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Input substitution in a trap fishery

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This paper proposes a production function for a trap fishery and develops its implications for the economic management of associated inputs. The field observations and anecdotes from fishermen are drawn from the American lobster fishery, but the approach may also be used for other trap fisheries. The development includes a spatial aspect of fixed gear fisheries and an intuitive rationale for a congestion externality in such fisheries. This effect does not involve population dynamics *per se*. However, the production function developed below could eventually be imbedded within a population dynamics model, although this is not done here. This eventual imbedding is necessary not only because of the biological issues explained by population dynamics but also because of the dependence of price on the age-class structure of the population. A principal finding is that there are plausible reasons to expect market failure associated with a trap congestion externality and a soak time too short for cost effectiveness. The numerical analysis is consistent with the theory, and if this finding is supported by further research, then operating costs could be reduced with no change in catch by using more traps and longer soak times.

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Soak time as a determinant of catch

In trap fisheries, the gear (called traps, pots, weirs, etc.), is typically fixed in space and time during a soak cycle. At the beginning of each cycle the gear is "tended". The meaning of "tending" varies with the gear and fishery. In the case of traps for crustacean species, tending means hauling the gears (traps or pots), emptying and re-baiting each trap and returning it to the bottom. In the case of a weir, there may be no analogue of re-baiting, but there may be maintenance expenses. In some fisheries, nature may dictate the soak time. For example, in the Minas Basin of Nova Scotia, during the late 19th and early 20th century, the twice-daily 15-m tides permitted an artisanal shad harvest using horses or oxen and sleds while the tide was at its lowest. In other cases and seasons, predation by opportunistic species are said to "force" re-baiting. Presumably there is a set of facts and economic reasoning which would convert "force" to "rationalize". Such a rationalization is a major motivation of this paper and it sheds light on an overlooked economic aspect of trap fisheries. This study develops an intuitive spatial rationale for both a trap congestion effect and excessively short soak time. This rationale also sheds new light on the well-documented territoriality of "lobster gangs" (Acheson, 1975). We may ask why there is a territorial motivation if there is no trap congestion. If, after all, the catch per trap of present fishermen is unaffected by the traps of a newcomer, why would those fishermen oppose the new entrant? Resource depletion is the easy answer to this question, but I will argue below that this is too facile, in that it ignores some awkward facts. However, this is not to deny the issue of resource depletion; rather it is that this study abstracts from such matters. Eventually it will be necessary to embed the production function in an age-class-structured model such as SIMLOB (Sutinen and Gates, 1995) to capture the interyear dynamics as the dependence of price on age-class structure (Gates, 1975; Richardson and Gates, 1986).

Fisheries biologists, including Bennett (1974), Bennett and Brown (1979), Caddy (1977), Auster (1985, 1986), and Skud (1979) have noted the importance of soak time (the time–lapse between successive hauls of a representative gear unit) for assessing the significance of catch per unit effort statistics. Miller (1990) clearly recognizes the possibility that the relationship between catch and soak time may not be monotonic. He examined the issue of optimal soak time but used a Mitscherlich–Spillman functional form that is monotonic (Miller, 1983). However, he implicitly regarded maximum return per trap haul as an appropriate index of economic optimality. In

so doing he committed a common error. Whatever the unit, it does not generally make sense to maximize the return per unit of any single input. We could maximize the return per trap on bottom, per trap hauled, per day at sea or per man hour of labour. Each of these objective functions would yield somewhat different answers. There are two cases in which maximizing the profit per trap on bottom makes sense. One would be that of a linear response (i.e. zero congestion), but if the response is linear, there is no reason to restrict traps per boat. The second case is when there is an effective constraint on the number of traps that can be deployed per vessel. If such a constraint exists, the LeChatelier principle (Averch and Johnson, 1962; Samuelson, 1965) predicts that producers will respond by "stuffing inputs"; an action which is second best to the true maximum. Unfortunately this abstract principle deals only with the existence of a distortion. A numerical analysis is necessary to determine the magnitude of the distortion. Also, the optimizing criterion must take into account a soak time constraint and the nature of open access which further complicates matters. Soak time is also critical for understanding the economics of regulation in such fisheries. "Economics of regulation" refers not only to the net income of fishermen, but also how fishermen can be expected to react to regulations and the implications of those reactions for the effectiveness of regulatory measures in achieving fishery management objectives. Among the fisheries studies cited, only those by Austin (1977), Miller (1983), and Sinoda and Kobayasi (1969) included a variable for "soak time". Unfortunately, these papers did not include enough other variables to be a complete economic representation of the production process. Moreover, it is suggested here that these studies do not adequately reflect a gear congestion externality associated with the number of traps on bottom. In this paper, a trap congestion effect is said to exist if ξ_{CT}, the partial elasticity of catch with respect to traps on bottom, is less than unity. Algebraically:

$$\xi_{cT} = \left(\frac{\partial C}{\partial T}\right)\left(\frac{T}{C}\right) < 1$$

Elasticities are common in many fields of science because they are dimension free. Thus, regressions done on data in metric vs. Imperial units may (depending on functional form) differ. The elasticities will be the same, provided the points of evaluation are comparable. The catch equation used by Schaefer (1957) is the most widely used production function in fisheries economics and can lay fair claim to being the "standard model". It asserts that instantaneous catch is proportional to the product of effort (E) and stock size (P); $C = qEP$. This function is log linear and the partial elasticities with respect to effort (E) and stock size (P) are both constant and equal to unity. The total elasticity of production is the sum of the partial elasticities for all inputs to production:

$$\xi_C = \Sigma_i \xi_{Ci}$$

However, while stock size is a factor of production, it is not a decision variable for an individual fisherman and is not an input in the sense we are using the term. Thus, while stocks will eventually adjust to effort variations, this fact will be ignored by fishermen and $\xi_c = \xi_{CE} = 1$ with the standard model. The elasticity of production is useful in economics as an index of the relative magnitudes of average cost (AC) and marginal cost (MC):

$$MC = \frac{AC}{\xi_c}$$

Thus, the standard model, MC=AC and, for fixed stock size, gives what appears to individual fishermen to be a constant cost industry. From an aggregate perspective, this is too simplistic and stock adjustments must eventually be taken into account via population dynamics. In general, elasticities are themselves functions, but in some cases, we have "constant elasticity" functions. Log linear functions (including the standard model) fall into this category. By contrast, the Mitscherlich–Spillman function, $C = 1 - e^{-qE}$, has a variable elasticity which approaches zero as E increases. This form has been used widely in fisheries and agriculture. Its users include Beverton and Holt (1957), Miller (1983), Russell (1972), Spillman (1923, 1924a,b, 1933), and Mitscherlich (1909).

Soak time, as used, in the Austin (1977) and in the Sinoda and Kobayasi (1969) papers provides an improved explanation of catch statistics, but the economic trade-offs involved have not been developed explicitly. As a consequence, the economic effects of regulation have not been addressed explicitly by these papers, nor do they claim to have done so. Austin (1977) proposed a log linear function to express the daily catch per trap haul as a function of soak time. Sinoda & Kobayasi (1969) proposed a Mitscherlich–Spillman-type production function for the same phenomenon. Russell (1994) reported results from applying these two functions to data for the American lobster fishery. Despite low coefficients of determination, the results were judged reasonable with the Mitscherlich–Spillman function performing marginally better for some data sets and the log linear function performing better for others. In none of these studies is there any suggestion of congestion effects arising from an excessive amount of fishing gear. That is, in part, because the congestion rationale developed below is expressed through a stock variable (traps on bottom), rather than a flow variable such as the haul rate.

Congestion externalities in trap fisheries

A rationale is developed here for a type of congestion effect from too many traps. In the absence of such an effect, catch would respond linearly with increases in traps on bottom. With a trap congestion effect the catch response to more traps is less than proportional to changes in the number of traps on bottom. Effort will be made towards developing the interrelationships between traps and soak time because the two are connected through a soak time constraint.

Opinions about the economically optimum soak time differ between fishermen. Most believe that unbaited traps will entrap some lobsters, but that periodic re-baiting is better than no baiting. There is also a consensus that the best soak time varies seasonally with abundance and lobster prices and with the activity of "sand fleas" (presumably amphipods) and other opportunistic organisms. By itself, this observation is interesting, since economic studies have not noted this dependence of soak time on product price and abundance and the received fisheries economics theory has no explanation for the phenomenon for the very good reason that existing literature has rarely recognized soak time and then only as a determinant of catch. The economic implications have not been explored. Also of interest was a widespread desire among fishermen to "stop the arms race". On questioning the phrase "stop the arms race", fishermen explained that what was meant was use of ever more inputs (gear, labour, fuel, bait, etc.), with no gain to show for the added expense. The arms race metaphor reflects a feeling by each fisherman that he must mimic the actions of his peers in order to remain competitive. However this desire co-existed with a scepticism about the relevance of resource depletion. This scepticism does not prove depletion irrelevant, but it is indicative of the perceptions and relative priorities expressed by some fishermen. The point here is not the validity of the opinions expressed nor how widespread those opinions may be. It is, rather, that these opinions induced me to reflect on the question of input management from the perspective of fishermen. Again, the standard model sheds no light on this difference of opinion between fishermen and adherents of the standard model. A congestion externality for traps on bottom is inconsistent with either the Austin (1977) or Sinoda and Kobayasi (1969) production functions, since the number of gear units on bottom is not an explicit argument of the production functions they advanced.

Examination of Maine statistics from Russell (1994) reveals that numbers of traps per boat almost doubled during 1968–1993. Trap-months on bottom increased from 1270 per boat in 1968 to 2424 in 1993. During this period, the total number of traps on bottom more than doubled from about 700 000 in 1967 to nearly 2 million in 1991 (Robinson, 1991). Catch per trap haul declined 31% from 0.38 lobsters per trap haul in 1968 to 0.26 in 1993. Krouse (1989) discusses the factors contributing to increases in the sophistication and catching power of traps for crustacean species. Despite these trends, relative abundance indices for the Gulf of Maine increased during the two decades ending in 1990 (NMFS, 1993). These trends are consistent collectively with the opinion of lobster fishermen that they are tired of financing an "arms race" and they suggest that there may be a congestion externality in such fisheries. This study presents more information on these trends in due course but first an intuitive rationale for the facts is examined and explained.

Spatial considerations in a trap fishery

Imagine an isolated, unbaited trap on an homogeneous bottom on which the target stock is uniformly distributed. We suppose initially that the trap is unbaited but attractive to its target species as a source of shelter. We further suppose that this attraction decreases with distance from the trap. For simplicity, let us suppose that the rate of decline is linear and uniform in all directions. These assumptions are not critical to the subsequent discussion but simplify the intuitive development. Given these assumptions, one can imagine an attraction radius at which the residual attraction of the unbaited trap declines to zero. The associated circular area on the bottom encloses the attraction zone of the hypothetical trap. The geometry of this outcome can be represented in three dimensions as a cone centred on the isolated trap with the height of the cone's peaks as an index of the unbaited trap's attractiveness as a shelter, and the base being a circular attraction zone. This attractiveness peaks at a point beneath the peak of the cone (i.e. at the trap).

Now suppose the trap is hauled and re-baited. Exploiting the geometric metaphor, the bait enhances the attractiveness of the trap which implies that the height of the cone is elevated by the fresh bait and the attraction zone is enlarged. Thus, one can view the function of bait as extending the attraction zone of the trap in which it is placed. Natural processes of dissolution, decay and theft by opportunistic organisms cause the bait's effectiveness to decline over time. As a result, the attraction zone oscillates in size over time. The characteristic frequency of oscillation will be the soak frequency (reciprocal of soak time) and the amplitude of oscillation which will be governed by the effectiveness of the bait used. This amplitude is added to the constant shelter attraction of the unbaited trap, which presumably does not decay with time. The difference in attraction radii for an unbaited vs. baited trap implies an associated zone of oscillation. Now suppose a second

trap is added to the bottom. If the two traps are sufficiently distant from each other, their respective attraction zones are disjoint sets, and the catch of the two traps will be additive. However, as the two are moved closer together, their attraction zones will begin to impinge on each other. Where they overlap, a competition frontier is created which is defined as a locus of iso-attraction for both traps. Of primary interest to us is the fact that the attraction zones and hence catch of the two traps is less than additive, due to the competition for the finite space within their joint attraction zone. If the overlap of zones is small, the combined catch will be almost linear. If more traps are added, a geometry of multiple overlapping circles is generated. These circles are mutually distorted by the existence of competition frontiers between each trap. Again, from location economics with homogeneous units, it is known that the limiting attraction zones will form hexagonal cells as noted by the location theorist Lösch (1944) and re-analysed by Greenhut (1970). The hexagon is the simplest regular polygon capable of packing a given area subject to the condition of iso-attraction between adjacent traps. These Lösch cells look like the honeycomb of a bee hive. Increases in the number of traps in a region will compress the attraction zone of the individual cells and reduce the catch rate of each cell while the aggregate catch remains relatively unchanged. Notice that this congestion externality is logically independent of inter-year population dynamics. Any production function must eventually be incorporated in a model which accounts for inter-year population dynamics, but this is not the focus of this paper.

Periodic baiting of the centre of one cell (trap) will cause that cell to oscillate in size at the expense of adjacent cells. If the attraction force of fresh bait is sufficiently strong, a freshly baited trap could have an attraction zone that engulfs and encloses an adjacent unbaited trap. When all cells engage in periodic re-baiting, the polar extremes are as follows. At the zenith of the soak cycle, the cells cannot become smaller in size if the bottom is already honeycombed. The greater abundance of bait makes life olfactorily pleasant for lobsters, but may not do much to increase aggregate catch. Conversely, as the soak cycle progresses and the residual bait approaches minimal quantity and quality, the attraction zones shrink and may revert towards a circular geometry or even pull apart and become isolated circles at the nadir of the soak time cycle. Thus, other things being equal, increases in the spatial density of traps on bottom, and decreases in soak time have effects that are similar, although not identical. In particular, the re-baiting process has, as described above, a characteristic frequency that is unaffected by the number of traps on bottom. Conversely, while re-baiting is necessary for each individual fisherman to maintain the attraction zones of own traps, the size of the attraction zone of each trap is also governed by the spatial density of traps on bottom.

The above geometry has not been developed algebraically because there are many factors to suggest that pursuit of such fine detail may be to pursue an elusive target. The fact that lobster fishermen tend to set traps in strings means that the austere symmetry of the Lösch cells would not be realized. If adjacent strings are separated enough, there may be competition only between adjacent traps on the same string. Conversely, one can imagine wide spacing on each string with competition primarily between adjacent strings. The ocean bottom is not an homogeneous plain, nor is the lobster population uniformly distributed. Water currents would distort the austere geometry described above. Seasonality of temperature, abundance of competing species, etc. would make attraction cells stochastic and irregular. This variability would be less pronounced for an aggregation of traps, because a negative deformation (from the circle or Lösch cell) for one attraction zone may be positive for an adjacent attraction zone. Such deformations do not qualitatively alter the implication of less than additive responses to additional traps. The point remains, therefore, that there is good reason to expect a strictly concave catch response to marginal traps. With this in mind, we develop an alternative production function for such fisheries. Another implicit input is bottom area. The revelation of a congestion externality in a time-series data set presumes that bottom area is constant or at least that area is known so that traps can be expressed on a per unit area basis. The geometry of Lösch cells is premised on input proportions (traps per unit area), not their absolute levels. Unless traps per unit area increase, there is no a priori reason to expect a strictly concave response to traps. Under open access conditions, the area fished per fisherman (or the lobster population accessible to him) would be expected to approach a subsistence level which can be escaped only by extending the aggregate area fished. Thus, the lack of area data may be less damaging to our paper than might be supposed.

A proposed function

These are the positive variables and parameters:

M = duration of time period (typically 30 days)
$M^{-1} < \Psi =$ "soak" frequency = number of times a typical trap is hauled per calendar day
$\theta = \Psi^{-1} =$ "soak" time = no. of calendar days between successive hauls of a typical trap
T = no. of traps (or pots) on bottom
h = no. of traps hauled per day at sea
β_0(month) = intercept (month dependent)
β_T = a trap-catch parameter

β_h = a catch-haul rate parameter
β_θ = a catch-soak time decay parameter (Mitscherlich–Spillman form)
$C(T,\theta)$ = stock entrapped at soak frequency θ when using T traps

Equation (1) states a functional form consistent with the hypotheses of congestion and soak time:

$$C(T,\theta)=\beta_0 T^{\beta_T} h^{\beta_h}(1-e^{-\beta_\theta}) \tag{1}$$

The hypothesis of trap congestion may be expressed as H_1:$\beta_\theta<1$. At low trap densities, additional traps need not infringe on each other's attraction zones and catch may respond linearly. However, it is rare to be concerned with lightly exploited fisheries, so it is reasonable to focus on the non-linear response case. At high densities, additional traps will simply compress the attraction zones of existing traps and lead to a catch response that is strictly concave in traps. This is not the only function we might choose to represent such an effect, but it combines elements of the general log linear model with the Mitscherlich–Spillman form for soak time response.

The soak time constraint

The duration of a discrete time interval or period can be defined as daily, weekly, or monthly etc. In this paper, we use a time period, M, 30 d or 1 month. This choice of period is based on data availability and a need to have a period longer than the longest plausible trap rotation period (soak time). Monthly decision-making about trap management is subject to the following "soak time" constraint: Let:

h = instantaneous (daily) haul rate for traps; traps hauled per day at sea
d = absolute effort measure = calendar days at sea per period
$e_{dm}=dM^{-1}$ = relative effort or effort intensity in days at sea per calendar day
H = hd = trap hauls per month
HM^{-1} = traps hauled/calendar day

The soak time constraint (identity) can be written in various ways. None is more fundamental but different formulations may be more intuitive than others. It is assumed, for simplicity, that T is fixed during a typical soak period. The soak time identity is:

$$\psi MT - hd \equiv \psi MT - H \equiv 0 \tag{2}$$

The term MT is trap-calendar-days on bottom during a period of M calendar days, since it is the product of traps on bottom and calendar days per period. The term, H is the number of observed traps hauled during the period and is the product of the haul rate per day at sea (h) and the days at sea (d) per period. The soak frequency, ψ, is the number of times a typical trap is hauled each calendar day. Soak frequency forces the two terms to be equal, by definition. The product $\theta T = T\psi^{-1}$ is the number of (calendar) days required to cycle through the stocks of traps on bottom.

We can divide this form by trap days on bottom (MT):

$$\psi - H(MT)^{-1}=0 \tag{3}$$

$$\psi=\theta^{-1}=(hT^{-1})(dM^{-1}) \tag{4}$$

$$\psi T=SOD=\theta^{-1}T=h(dM^{-1})=he_{dM} \tag{5}$$

The ratio hT^{-1} is traps hauled per day at sea divided by traps on bottom. It measures the intensity with which the stock of traps on bottom is tended. Its reciprocal (Th^{-1}) measures the days at sea required to cycle through the stock of traps on bottom. The ratio dM^{-1} is the instantaneous effort intensity (E_{dm}) during the month and is measured in days at sea per calendar day. "Set-over-days" (SOD) is one way to try to capture soak time via a composite variable, T × SOD. If both SOD and soak time are known, the ratio of soak times in the two time metrics (days at sea and calendar days) is the instantaneous effort intensity, e_{dm}. Unfortunately, we do not have time series observations on days at sea or on soak time. We do have observations on haul rate and SOD.

I have used the following differential equation:

$$\frac{dC}{d\theta}=[1-e^{-\gamma T}][\beta+e^{-r\theta}][1-y(\theta,T)]-\mu y(\theta,T) \tag{6}$$

where:

$0 \le \mu$ = exit (and repulsion) parameter
$0 \le y(\theta,T)$ = fraction of stock entrapped during a soak cycle of duration θ with T traps
$0 \le r$ = instantaneous bait decay parameter.

This equation has some appealing attributes. It is parsimonious in number of parameters. It embodies very simple, plausible hypotheses about entry exit processes. It has a solution which converges on the Mitscherlich–Spillman form as $\mu \to 0$. For non-zero parameter values, integration by parts yields an infinite regress of terms but the series satisfies convergence tests so that the existence of a solution is assured. Unfortunately, an analytic solution was not found so solution is necessarily numerical. For plausible parameter values, the resultant curve in catch–soak time space is shaped like an asymmetric inverted U with an elongated right tail. Lobster fishermen and fisheries biologists suggest a form consistent with $\mu=0$. However, Geoghan has presented data consistent with $\mu>0$. Since that time, he advised that the

descending right limb in his data may be a confounding with seasonally associated with availability (P. Geoghan, pers. com.). Accordingly, I have retained the analysis based on Equation (1) which has an asymptote but no descending portion. This analysis occupies the bulk of the remainder of this paper. However, the implications of Equation (6) are quite profound as described below. In the analyses that follow, by using Equation (1), I will focus necessarily on the ascending portion of the catch–soak time curve since that is the only portion that Equation (1) has and it fits with conventional wisdom. Eventually, however, I will return to Equation (6) and question this wisdom.

Bait per trap haul

At first, I assumed a bait per trap haul that was independent of soak time. A lobster fisherman commented that bait per trap haul is increased for long soak times. Regression analysis of our survey data indicated the following relationship:

$$b = b_0 \theta^{\xi_{b\theta}}$$

where b=bait cost per trap haul and the exponent $\xi_{b\theta} \approx 0.2$, is the elasticity of bait cost per trap haul with respect to soak time. This relationship had a low coefficient of determination, but $\xi_{b\theta}$ was statistically significant and the sign agrees with P. White, Maine Lobstermen's Association (pers. com.). Unfortunately, the estimated elasticity, $\xi_{b\theta} \approx 0.2$, is probably too low. An increase of soak time from three to seven days would double bait per trap haul. This implies an elasticity $\xi_{b\theta} \approx 0.75$. This simple change has significant effects on optimal trap management because bait cost is now affected by a multiplicative form involving soak time and traps hauled, instead of just traps hauled multiplied by a constant bait cost per trap haul.

Input trends in the Maine lobster fishery

A survey of lobstermen was directed in 1994 by the author and Jon Sutinen. The following comments are constructed from that which the fishermen told us. The daily haul rate, has been increased by mechanization (pot haulers are now in universal use) and by carrying a larger crew. In the lobster fishery, bait is a major operating cost and has been increasing over time as trap hauls have increased. Most commercial lobster fishermen we interviewed say they maintain 600–1200 traps on bottom but these numbers have been increasing over time. The individuals in our sample were deliberately selected to focus on fishermen who considered themselves to be full time commercial lobster fishermen. Krouse (1989) suggests a figure of 365 traps per boat in 1985. This accords well with the data used in our estimations described below. Thus, the number of traps in use by fishermen in our survey is approximately double the average for all Maine inshore lobster fishermen. In one anecdote, an inshore lobster fisherman (not in Maine) was allegedly working 5000 traps. Notice that, with a congestion externality, blanketing the bottom and using a long soak time (low soak frequency) is metaphorically equivalent to a peremptory strike to assert possession of all the bottom space in the area. Notice also, that bottom pre-emption makes no sense if there were not a trap congestion externality.

Days at sea per week or month can be varied within a range. Social norms used to rule out weekends which limits the number of days per month to, perhaps 26. However, these norms are reportedly breaking down under the stress of competition (R. Allen, pers. com.). The need to perform repair and maintenance further limits days at sea per month. Family obligations, medical appointments, etc. may further limit days at sea. In the lobster fishery our observations suggest 5–22 days at sea per month, with the higher end of the range being associated with seasonal peaks in revenue rates. For M=30 then, the instantaneous effort rate in days at sea per calendar day (E_{dM}) lies in the range 0.17–0.67 during the 1994 season, based on our survey. These seasonal values were weighed by h to construct a synthetic time series for θ. Unfortunately, this construction is unable to capture the alleged increasing trend in E_{dM} described by fishermen in our interviews.

A 1968–1993 data set for the Maine inshore lobster fishery was obtained from the New England Regional Fishery Management Council (Russell, 1994). These data consist of monthly observations for May–October for the years 1968–1993. Thus, in reading figures based on these data, there are six observations in each year. Table 1 contains descriptive statistics for this data set. The month variables are periodic (May=5, June=6, etc.) which are used in several regressions to be presented later. The mean values for traps, set over days, haul rate and catch-per-day at sea are 347 traps, 3.2 days, 173 traps hauled and 86 lobsters per day at sea, respectively. The data set does not explicitly give days at sea; it is imbedded in the denominator of the catch rate in number of lobsters per day at sea. In our survey of Maine inshore commercial lobstermen the mean values for traps, soak time, haul rate, days at sea and catch were 648, 2–3, 293, 20 (during summer months) and 260. Inputs and landings of the lobstermen in our survey were much larger than average. Considering the survey focus on full-time commercial fishermen, we may speculate that they may be more motivated by pecuniary returns than smaller fishermen. Below are the results of some simple trend fitting for selected variables. It should be noted that the same functional form will be used more than once below. While the form is reused, the

Table 1. Descriptive statistics for the Maine Inshore Lobster fishery for May–October, 1968–1993.

Statistic	Traps, T	Synthesized soak time, θ (days)	SOD (days at sea)	Haul rate, h (traps per day)	Catch
Mean	346	2	1.99	173	86
Mode	238	1.9	1.27	172	118
Min	160	1.2	1.20	91	31
Max	943	4.6	4.64	258	202
Range	783	3.4	3.44	167	171
Variance	11 475	0.19	0.20	816	1278
Standard deviation	107	0.43	0.44	28.6	35.7
Coefficient of variation	31	21.6	22.4	16.5	41.4
Skew	1.44	1.57	1.56	0.03	0.90

coefficient values will differ between applications. The time-series components were modelled following Waugh's (1970) method as f(t) in Equation (7):

$$f(t)=\rho_0+\rho_1 t_1+\rho_2(\alpha_1\sin(\eta+yt_2)+\alpha_2\cos(\eta+yt_2)) \qquad (7)$$

where:

t_1 = Year − 1967;
t_2 = month number, January = 1 and December = 12
ρ_0 = intercept term
ρ_1 measures the time rate of increase in the dependent variable
ρ_2 measures the amplitude of seasonal oscillations
η and y are phase and frequency parameters respectively
α_1, α_2 are relative weights for sine and cosine terms

Usually seasonality is assumed of constant amplitude, but a simple extension of covariance variables allows for regimes of differing amplitude. The η and y parameters are phase shift and frequency parameters. We can extract some information about SOD trends from the data. SOD can be regarded as soak time expressed in days at sea rather than calendar days. However, while true, this is misleading unless days at sea is constant seasonally and between years. What trend is there in the SOD variable? To answer this, the log of SOD was regressed on year and on month covariates as indicated in Equation (7). From the regression estimate of ρ_1, there was a 1.7% annual increase in SOD. Strong seasonality is also evident with significant sine and cosine coefficients. This simplistic approach does not attempt to capture the decision making processes of fishermen and the simple harmonics of f(t) do not capture this seasonality except in a very limited way. The net effect on catch rates of increasing input trends depends on how the inputs are assembled in a production function. This is explored empirically below.

Estimated production function

The production function to be used is the following hybrid of log linear and Mitscherlich–Spillman forms:

$$C(t)=\beta_0 e^{f(t)}T^{\beta_T}d^{\beta_d}(1-e^{\beta_\theta\theta}) \qquad (1')$$

See Table 2 for variables. For data on soak time, a pseudodata series was generated using Equation (7) and the seasonal values for d from our 1994 survey. The functional form f(t) is used from (7) but the parameters were re-estimated for the catch data. This procedure captures the seasonality aspect of days at sea, but it does not capture the hypothesized increasing trend over time in E_{dM}. Because of the way the pseudodata for soak time was generated, β_θ was imposed as an exogenous estimate derived from a local fisherman's data. These data suggest a value β_θ of 0.91. Data in Fogarty and Addison

Table 2. Regression parameter estimates for equation (1′).

Variable	Parameter	Final
Intercept	ρ_0	0.4465
Trend (t_1)	ρ_1	−0.031
Seasonality parameters:		
t_2 (first two decades)	ρ_{20}	0.106
t_2 (after two decades)	ρ_{21}	0.168
Sine	α_1	−0.9416
Cosine	α_2	2.2425
Phase	η	−1.734
Frequency	γ	0.908
Structural parameters:		
Traps	β_T	0.3241
Days at sea	β_d	0.6614
Soak time	β_θ	0.9 (constrained)
$R^2_{linear}=0.695$	N = 156	

The same functional form and parameter symbols have been used for f(t), the time series components, in both equations (1′) and (11). The parameter values are different.

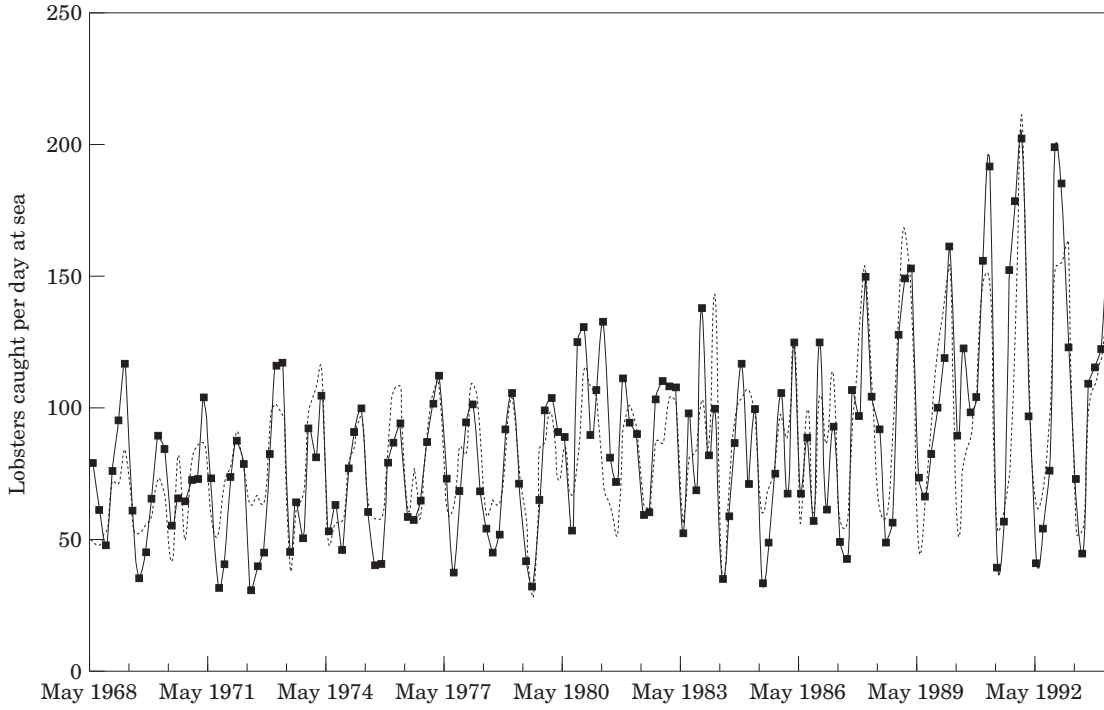

Figure 1. Catch per day at sea. Observed (—■—) and estimated (- - - -) for May–October, 1968–1993.

(1997) suggest a value for β_0 in the range 0.23 to 1.1. Both the Fogarty and Addison data and the fishermens' data suggest a Mitscherlich–Spillman form to be the appropriate form of response. Therefore, in the economic analysis which follows, this form is used. Fitting equation (1′) with constrained β_0 ensures that the intercept coefficient is properly scaled for subsequent numerical analyses. The form actually fitted was $\ln(CT^{-1})$. Conversion back to equation (10) involves multiplying by T. This enables us to generate scenarios, but the scenario validity is only as good as the functional forms and parameter constraints imposed. Non-linear least squares in Excel was used to fit the model. The term f(t) is a periodic function described in Equation (7), but with the added feature that the amplitude parameter differs during the last three years (after month 117). Figure 1 contains the observed catch data with the estimated or predicted values superimposed. The data consists of six monthly observations (May–October) for each year from 1968–1993. The largest source of variation in the data is the pronounced seasonal cycle, which is captured quite well by the fitted equation. Furthermore, the response surface (non-linear least squares) is evidently quite flat with respect to soak time. Variations in a priori constraint bounds on β_0, the parameter for soak time cause only very small changes in the goodness of fit.

The time series components hold no great interest except as a mechanism to adjust for seasonality and time trend and to lower residual variance; it is the structural coefficients which are of primary interest. The estimate for $\beta_T=0.32<1$ is consistent with a trap congestion effect, although there may be complicating factors which are discussed briefly below. We need to ask what other evidence exists for the congestion hypothesis. The so-called "Law of diminishing returns" is a less precise statement of this law. An alternative statement is the mathematical property of quasi-concavity. The stronger property of concavity is often justifiable in production problems and is what people often mean by "diminishing returns". The import of this Law is that we should (but do not) have measurements of T on a per-unit-area basis. Krouse (1989) makes the following statement: "Whereas in 1900 there were 3105 licensed Maine lobstermen fishing 327 000 traps close to shore, in 1985 7879 fishermen . . . used about 2 million traps . . . or an average of 365 traps per boat. . . . Although the spatial distribution of fishing effort has not been defined, it is not uncommon for today's inshore lobstermen to fish 10–20 miles offshore."

While we lack a time series on economic and travel time, Krouse's observation carries an implication which is consistent with (but does not prove), the congestion hypothesis. It seems quite possible to me that the omission of bottom area fished may be affecting the estimation problem, and the direction of bias is of concern to the hypothesis of trap congestion. We cannot properly address this possibility without data on area. Following Krouse's observation about a secular trend

away from shore, we would expect such a trend to be accompanied by higher costs for fuel and opportunity cost of time. Accordingly, we would expect a marginal reward to moving offshore over time, and/or trap congestion effects that are more severe closer to shore; otherwise what incentive exists to incur the higher costs of offshore operation? If this reasoning is accepted, the bias, if any, would be in the direction of underestimating the congestion effect in time series data. Related to this pattern of moving to new areas is the well documented territoriality of "lobster gangs" (Acheson, 1975). Why is there a territorial motivation if there is no trap congestion? If, after all, the catch per trap of existing fishermen is unaffected by the traps of a newcomer, why would existing fishermen oppose the new entrant? I am inclined to conclude therefore, that $\beta_T \approx 0.32$ is correct, but the precision and bias of the estimate are unknown and should be checked with other data sets. At this point, I will accept it provisionally and explore the economic and behavioural implications.

To explore economic behaviour we draw on the assumption of constrained cost minimization. We ask the outcome if, at each and every observed monthly harvest rate, the costs of harvest were minimized. This is a weaker assumption than profit maximization, but it allows us to obtain conditional derived demands for inputs. Profit maximization yields unconditional derived demands for inputs in that inputs are cost effective and are increased until the marginal cost of catching the last lobster equals lobster price. By contrast, we will force catch to equal observed catch but minimize the cost of achieving the observed catch. Costs in this case include more than accounting costs. The supply price of labour depends, *inter alia*, on the conditions of work. We would expect a higher supply price for labour if the number of traps hauled per person-day increases. To include this aspect, the data on catch per day at sea were converted to an equivalent revenue per day and a lay system applied to determine revenue per person-day at sea. A supply price for labour was hypothesized as Equation (8):

$$P_1 = \beta_0 e^{f(t) + \omega_u U + \omega_w W + \omega_h h} \tag{8}$$

where:

P_1 = supply price of labour calculated from daily revenue per crew member
f(t) = an harmonic function as in Equations (9) and (10)
U = unemployment rate in Maine (from Bureau of Labor Statistics)
W = wage rate of non-supervisory workers in manufacturing in Maine Standard
Metropolitan Areas, indexed to May, 1985 = 1.

Table 3. Regression parameter estimates for equation (11).

Variable	Parameter	Estimate
Intercept	ρ_0	1.5118
Month (t_2)	ρ_2	0.3923
Phase	η	0.8929
Frequency	γ	0.7597
Sine	α_1	0.6044
Cosine	α_2	− 0.1900
U	ω_u	− 0.0846
W	ω_w	1.3125
h	ω_h	0.0058
$R^2_{linear} = 0.676$		

Symbols as Table 2.

The parameter estimates are in Table 3. As expected there are strong seasonalities, but the structural components, i.e. unemployment, non-supervisory manufacturing wage rate in Maine and the haul rate, have the expected signs. We will use this relationship later in optimizing input management decisions. It allows us to include the effects of labour supply conditions which fluctuate seasonally, with the unemployment rate, and the prevailing wage rate on shore and the haul rate.

Analysis and implications of the estimated production function

Economists often use optimization methods to study human behaviour. Depending on context we may assume producers are profit maximizers and that consumers are utility maximizers, or that they are constrained cost minimizers. There are good reasons to support this. Firstly, as numerous writers have noted, under competitive conditions it can mimic the outcome of a selection process. Use of optimization methods has no teleological significance; only a pragmatic one of usefulness. Unfortunately, it can be difficult to discern an appropriate objective function in a specific situation. In principle, it would seem sensible to suppose that fishermen seek to maximize utility. This is possible with a more complete data set but not with that at our disposal. A lower objective, such as maximizing a discounted time integral of profits is also appealing. Such an objective contains two components, viz. (1) minimization of cost for any arbitrarily chosen catch rate, and (2) choosing a level of catch that maximizes discounted profits. We can split these components by examining the behavioural implications of a constrained cost minimization. Suppose a lobster fisherman seeks to minimize cost subject to a constraint on minimal target rate of monthly harvest (isoquant). By settling this target rate at observed catches we can finesse issues of the optimal harvest rate and focus instead on cost effectiveness of inputs. The choice of a one-month period is somewhat

arbitrary but the period must be long enough to encompass a soak cycle, which is an endogenous variable. A month also fits with the data sampling frame in our data set. The associated Lagrangian function is Equation (9a) with constraints in Equation (9b):

$$£ = C(T,h,d,N) + \lambda_Q[Q - F(T,\theta)] + \lambda_\theta[MT - \theta hd] + \lambda_h[h - hpm\Sigma_i L_i] + \lambda_i[\bar{L} - \Sigma_i L_i] \quad (9a)$$

Constraints:

$$Q - F(T,\theta) \leq 0 \text{ Isoquant} \quad (9b)$$

$$MT - \theta hd = 0 \text{ Soak time}$$

$$h - hpm\Sigma_i JL_i] \leq 0 \text{ Haul rate}$$

$$\Sigma_i L_i = \bar{L} = 1 \text{ Crew size}$$

$$0 \leq L_i \leq 1$$

Decision variables:
(1) Primal variables: T, h, θ, d, L

L_i; 1=(1,2,3) for (captain only, captain+one sternman, captain+two sternmen)

(2) Dual variables:

λ_Q=marginal cost of catch (isoquant)
λ_θ=marginal cost reduction enabled by a unit change in soak time
λ_h=marginal cost reduction enabled by a unit relaxation of the haul rate constraint
λ_i=marginal cost reduction enabled by a unit change in man-days

Functions:

F(.)=the production function of Equation (7)
$P_{li}(L_i) = \alpha_{li} e^{\beta h}$
C(T,h,d,N)=variable cost function.

Formally, costs should be discounted. However, the duration of the discounting process is the soak time (approximately 1 week, maximum). The ratio of the terminal to initial discount factors would be less than 0.02% which would have a quite trivial effect on the outcomes. As a matter of judgement I choose to omit this detail.

$$Cbait = b_0\theta^{E_{b\theta}} = \text{bait cost per trap haul} \quad (9c)$$

$$C(T,h,d,n) = od + tm*T + d[p_1(L_1)L_1 + (p_1(L_1) + p_2(L_2))L_2 + (p_1(L_1) + 2p_2(L_2))L_3 + b_0\theta^{\xi_{b\theta}}h] \quad (9d)$$

Parameters:

Q=target isoquant
$\bar{L}$=labour supply index; [=1, 2 or 3
hpm=estimated maximum traps hauled per man-day at sea=150
o=operating cost per boat day at sea=46
b=mean bait cost per trap hauled at a 3.8 day soak=0.17
b_0=0.062 and $\xi_{b\theta} \approx 0.75$
tm=monthly cost per trap on bottom=0.09
p_i=daily opportunity cost of captain, sternman 1, sternman 2

The daily opportunity cost of captain and sternmen were differentiated based on the differential (16%) obtained in the 1994 survey and applied to Equation (9b). The primal solution vector to this minimization problem is Equation (10):

$$T^* = T(Q, o, w_i, b_0, \xi_{b\theta}, tm, hpm) \quad (10)$$

$$h^* = h(Q,o,w_i,b_0,\xi_{b\theta},tm,hpm)$$

$$d^* = d(Q,o,w_i,b_0,\xi_{b\theta},tm,hpm))$$

$$\psi^* = \psi(Q,o,w_i,b_0,\xi_{b\theta},tm,hpm))$$

$$l_i^* = l_i(Q,o,w_i,b_0,\xi_{b\theta},tm,hpm))$$

These primal variables are cost-constrained conditional (-on target catch) derived demands for traps, haul rate, days at sea, soak time and labour expressed as functions of catch level Q, input supply prices and crew size. Due to inequality constraints and non-linearities, analytic solutions are unavailable. Instead, numerical methods were used to solve for optima at each value of parameters of interest. If it were known that fishermen are cost effective and cost data were available it would have been possible to use duality theory and statistical estimation to obtain cost functions and conditional derived demand equations directly. Unfortunately, we lack a time series on the required input cost parameters. Moreover, if we are correct in our development of a trap congestion externality and open access baiting pathologies, cost effective behaviour is in question and a dual approach would estimate an actual cost function rather than the cost minimizing one. If we are correct, the primal approach we are following will indicate cost effective input demands that are less, for any target output, than those actually demanded by fishermen. Of course, a lack of correspondence between theory and observation may also mean that the theory is wrong. Conversely, if our results are consistent with the inputs actually chosen, it would indicate that fishermen are in fact cost effective. The outcome is not obvious because

traps and soak time are substitutes in the soak time constraint. It may be cheaper to use an excess of traps so as to increase soak time. On the other hand, if the rush to re-bait dominates, then a shorter soak time and fewer traps may be preferred, even if it is not cost effective. Alternatively it may pay to add a sternman so as to increase traps and decrease soak time simultaneously. If the derived demands of Equation (10) are substituted into Equation (9a), the terms involving constraints vanish due to the complementary slack conditions, and we are left with the Indirect Cost Function of Equation (11):

$$£^* = TVC = C(T^*,h^*,d^*,\theta^*,L^*) = V(Q,o,w_i,b_0,\xi_{b\theta},tm,hpm) \quad (11)$$

Equation (11) expresses the minimum variable cost required to harvest catch Q given input supply prices, trap hauls per man-day and input supply constraints. The properties of the indirect cost function V(.) are well established and include the property that the partial derivatives with respect to input prices are the cost minimizing conditional derived demands of Equation (10). In general, analytic solutions for Equation (10) and Equation (11) are known only for rather special cases involving functions simpler than those we are using. In our case we must resort to numerical methods. The cost minimization problem was expressed in GAMS (Brooke *et al*., 1988) and solved using the CONOPT solver. The observed values of catch for 1985–1993 were selected for target isoquants (isoquant = daily catch, Q, multiplied by days at sea), and the model solved repeatedly for the observed catches in the data set. Our immediate interest is in comparing observed and cost minimizing inputs at output levels actually selected by fishermen. The results are indicated in the following series of Figures. These data contain six monthly observations (May–October) for each year from 1985–1993. In most Figures we have both a minimum cost variable and its observed counterpart plotted against month and year. In a few cases (soak time and crew size), we lack the observed values. In most cases there is an obvious seasonality in both the observed and minimum cost variables. The correspondence is imperfect in part because the cost minimization model uses a forecasted production function which contains imbedded within it the harmonic function of Equation (7). Unlike in nature, such a function has no random shift in phasing or amplitude. Differences in phasing and amplitude between observed and minimum cost values of variables are the joint product of both the forecasting and optimization processes. Since our hypothesis is that observed inputs are not cost minimizing, we do not expect the model outputs to replicate the observed data. However, it is somehow reassuring if we see echoes of observed seasonality in the model output.

Cost minimizing and observed traps on bottom

Figure 2 contains the graphs of four measures of traps on bottom. Two of these are the observed and cost minimizing number of traps given the observed daily catches during 1985–1993. Also shown is the cost minimizing traps (''Traps Limit'') when the solution is constrained by a 1200-trap limit. This variable tracks the unconstrained cost minimizing number of traps except in months where the latter exceeds 1200. In those months, the peaks are truncated at 1200 traps. To assist in seeing the effect of this constraint, I have also included a fourth series which is an arbitrary horizontal line (''Traps constraint'') at 1200 traps, illustrating graphically the positioning of this constraint. It appears that the optimization model contains a reasonable representation of seasonality, but the average level, trend and amplitude of seasonal variation in traps is much larger than observed. This may be due to the absence of any consideration of weather conditions or the labour required to vary traps on bottom. It may also be due to the use of a synthesized estimate of days at sea (d), which estimate is a co-determinant of monthly catch. The other difference in Figure 2 is that the cost minimizing level of traps given the observed landings is (almost) uniformly larger than the observed number of traps. The effect of a 1200-trap limit is to truncate the peaks in the optimal number of traps on bottom, but the observed number of traps on bottom would have to double or triple before the limit would have any effect on decision making. There is some reason to be suspicious of the true optimality of the extreme changes in amplitude in the minimum cost series. We have oversimplified by using a monthly depreciation charge for traps on bottom. This oversimplifies in two ways that work in somewhat opposite directions. First, this charge should be the sum of the difference (if any) between depreciation on bottom and on shore and the difference (if any) in month specific risk of trap losses on bottom vs. on shore. Secondly, we have assumed that inter-month variations in traps on bottom are costless. This is surely an oversimplification. If the required cost information were available, it is possible to modify the model to include such fine detail. It seems likely that such changes would attenuate the amplitude but not the average level of the cost minimizing solution.

Cost minimizing and observed soak time

Figure 3 shows the ''observed'' and cost minimizing soak time given the observed daily catches during 1985–1993. Observed is in quotes because, as discussed earlier, it is pseudodata. In an earlier version of this paper, bait per trap haul was assumed to be fixed. Under this specification, it proved necessary to upper-bound soak time. The upper bound I chose was seven days because a

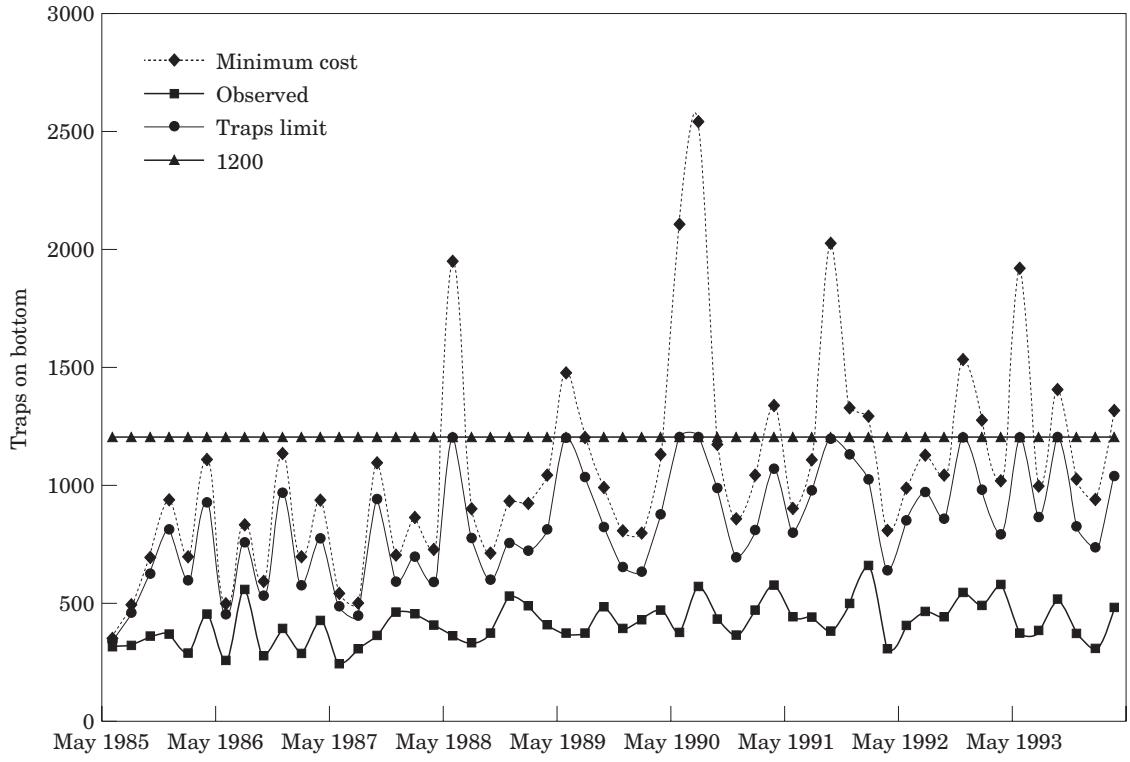

Figure 2. Minimum cost and observed traps on bottom, for May–October, 1985–1993.

week is one of the natural cycles that influence our lives, but this was entirely *ad hoc*. In reviewing results with lobster fishermen, the relationship in Equation (9c) was discovered. When this relationship is used, the optimal soak time is now an interior solution and it is no longer constant. This soak time is used, the optimal soak time is now an interior solution and it is no longer constant. This soak time is significantly longer than the observed soak times reported in our 1994 survey; with the exception of winter, when a soak time of seven was reported. The fact that it was necessary to upper-bound the soak time is significant and is discussed below in connection with Equations (1) and (6).

Clearly, the least cost solution involves a stock of traps on bottom larger than the observed and a longer soak time. Of course, this discrepancy could be due to the heterogeneity of individuals included in the average data used. For part-time fishermen, the incentives for cost minimization are less poignant. This interpretation is supported by the discrepancy between marginal cost of harvest and product price. The dual variable on catch is uniformly less than ex-vessel price; a fact that suggests the ''average'' lobsterman produced much less than the landings that would have maximized profits. We will revisit this topic later when we explore the cost savings achievable by full-time commercial lobstermen.

Cost minimizing and observed haul rate

Figure 4 shows the observed and cost minimizing haul rates (h) given the observed daily catches during 1985–1993. The average and least cost haul rates are about equal, and the latter haul rate, shows strong seasonality that is fairly similar to that observed. The seasonality imbedded in production is not exact, it is imposed by the Waugh time-series function which assumes that seasonality is unchanging from year to year. The haul rate is upper bounded at hpm=170 per man-day. The only way to raise this is to add a sternman. This has been happening with greater frequency in the optimum solution for recent years and also fits with that which lobstermen told us. In our 1994 survey of commercial fishermen, the haul rate ranged from 230 to 290 seasonally. This is a much more stable rate than the observed rate in Figure 4. The most obvious interpretation would again be the heterogeneity imbedded in the average fisherman which includes many part timers in the summer months. While the supply price of labour does increase with the haul rate (Equation (8)), the increase is modest relative to the cost of bait and the seasonality of catch rates.

Cost minimizing crew size

The labour on a lobster vessel always includes a captain. It may or may not include one or more sternmen.

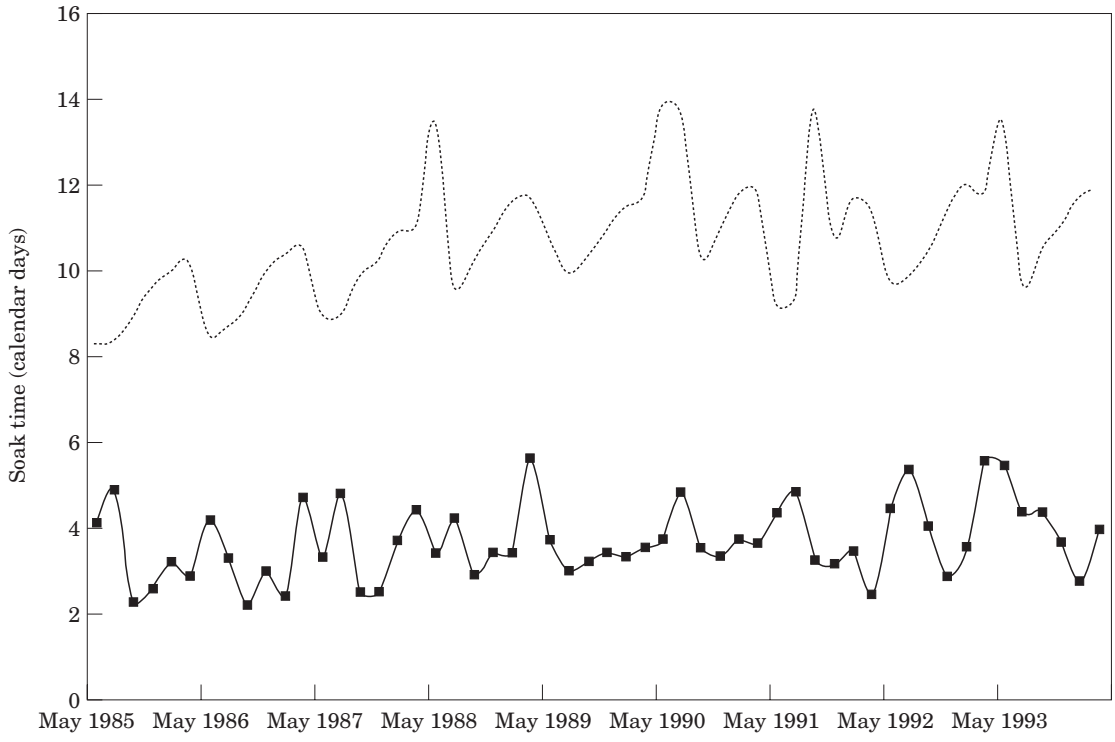

Figure 3. Soak time: minimum cost (· · · ·) and observed (—■—), for May–October, 1985–1993.

Collectively we will refer to this labour as "crew size". If traps hauled per day at sea increase, a point is reached where adding a sternman becomes increasingly desirable if not obligatory. Figure 5 shows the cost minimizing crew size by month during May–October 1985–1993. This figure shows clearly a trend over time towards larger crew sizes during peak periods of activity. We do not have observations on this variable, but the pattern fits with that which fishermen told us had been happening. The variability of crew size in Figure 5 would probably be greater had we not included the labour supply price Equation (8). The seasonality of this supply price captures the willingness of some sternmen to lobster only during a peak month whilst others demand greater employment stability for lobstering to be attractive.

Cost minimizing and observed set over days

Figure 6 contains a graph of observed and cost minimizing set over days plotted against time during the months May through October of 1985–1993. The ratio of observed to minimum cost SOD is also plotted in this figure. The least cost SOD are noticeably higher than the observed, and have a greater amplitude of seasonal oscillation. This pattern stems from the greater seasonal amplitude of optimal traps on bottom as discussed above. Figure 6 shows the observed and cost minimizing SOD for given the observed daily catches during 1985–1993. From the regression results with Equation (7) we saw that SOD increase by 1.7% per y. One interpretation of this secular trend is that fishermen are aware of the greater cost effectiveness of longer soak times and are adjusting in a direction that is more cost effective. Another interpretation is that fishermen who set more traps than average are just being greedy. It may be the latter interpretation which drives current efforts to impose trap limits. Both interpretations may have some truth, but seems to me that the case for the cost effectiveness of trap limits is not self evident.

It is concluded (subject to some caveats listed below) that the average Maine lobster fishermen is not combining inputs in the most cost effective manner. This behaviour may be due to the soak time effect and to congestion effects between fishermen. Excessively high soak frequencies arise from an externality imposed by each fisherman on his neighbour. A collective decision to increase soak time would lower the costs of all. Unfortunately, Hardin's (1968) "tragedy of the commons" applies here. Hardin's phrase has taken root in the lexicon of natural resource (mis)management despite the fact that it is a malapropism for open access to a fugitive resource. Unilateral action to increase soak time by an individual fisherman might only shift revenues

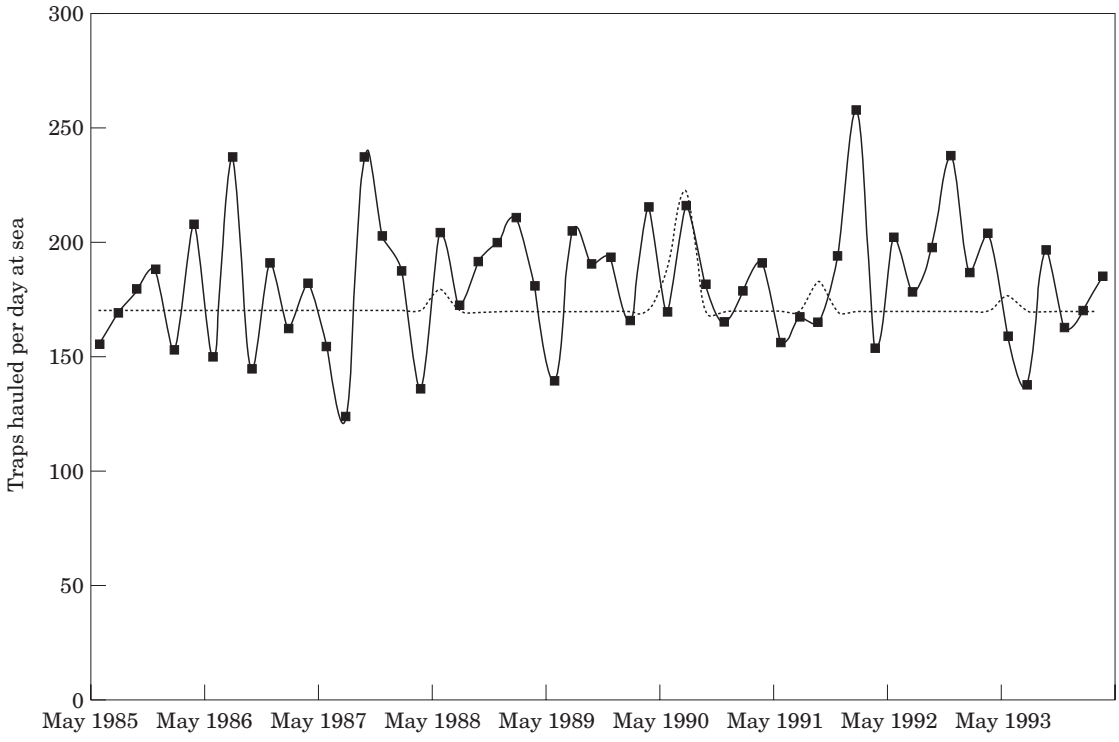

Figure 4. Haul rate: Minimum cost (· · · ·) and observed (—■—) for May–October, 1985–1993.

from him to his peers. If we make an analogy to forestry, each forest (trap) is harvested prematurely (re-baited) lest a neighbour does so and thereby attracts lobsters away from traps with older bait.

Our survey data from 1994 differs significantly from the average time-series data used to this point. By design, the survey focused on lobstermen who considered themselves to be full-time commercial fishermen. These commercial fishermen used far more traps and caught much more. Using the earlier model we solved a dual version with inputs as indicated in the survey and maximized output attainable with these inputs and the average production function. The results indicated that the productivity per trap hauled is substantially more for the commercial fishermen. This may be due to differences in skill and productivity of grounds. In any case, after adjusting the production function for these productivity differences, we solved for the minimum cost solutions given the reported commercial catches. Much the same story emerges of excessive inputs and operating costs relative to minimum cost.

The alternative function: a re-consideration

There is some disagreement about the existence, or indeed relevance, of the right tail (catch rate decreasing with soak time) of the curve numerically integrated from Equation (6). Biological scientists advise that while there was some uncertainty about the curve at very long soak times, the issue was of little practical importance, since no one would want to adopt a soak time so long that catch rate is diminished relative to the maximum. The plausibility of this assertion seems re-enforced by the fact that fishermen do not adopt such a long soak time. However, preconceptions can be misleading. Why did the mathematical programming solution always yield a corner solution when we assumed a constant bait cost per trap hauled? Answers to this depend in part on whether bait cost per trap haul is independent, or a function of soak time. For the purposes of this section only, we will temporarily assume that bait per trap is unaffected by soak time. Figure 7(a) and 7(b) help us to answer conditionally this question and highlight the need for field experiments to establish the appropriate functional form for the soak time relationship. Using the functional form of Equation (1), catch rate is non-decreasing in soak time and approaches an asymptote. As soak time increases over a wide range, costs decrease so that with Equation (1), increasing soak time is always cost effective: it pays to select the maximum allowed soak time. That is why the "optimal" soak time was always a corner solution in earlier versions of this paper. Figure 7(a) contains superimposed graphs of Equations (1) and (6) so the differing responses at long soak time is

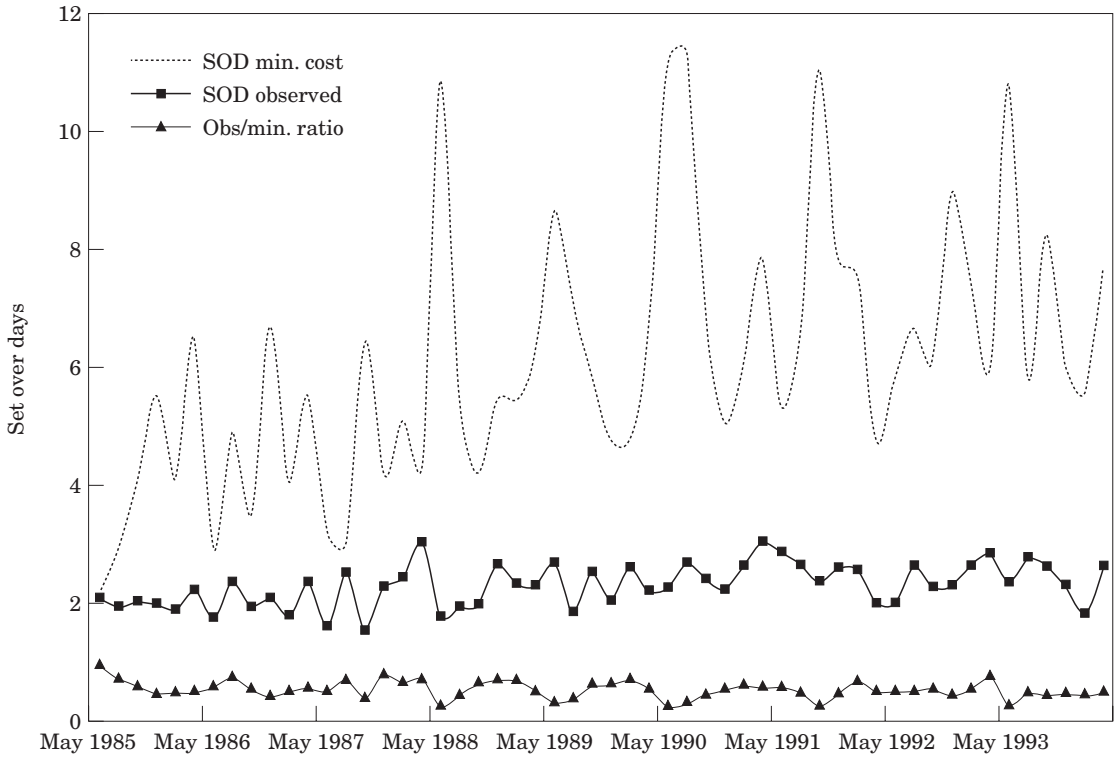

Figure 5. Cost minimizing crew size, for May–October, 1985–1993.

clearly evident. To emphasize the differences in shape an unrealistically large escapement parameter value (μ in Equation (6)) is assigned. A more realistic value would show only a slow (if any) decline in catch rate at long soak times. We know this because the studies reviewed by Miller (1983) show only ambiguous evidence for such declines. Now we focus on the "alternative" production function and its numerically integrated graph in Figure 7(a). Consider points A, B and C in Figure 7(a). In moving from A to C:

- catch rate increases
- revenue increases
- costs decrease
- profits increase

In moving from B to C

- catch rate increases
- revenue increases
- costs increase
- profit change uncertain

In moving from A to B:

- catch rate is unchanged
- costs decrease
- revenue is unchanged
- profits increase

We can conclude therefore that a soak time less than that associated with point C can never be cost efficient when bait cost per trap haul is constant. The relevant economic region always involves a soaktime at least as great as that associated with point C. This is true when using Equation (1) or (6) as the basis of our production function. This may indicate that we have an inappropriate functional form and are focusing on the wrong region. The key lies in the fact that a move from A to C involves increasing catch and decreasing cost. Such a move will always be economically advantageous, we do not need empirical data to deduce this. However, we are conditioned by training and experience to suppose that the relevant region on a production function lies between the origin and the maximum of the curve. Now suppose we shift to soak frequency instead of soak time. When we do so, we obtain Figure 7(b). Using the alternative functional form, we still have a curve which increases, reaches a maximum and then falls. The positions of A and B relative to C have been switched. As we ascend from B towards C, catch rates increase as do costs, and the profit maximization question requires finding an equality between marginal costs and lobster price. How far to go involves a balancing of the additional monthly revenue realized from a higher soak frequency vs. the additional operating costs necessary to decrease soak time. This may also shed light on why past econometric attempts to estimate a multivariate production function for the lobster fishery have had little success. If data are clustered too narrowly around the

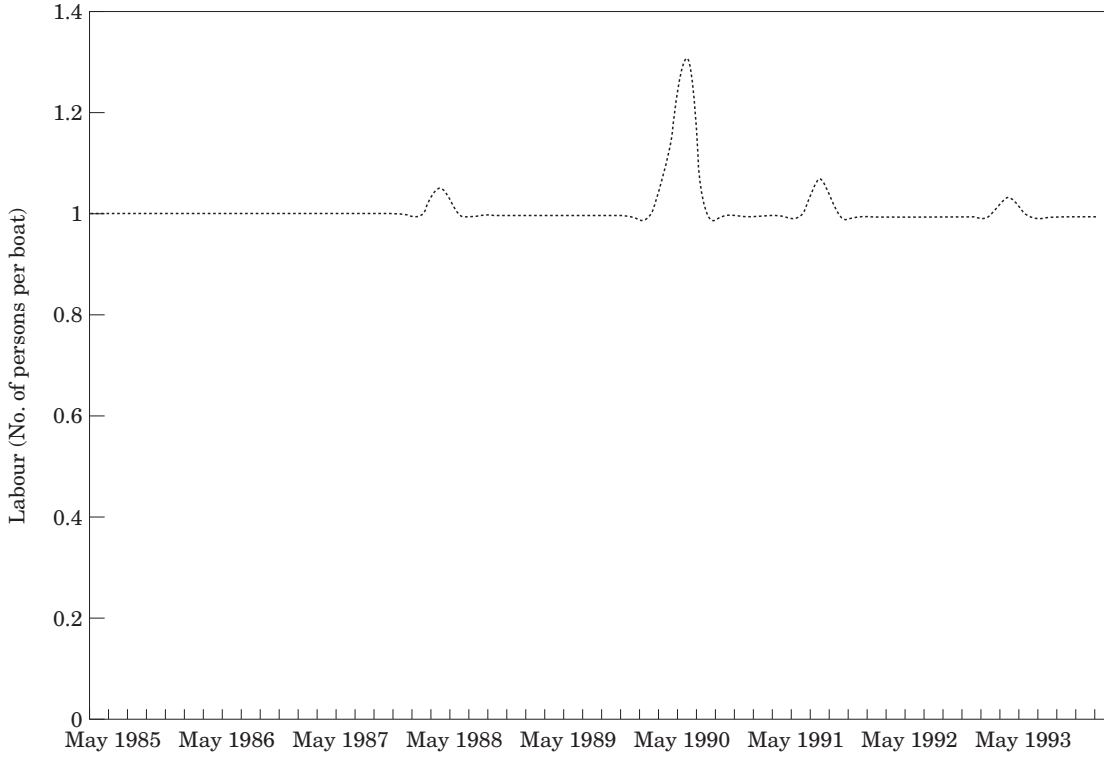

Figure 6. Set over days: minimum cost and observed, for May–October, 1985–1993.

stationary point C, the structural components of any model are difficult to distinguish from the random noise component. Measurement of curvature requires a wide range of variation in variables. Thus, a simple change of variable from soak time to soak frequency focuses attention on the economically relevant region. If points B and C fall on a horizontal line (as they almost do with Equation (1)), then increasing soak time lowers cost while leaving catch and revenue constant, or nearly so. Cost effectiveness implies simultaneous substitution between capital (in the form of number of traps) and operating costs. In general, the costs of traps are so low that even with trap congestion, the optimal solution involves more traps and longer soak times than those we observe. Notice how the change from soak time to soak frequency has compressed the graph of Equation (1) for long soak times (low soak frequency). In the neighbourhood of the *status quo* (soak frequency ≈ 0.5), with the proposed function we can reduce soak frequency, reduce cost and increase catch. Thus, Equation (1) always leads us towards the highly compressed region with a soak frequency as low as we allow it to be. This is of course possible; nature and trap technology may make it so. Another way to look at the matter is as follows. Suppose a change in trap design reduces the rate of escapement. Such a change should lead lobster fishermen who are cost effective to increase their soak time because it moves the right tail of the catch rate–soak time relationships towards a horizontal line. If the alternative functional form of Equation (6) applies, then economic decisions, rather than an arbitrary constraint will determine the optimal soak time. It is, therefore, a matter of considerable economic and behavioural importance to establish the correct functional form when selecting management restrictions such as a trap limits which may raise costs, yet offer little conservation benefit.

If it is more realistically assumed that bait per trap haul increases with soak time, the above changes. In particular, from A to C, it is no longer the case necessarily that costs decrease. That is why, with the specification in Equation (9c), the optimal soak time is longer than a week but it is unconstrained, a solution interior to the logical maximum of 30 d.

Since the parameter $\beta_T \approx 0.32$ is also uncertain, it is also appropriate to consider what would happen if it were unity (no congestion). Because traps would no longer suffer from diminishing productivity, an absence of congestion would cause optimal number of traps to be larger and soak time longer (assuming the Mitscherlich–Spillman form is retained) than we have indicated in this analysis. For the most part, the one-person boat was most cost effective. However, this varies seasonally and use of a sternman is more often optimal in recent years in order to work the larger numbers of

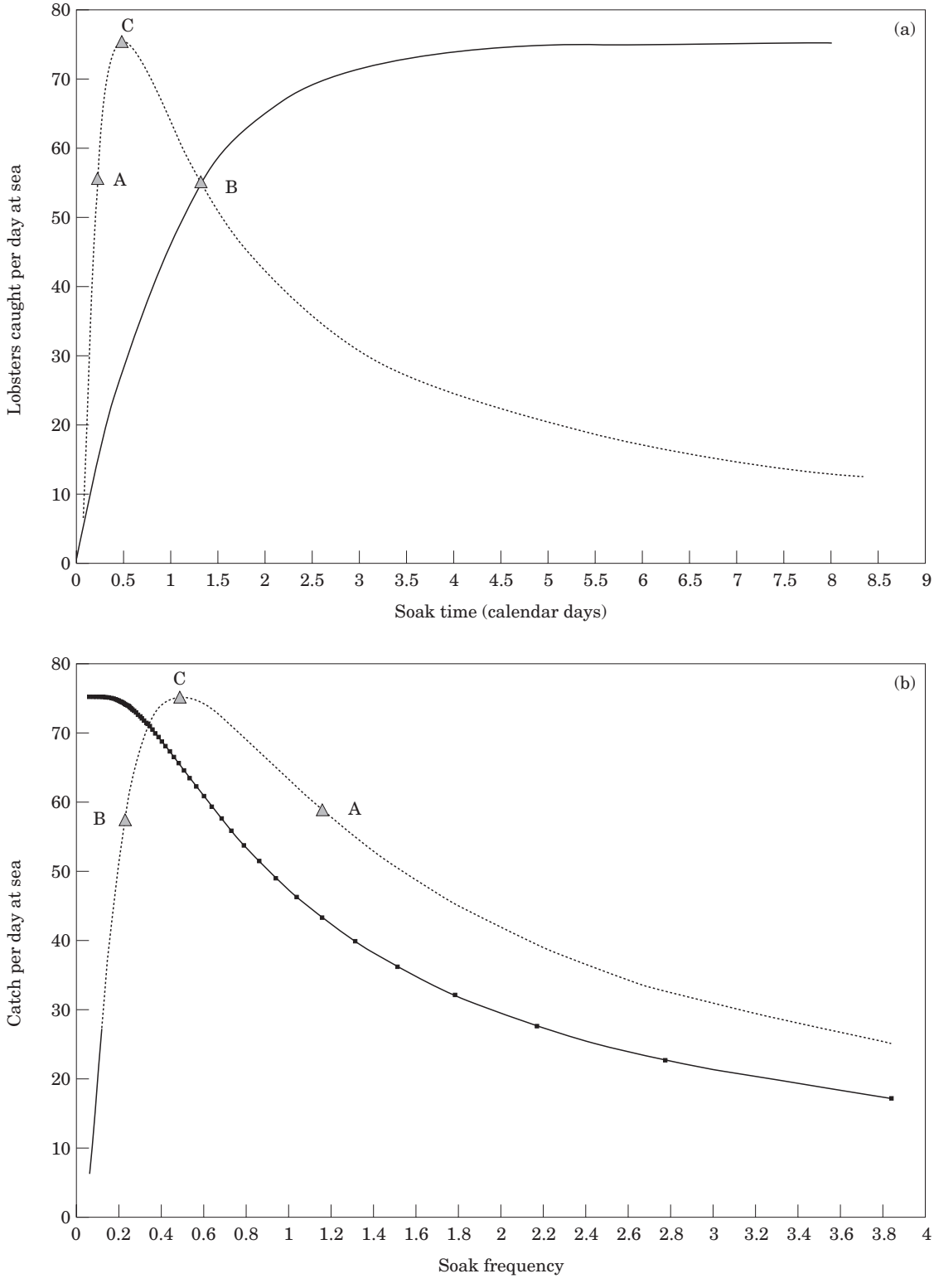

Figure 7. (a) Catch rate vs. soak time. (b) Catch rate vs. soak frequency.

traps during months of peak availability. If product price were to rise sufficiently, or if trap limits were to become effective constraints, the effect could be economically perverse as fishermen race to preserve their share by further reducing soak time at great cost. It is also clear that a typical fisherman could (if lobster prices warrant), substantially increase catch rate by increasing labour and trap inputs. While this may be true at an individual level, in the aggregate it seems unlikely that such an increase would be biologically achievable much less sustainable (we are not attempting to capture the inter-year population dynamics of the fishery). However, it is possible to increase the fishing mortality coefficient sevenfold since this coefficient is unbounded from above. If we convert to a fishing mortality basis, we can say that there is considerable elasticity remaining in the supply curve for fishing mortality (F), and a trap limit of 1200 traps per boat is unlikely to constrain aggregate F for a long time to come. Unfortunately, an effective trap restriction may have the perverse effect of preventing more cost effective soak time decisions. This may be an unavoidable consequence of the many difficulties which limit manager's options for conservation, but it is an issue which both fishermen and managers should consider. Fishermen resolutely resist self taxation because taxes obviously raise costs, but often favour management measures, such as trap restrictions, which will have the effect of raising costs (or preventing a reduction in costs). A system of individual catch rights might provide an incentive for more cost effective input combinations. So too might a tax on bait. The administrative and political feasibility of either is questionable. The willingness of New England fishermen to impose taxes on themselves is conspicuous by its absence. A local management agency with appropriate authority could enforce individual quotas. Whether it would be granted powers of monitoring and enforcement adequate to the task and whether it would choose to exercise those powers is unknown. Governance at any level costs money to operate programmes of monitoring and enforcement. Historically such cost issues have been avoided by passing the costs of management to the general taxpayer. A contribution we can make by this analysis is to indicate the potential savings in harvest costs if fishery management measures led to inputs that were more cost effective. These savings provide an upper bound on the savings available to support management measures leading to such cost savings. Additional economic benefits to fishermen and consumers are also realizable from reducing fishing mortality levels: that topic is developed in other papers including Richardson and Gates (1986). Thus, it is a matter of some interest to determine the magnitude of cost savings from more efficient input management. The following section presents such a determination.

Cost savings from efficient input management

With the concepts now at our disposal, the cost increases associated with inefficient input management can be examined. To do this, survey data from commercial fishermen as discussed above were used. Examination of data for full time commercial fishermen from our survey and for the average Maine lobsterman suggests that the former are technically more efficient producers. To formalize this, we fixed inputs at observed values and maximized output with the estimated average production function. The ratio of observed catches of commercial lobstermen to these maximum outputs indicates the greater productivity of commercial fishermen relative to that of average fishermen, taking into account differences in inputs chosen by the two. This relative productivity allows us to rescale the production function to allow for the greater productivity of commercial lobstermen. This greater productivity may be due to correlated differences in abundance or hours worked per day at sea.

The indirect cost function of Equation (11) expresses the minimum cost required to land monthly target catch Q, given input prices and constraints. We can subtract this minimum cost function from actual costs at observed input levels to obtain the cost reduction per boat–month, or we can compare average costs per lobster landed. When this is done we find that minimal operating costs, given the reported landings of a typical commercial lobsterman, could be about one-quarter lower or about $2800 per vessel-year in cost savings. Actually, the saving is for the May–October portion of the year because we did not have data for November–April for average fishermen from which to adjust for relative productivity. For the average lobstermen the savings would be lower in absolute magnitude but possibly higher in percentage terms.

The tragedy of open access in a fixed gear fishery can have soak time and input stuffing (excessive traps, bait, fuel) as well as a stock externality. Unfortunately, this reasoning is difficult to test with individual cooperators unless the fishing grounds of the individual are geographically isolated from competitors. A potentially observable implication of such isolation is that the congestion and soak time effects would be internalized by the individual fisherman who, it is predicted, would operate with more traps and longer soak times than is the case with lobstermen who are adjacent to competitors. With such isolation, a direct test would require a collective agreement by a significant fraction of fishermen within an area. Such a collective action would be analogous to the practice of "unitization" in common pool oil fields. In such fields, a marginal well entrant realizes benefits partially at the expense of surrounding well-owners. The same problem exists for groundwater

aquifers. In all such cases, some sort of joint management is essential to avoid wasteful rates of exploitation. Unless an individual fisherman is isolated, his unilateral action would only impoverish him whether the action were reduced traps on bottom or increased soak time. The results presented are consistent with such a conclusion, and other evidence also exists. Acheson (1975) found significantly higher catch rates and economic returns in isolated communities with strong barriers to entry by outsiders. It seems unlikely that such differences in rather small areas could be accounted for by standard population dynamics (whose effects are global, or at least regonal, rather than local), in the absence of a local congestion externality. The results obtained above suggest that more traps with a doubled soak time would be more cost effective for a given fishing mortality and catch. This is achieved (in the optimization model) by halving (approximately) the days at sea per boat-month. If correct, these results suggest the existence of significant input stuffing in the form of unnecessarily high monthly operating costs for labour, fuel, and bait.

In view of local, regional and seasonal differences and random events, it would be absurd for a central planner to attempt a unique global optimum. Regional or local organizations would be better positioned to negotiate a local collective agreement on such matters as traps on bottom and soak times, or even individual quotas. As part of the negotiation process, such an organization might be well advised to explore some locally organized collective experiments to determine the cost effectiveness of such measures.

If natural resources are to be managed in a sustainable way, the governance mechanisms must be sustainably financed. Based on the findings in this paper, producer self-taxation on bait might be a useful way for a local management entity to be sustainably financed. However, there are significant political, administrative and trans-jurisdictional issues with pursuing this option. Presumably, it is at least as difficult to monitor flows of bait as it is to monitor flows of catches at a local level.

In conclusion, there are three caveats. The first is that the data used are less than ideal, so the whole analysis is only suggestive. It should not be acted on without further testing. While the data from commercial fishermen were more complete in some respects, the survey data suffer from the fact that focus groups were used which may have various biases to which that method is subject. The second caveat concerns the way data are collected and the bias that this analysis may impart against part-time fishermen. Since data are reported per trip, we have treated the average data as if all trips were of equal duration in hours at sea. In fact, some part-time lobster fishermen tend traps after completing their shift in a job on shore. We have assumed implicitly that all days at sea were of equal duration and have included operating costs, bait costs and labour costs for a full day. This overstates the instantaneous effort (E_{dM}) and associated costs for part-time fishermen. This point probably accounts in part for the productivity adjustments we had to make between average and full-time lobstermen. For the following reasons this problem is not as severe as might be supposed. We have used a supply price of labour which is calibrated to actual revenues and bait costs based on observed haul rates. In calculating cost savings we also tried to finesse this problem by calculating cost savings only for commercial lobstermen and then only for those months (May–October) for which we had data for both groups. However, the results and conclusions reached above should be regarded more as illustrations of a method for analysing the issue than as firm conclusions about optimal input combinations.

The third caveat raises issues beyond the scope of this paper. Ciriacy-Wantrup (1952) commented on proposals to limit effort in the Maine lobster fishery. In his comments he pointed to an ambiguity inherent in a purely production oriented analysis (such as this). If lobstermen are willing to accept pecuniary rewards lower than their opportunity costs, or to use cost ineffective input combinations in order to enjoy more days on the water, then market measures of cost may be an inappropriate metric from which to judge economic efficiency. That is certainly true with sport fisheries where ''willingness to pay'' measures are the preferred indicator of net economic return. Economists since Adam Smith have stressed that while pecuniary rewards are useful predictors of behaviour, it is also true that individuals are motivated by considerations other than pecuniary return. Thus, while these results suggest that fishermen are foregoing potential income by using input proportions that are not cost effective, it is unclear whether this choice of input proportions is due to a specialized tragedy of the commons or to a psychic income from being on the water. There may be a mixture of both. Commercial lobstermen, with whom we spoke expressed a strong interest in ''controlling the arms race''. This interest suggests that in their minds the former element is dominant. Conversely, for part-timers, the principle of diminishing marginal rate of substitution would suggest that, for part-timers, there may be a marginal willingness to pay for hours at sea.

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