The fleet size, total trap hauls and catch per trap haul, however, vary considerably with the production function used (Fig. 6). Because catch per trap haul is much higher with the *Post 2000* production function model the same annual catch is taken with a much smaller fleet and far lower monthly trap hauls. Both variable and fixed costs are consequently much lower resulting in higher profit with the *Post 2000* production function model (Fig. 7). The models with the *Long Run* and *Pre 1994* production functions suggest relatively small (20–25%) reductions in the net revenue maximizing fleet size (relative to that required to maximize net revenues with 2006–2007 starting biomass and recruitment), but the model with the *Post 2000* production function suggests the net revenue maximizing fleet size would be less than half what is needed to maximize net revenue given 2006–2007 starting biomass and recruitment.

4. Discussion

Many of the coastal areas in Maine, particularly the inhabited islands, are heavily dependent on the lobster fishery for income and jobs. Preserving the profitability of the fishery if recruitment declines (or input prices continue to rise faster than lobster prices) will be critical to maintaining the economic viability of these communities. However, maintaining economic viability may conflict with objectives of maintaining participation and jobs in the fishery. Planning for a reduction in the number of vessels and individuals

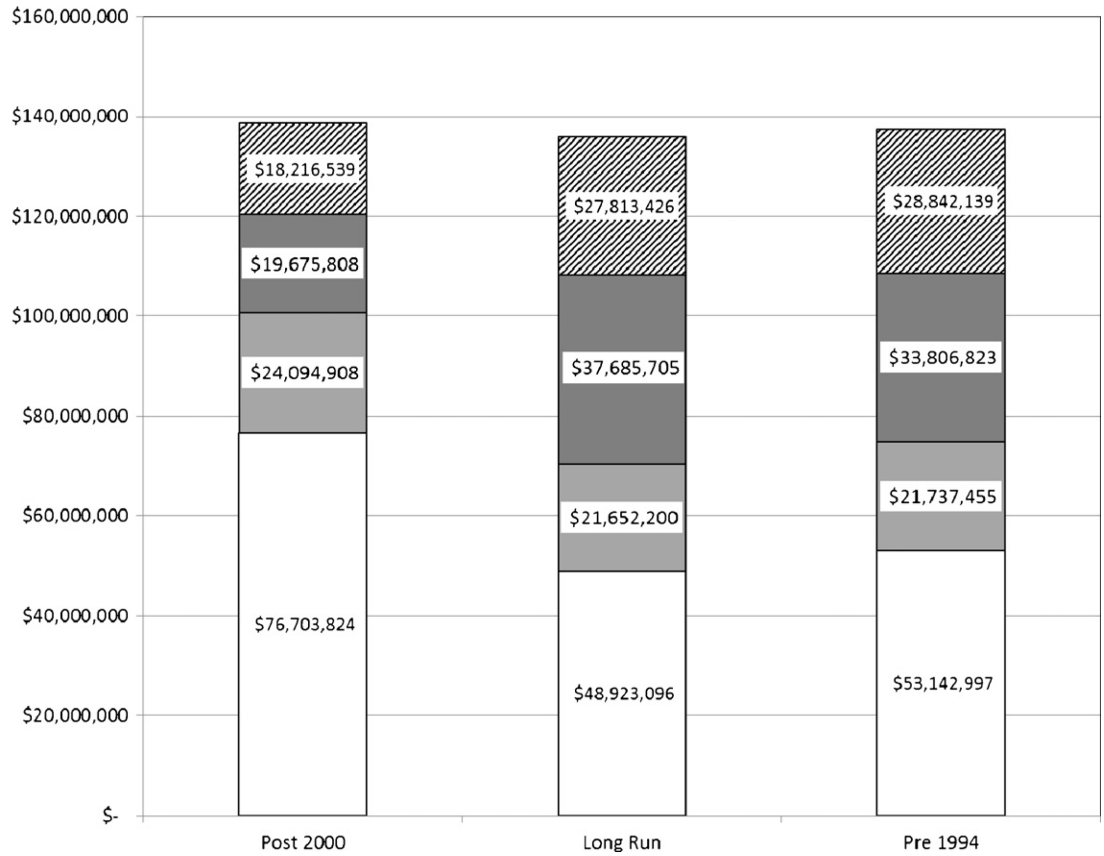

Fig. 7. Breakdown of total annual revenues into owner-operator profit (white), crew share (light grey), fixed costs (dark grey) and variable costs (diagonal stripes) from simulations with alternative production functions, 1988–1989 recruitment, 2006–2007 economic conditions and a management objective of economic of net revenue maximization.

participating in the fishery and putting resources toward developing alternatives sources of income and jobs will help to reduce the impact of the eventual reductions in recruitment and catch if and when they come.

This analysis suggests that even if recent high biomass and recruitment levels persist, the profitability of the Maine lobster fishery could be substantially increased by reducing the fleet size and by shifting some effort and catch from the late summer and fall into the winter and spring. However, because of higher catchability in the late summer and fall it still makes sense to concentrate production in those months despite the fact that the product is of lower quality and the concentration of landings drives down price. Some of the loss in revenues associated with concentrated landings might also be offset by "pounding" lobsters – i.e. storing and feeding live lobsters in enclosures and selling them at times of year when landings are low and prices higher. Nevertheless, an optimal effort and harvest schedule almost certainly involves considerably fewer vessels.

The optimal total annual trap hauls, however, may not be much different from current levels. Although the number of vessels fishing and total trap hauls in the fall would be reduced, and catch per trap haul in the fall would increase as congestion decreased, more of the catch would still be taken in the winter when catchability is low requiring high levels of effort.

Since the model only runs for one year it does not assign any value to leaving a greater biomass of lobsters in the water at the end of the year. Consequently, the analysis may overestimate the profit maximizing level of catch and effort since it does not take into account the potential gains in catch per trap haul (and reduced cost per unit of catch) that might be realized by reducing catch and allowing the fishable lobster biomass available in the subsequent years to grow. It also does not allow for any potential increase in recruitment that might results from a larger mature biomass (though such a stock–recruitment relationship has not been demonstrated).

The simulations suggest that much greater reductions in the fleet size will be required to optimize net revenues or profit if recruitment falls to the levels seen prior to 1990. Depending on the management objectives and the production function used in the simulations, optimal fleet sizes range from 17% to 50% of the existing fleet if recruitment levels were to fall to the levels prevalent prior to 1990.

Although reductions in fleet size and effort would be optimal regardless of the production function used in the simulations, optimal effort levels are sensitive to the production function chosen. If changes in the production function are due mainly to technology improvements, the production function may be little affected by a reduction in recruitment, and the results from the model that embeds the *Post 2000* production function may more accurately predict future catch rates and optimal effort levels. However, if changes in the production function relate more to the spatial dynamics of the lobster stock itself, the *Long Run* or *Pre 1994* production function may be more appropriate. In the latter case smaller reductions in fleet size and effort may be called for than if the *Post 2000* production function continues to hold due to lower catch per trap haul, but there may also be larger decrease in profits. Unfortunately, a unidirectional trend in catches and recruitment over the last two decades makes it difficult to distinguish whether changes in the production function are due to changes in the spatial dynamics of the fishery or technological change, and the lack of spatial catch and effort data makes it impossible to evaluate how the spatial dynamics of the fishery have changed and how that may have influenced the production function. To develop an understanding of what is driving changes in the production function it will likely be necessary to collect spatially explicit information on lobster catch. However, even these data are unlikely to tell us much until we observe changes in the fishery such as a major decline in recruitment since we cannot recover these data for prior years.

Understanding the relationship between effort and catch is important for many fisheries, not only for social and economic planning, but because many fisheries are managed indirectly with effort controls rather than catch controls, and the economic performance and biological sustainability of the fishery depends on setting effort levels appropriately. Models used to guide management decisions often assume the catch per unit effort will change in proportion to fishery biomass so that fishing mortality remains the same as long as nominal annual effort levels remain the same. As this analysis shows, CPUE may decline much less than biomass and the seasonal distribution of effort and trap soak times can also greatly affect the catch for a given level of licensed traps. Furthermore, the functional relationship between effort and catch may change substantially over time as a result of changes in spatial dynamics of the fishery or with technological change.

When the relationship between regulatable inputs (e.g. licenses or licensed traps) and catch is not well understood or is influenced by unregulated decisions (such as when to fish, how many traps to haul, and soak times), managing nominal fishing effort may be an ineffective means of achieving either economic or biological objectives. In such cases individual quotas or cooperatives with quotas may have some advantages. However, in this fishery individual quotas may still not fully control economic rent dissipation due to congestion externalities and seasonal depletion (Holland, 2011). Enforcement might also be costly, and, at this point, individual quotas appear to be politically unacceptable. Removing latent effort and creating quarterly trap tag allocations (to control the amount of effort over the year) would increase the ability of managers to achieve biological and economic objectives though this might be expected to incentivize fishermen to use shorter than optimal soak times to maximize catch from their limited trap allocations.

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Appendix A. Bioeconomic model

The model maximizes either net revenue, which is gross revenue less the cost of fuel and bait, or profit which is net revenue less fixed costs, crew share and the opportunity cost of the captain's labor. Gross revenue in month t is modeled as the product of total landed catch in month t, Q_t and ex-vessel price, p_t, which is determined endogenously as a function of Q_t and the observed economic conditions as described by the demand function in Section 2.2 of this paper (Eq. (2)).

$$Rev_t = p_t Q_t \tag{A1}$$

The total landed catch is the product of the number of boats fishing in month t, $Boats_t$, the number days each boat fishes, $Days_t$ and the catch per boat-day, q_t.

$$Q_t = Boats_t * Days_t * q_t \tag{A2}$$

The number of boats fishing each month is a control variable of the optimization and the number of days fished is determined as the maximum number of days the boat could fish given the trap limit of 800 traps, a 30 day month, the numbers of traps hauled per day which is fixed at 250, and the average soak time which is another control variable for the optimization.

$$Days_t = \frac{800 * 30}{soaktime_t * 250} \tag{A3}$$

The catch per boat-day in month t, q_t, is determined by the production functions described in Section 2.1 of this paper (Eq. (1)). Inputs to this function include the month, the number of traps hauled (fixed at 250), the soak time (a control variable), the total number of traps hauled in Maine for the month, $Ttraps_t = Boats_t * Days_t * 250$, the bait used per trap, $baitpt_t$, the legal-size fishable biomass, B_t, and the observed legal-size fishable biomass in August (as estimated from the stock assessment for the modeled period), $AugB_t$. The bait per trap is determined by a linear function of soak time which is estimated with the port sampling data.

$$baitpt_t = 2.23 + 0.086 * soaktime_t \tag{A4}$$

The legal-size fishable biomass in month t, B_t, is set at the level estimated by the stock assessment for July (the first month of the modeled fishing season when the new crop of lobsters in molting into the fishery) but is determined endogenously for the following months as

$$B_t = B_{t-1} - Q_{t-1} + R_t \tag{A5}$$

where R_t is the assumed recruitment of legal size lobster into the fishery that month which is calculated by adding the actual observed catch from that month to the observed changed in legal-size biomass as estimated by the stock assessment.

To calculated net revenue each month, the model subtracts the costs of fuel, $Cfuel_t$ and bait, $Cbait_t$. Fuel cost is the product of the price of fuel, $Pfuel$, which was set at $3 per gallon for these simulations, the total number of trap hauls that month, $Ttraps_t$, and the fuel use per trap haul estimated at 0.09 gallons per trap haul.

$$Cfuel_t = Pfuel * Ttraps * 0.09 \tag{A6}$$

The total cost of bait is calculated as the product of bait price, $Pbait$, which is set at $0.25 per pound for these simulations, and bait per trap, $baitpt_t$, as determined by Eq. (A4), and the total number of trap hauls, $Ttraps_t$.

$$Cbait_t = Pbait * baitpt_t * Ttraps_t \tag{A7}$$

Net revenue can be calculated by month as

$$Netrev_t = Rev_t - Cfuel_t - Cbait_t \tag{A8}$$

Profits, π, can only be calculated for the entire fishing season (July–June) since fixed costs are determined by multiplying the maximum number of boats that fished in any month, $Maxboat = \max(boats_t)$ by the fixed costs per boat set at $35,000. To calculate profit, π, fixed costs, crew share and the opportunity cost of captain's labor is subtracted from net revenue. Crew share is calculated as 20% of the gross revenue and the opportunity cost of captains' labor is calculated by multiplying the total boat days fished for the year by $150 (assuming $15 per hour opportunity cost wage and an average 10 h day).

$$\pi = \sum_t Netrev_t - 35,000 * Maxboat - 0.2 * \sum_t Rev_t - 150 * \sum_t Boats_t * Days_t \quad \text{(A9)}$$

The optimization model maximizes either net revenue or profit by simultaneously optimizing the number of boats fishing and the soak time in each month subject to the specified economic and biological conditions, the constraint that catch not exceed observed catch, and the functions that determine catch and costs as described above. As noted, simulations are run with alternative production functions and alternative recruitment assumptions.

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