
Testing Ecological Models: The Influence of Catch Rates on Settlement of Fishermen in Newfoundland, 1710-1833¹

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Abstract

Perhaps the most fundamental theory of natural renewable resource exploitation is Scott Gordon's bio-economic model for an open access fishery. I test this theory using a superb data set from fishing communities in three bays in Newfoundland from 1710 to 1833. Gordon's theory predicts very well the pattern of settlement in these three bays during this period. Fishermen in each tended to settle when catch rates were greater than forty quintals of dried salt cod (about ten metric tonnes of fresh cod) per man a year to emigrate when catch rates were less. The mean catch rate per man per year during the 1700s and early 1800s remained remarkably constant, presumably because of this population movement. Remarkably, the catch rate of ten metric tonnes per year was the average of inshore fishermen in Newfoundland until the collapse of the fishery in the 1990s.

Introduction

In a seminal analysis, Scott Gordon developed a simple, yet profound, model of why natural renewable resource exploitation to become unprofitable over time.² He demonstrated that new exploiters entered the system until the profit margin reached zero. Although there is wide acceptance of Gordon's model, there are few analyses that firmly demonstrate its empirical validity.³

¹I would like to thank Daryl Janes, Stacy Fowlow, and Nicholas Barrowman for assistance. Suggestions by Jeff Hutchings, Tim Smith and David Starkey improved the manuscript.

²H.S. Gordon, "Economic Theory of a Common-Property Resource: The Fishery," *Journal of Political Economy*, LXII (1954), 124-142.

³See, for example, C.W. Clark, *Mathematical Bioeconomics: The Optimal Management of Renewable Resources* (2nd ed., New York, 1990).

The Gordon model of the bioeconomics of the exploitation of fish populations forms the basis for many of our present attempts to understand and regulate commercial fisheries.⁴ The model, and its subsequent elaborations, describes the entry of fishermen into the fishery in terms of the profit or catch rates. The purpose of this essay is to examine empirically a key component of this model: the behaviour of fishermen in entering and leaving a fishery, using an extraordinary time series of population and catch data for the Newfoundland salt cod fishery from 1710 to 1833. There are several reasons that Newfoundland in this period offers an ideal case to test the theory. First, excellent records exist. There are annual reports that specify details of the fishery and settlement for nearly all years. Second, there was an almost unlimited opportunity for settlement. There were hundreds of thousands of migrant fishermen in the region, but the total resident population was less than 20,000 by the 1790s.⁵ A further advantage of these data is that it is possible to break them down into distinct regions, enabling me to cross-validate the models and parameter estimates of “replicate realizations” of the same process.

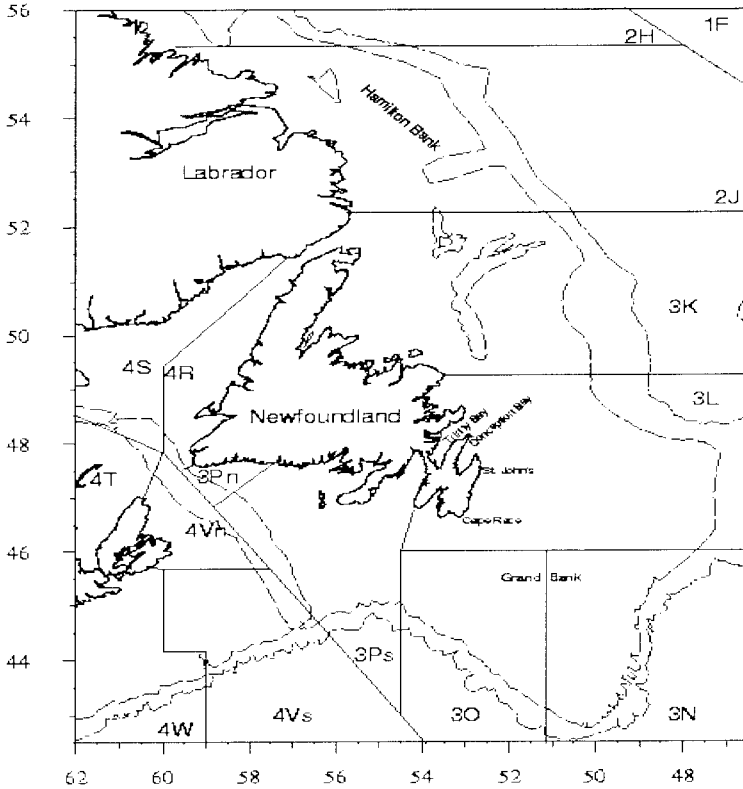
During this period the shore-based cod fishery along the east and north coasts of the island of Newfoundland was exclusively in the hands of the British. The only other cod during this period was an offshore fishery by the British and French on the Grand Banks. These cod are now believed to be largely an independent stock from those nearer to shore.⁶ The fishery in each harbour in the British fishery was monitored by a “fishing admiral,” who was required to report each year the catch, number of fishermen, and a variety of demographic and economic information. Although there are gaps and various problems with these data, they allow us to study entry into the fishery, in particular when fishermen entered and left. We compiled what appeared to be reliable data from three regions, a procedure that allowed our test to be replicated: Trinity Bay, Conception Bay, and the region from St. John’s to Cape Race (see figure 1). In this article I will concentrate on testing Gordon’s bioeconomic theory to explain settlement. I will also address other hypotheses briefly in the section headed “discussion.”

⁴C.W. Clark, *Bio-economic Modelling and Fisheries Management* (New York, 1985).

⁵W.G. Handcock, *Soe Longe as There Comes Noe Women: Origins of English Settlement in Newfoundland* (St. John’s, 1989).

⁶D.E. Ruzzante, C.T. Taggart and D. Cook, “A Nuclear DNA Basis for Shelf- and Bank-Scale Population Structure in Northwest Atlantic Cod (*Gadus morhua*): Labrador to Georges Bank,” *Molecular Ecology*, VII, No. 12 (December 1998), 1663-1680.

Figure 1
Trinity and Conception Bays; St. John's to Cape Race;
and Modern Fishing Regions



Source: See text.

Gordon's Bioeconomic Model

My goal is to describe empirically the relationship of the change in the number of fishermen to the catch per unit effort (CPUE). I will use a dynamic version of Gordon's open-access fishery model developed by Barry Smith.⁷ Consider the dynamics of a fish population, X , given by the Shaffer logistic model, where

⁷J.B. Smith, "Stochastic Steady-State Replenishable Resource Management Policies," *Marine Resource Economics*, III, No. 2 (1986), 155-168.

harvesting is a simple function of the ability to catch fish, q , and effort, E . That is,

$$\frac{dX}{dt} = rX \left(1 - \frac{X}{K} \right) - qEX,$$

where r and K are the intrinsic growth rate and the carrying capacity of the population, respectively.

The key to Gordon's model is that the rate at which fishermen enter the fishery is an increasing function of the profit that can be made from fishing. That is, they join the fishery until the catch rate decreases to the point where no profit can be made: the population may be said to reach a "bionomic equilibrium." Gordon did not explicitly specify the functional form for the rate of change of fishermen, but Smith assumed that the dynamics of effort – in our case, the change in the number of resident fishermen – is proportional to current revenues. That is,

$$\frac{dE}{dt} = k\pi,$$

where k is a constant. The current net revenues are simply the difference in the revenues – the price of the catch, p , times the catch – which are assumed to be a linear function of effort, qEX , minus the cost of one unit of effort, c . That is,

$$\frac{dE}{dt} = k(pqX - c)E,$$

or

$$\frac{d(\log E)}{dt} = k(pqX - c).$$

Since we do not know the true abundance of fish, the above equation will be examined in terms of the CPUE, which is assumed to be proportional to true abundance, i.e., $C/E = qX$. Thus, we have

$$\frac{d(\log E)}{dt} = k \left(p \frac{C}{E} - c \right).$$

This formulation is for simplicity; a more complex model developed by Clark shows that investment decisions may be better described as a threshold: fishermen enter the fishery if it is profitable to do so.⁸ The point I wish to make here is that the derivative of the log of effort – for example, the number of fishermen – should be an increasing function of CPUE. This is at the heart of most models of fishermen's behaviour, and it is this relationship that I will test.

Data on the Salt Cod Fishery in Newfoundland

Data were compiled annually throughout the eighteenth and into the nineteenth century by the Colonial Office in London on the fishery in each major harbour in Newfoundland. During this period, fishermen on the east and north coasts of Newfoundland were mainly from the "west country" of England, especially Devon and Cornwall, or southern Ireland. There were three categories of fishermen: migrants, "bye boatmen," and inhabitants. While migrants transported their fishing boats to Newfoundland each year, bye boatmen kept their boats in Newfoundland harbours and migrated to the island annually for the summer fishery. Inhabitants settled on the island. I will concentrate on the dynamics of the inhabitants because they had to be committed to the fishery to sustain a permanent home in Newfoundland. It is also clear that they had greater access to the best fishing areas.⁹ In many ways this is a perfect empirical situation to test a model of open-access entry to a fishery because high mobility was feasible. It was relatively easy to settle after becoming established in the fishery. The land-based fishery was carried out from small boats, often shallops, using baited hooks. The cod were salted and dried on land.

There have been several studies using the data from Colonial Office (CO) 194.¹⁰ I started with a compilation of the Forsey and Lear material, but carried out extensive checks using the raw data in the microfilmed edition of the CO 194 statistics at the Centre for Newfoundland Studies at Memorial University of Newfoundland. The records recorded the statistics by fishing harbour for each year. The initial checking consisted of three steps: a comparison of the data from the three studies cited in note 10; a check of the microfilm records to determine if data from any fishing harbours were missing for a given year; and a check of

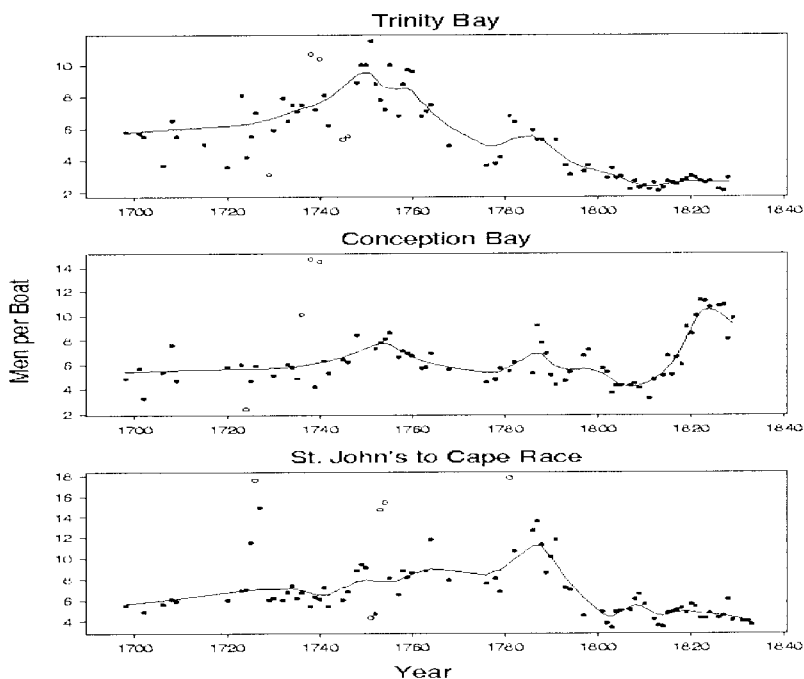
⁸See Clark, *Mathematical Bioeconomics*.

⁹C.G. Head, *Eighteenth Century Newfoundland: A Geographer's Perspective* (Toronto, 1976).

¹⁰*Ibid.*, R. Forsey and W.H. Lear, "Historic Catches and Catch Rates of Atlantic cod at Newfoundland during 1677-1833," *Canadian Data Report on Fisheries and Aquatic Sciences*, DCLXII (1987); and S. Ryan, *Fish Out of Water: The Newfoundland Saltfish Trade 1814-1914* (St. John's, 1986).

any sudden fluctuations in any of the time series. There were numerous mistakes detected in the Forsey and Lear study, including addition errors, totals for regions where data from some harbours were missing, and highly unlikely fluctuations from year to year in catch, effort, or number of inhabitants. These could almost always be resolved by examining the original census reports. For some years data were missing for a harbour in one of the regions I considered. In such cases the data were excluded for the entire region for that year.

Figure 2
Men Per Boat over Time for Trinity and Conception Bays,
and St. John's to Cape Race



Note: The supersmoother technique was used (solid line) and outliers are shown as open circles. The outliers for men per boat were determined using the supersmoother and considered to be greater than two or less than -2 standard residuals, where standard residual was calculated to be the residual/standard error.

Source: See text.

I further eliminated outliers by examining the trend over time in the number of men per boat, since it was unlikely that crew size would change abruptly. A crew typically consisted of three fishermen per boat, plus two men processing on shore.¹¹ Few women were involved in the fishery during this period.¹² But the number of men per boat changed over time and varied between regions (see figure 2). Some of the sudden shifts in the number of men per boat were unlikely. For example, in Conception Bay the average number of men per boat increased from 4.2 in 1739 to 14.5 in 1740. Since it is impossible to understand why this might have occurred, I eliminated all data where the standardized residual from a long-term smooth curve had an absolute value greater than two. The long-term mean was defined by a “supersmoother,” and the standardized residuals were calculated by dividing by the standard error from the smooth.¹³ The long-term mean men per boat varied between three and seven. This eliminated between four and six years of data per region. While the causes of the long-term changes in the number of men per boat are unclear, it is important that any analysis should be sensitive to them. For this reason, I will here consider two indices of CPUE, catch per boat and catch per man.

Although some data go as far back as 1677, I started in 1710 because they were collected more consistently thereafter; indeed, the years 1710-1833 were remarkably homogeneous in this regard. The last yearly census was in 1833.¹⁴ Although there were numerous wars in this period, there were no French raids on English settlements in Newfoundland. Nor were other nations allowed to fish in any of the three regions in question.

Catch is measured in “quintals,” 112 pounds of split, salted, and dried cod. It took about one metric ton of fresh cod to produce 4.2 quintals of dried fish. The derivative, $\frac{d(\log E)}{dt}$, was estimated by smoothing $\log E$ and calculating the finite difference of the smoothed curve one-half year before and after the year of interest. Smoothing was necessary because of the large variation in the estimated

¹¹Head, *Eighteenth Century Newfoundland*.

¹²Handcock, *Soe Longe as There Comes Noe Women*.

¹³This procedure is discussed in J.H. Friedman, “A Variable Span Smoother,” Stanford University, Department of Statistics, Laboratory for Computational Statistics, Technical Report No. 5, 1984.

¹⁴S. Ryan, *Abstract of Returns for the Newfoundland Fishery 1698-1833* (St. John's, 1969).

number of fishermen. A robust local smoother (lowess), with a window of fifteen years, was used for this smoothing.¹⁵

It is not a simple matter to assess the statistical significance of the correlation between $\frac{d(\log E)}{dt}$ and CPUE because of auto-correlation and a large number of missing values. A “Monte Carlo” approach was used to estimate the probability of the observations occurring by chance.¹⁶ I modelled the $\frac{d(\log E)}{dt}$ and CPUE as first-order auto-regressive processes, with the auto-correlation estimated from each series, and generated 1000 pairs of time series with the characteristics and length of the observed ones (except there were no correlation between them). Data points in the simulated time series were removed in the same pattern as the observed ones, and histograms of the correlations between the simulated time series were plotted. The statistical significance of an observed correlation was estimated from these histograms.

An alternative approach to estimate statistical significance is to use a product-moment correlation and to correct the number of degrees of freedom by the degree of auto-correlation in the two time series. This will effectively reduce the degrees of freedom for tests of statistical significance.¹⁷ Since both methods gave similar results, I will only report the results from the Monte Carlo method.

Results

The basic data used in the analysis were the number of men, catch per boat and catch per man (figures 3-5). While catch rates in 1710 were typical of those of later times, the catch rates between 1714 and 1727 were consistently the lowest in the time series. Keith Matthews has detailed this collapse of the fishery; it was perhaps the worst period before the collapse in the 1990s, and there was virtually no new settlement during this period.¹⁸

Higher catch rates were observed around 1745 for all regions; this increase corresponds to the largest relative growth in population during the time period. In Trinity Bay, the population increased from around 400 men in the early

¹⁵See W.S. Cleveland, “Robust Locally Weighted Regression and Smoothing Scatterplots,” *Journal of the American Statistical Association*, LXXIV (1979), 829-836.

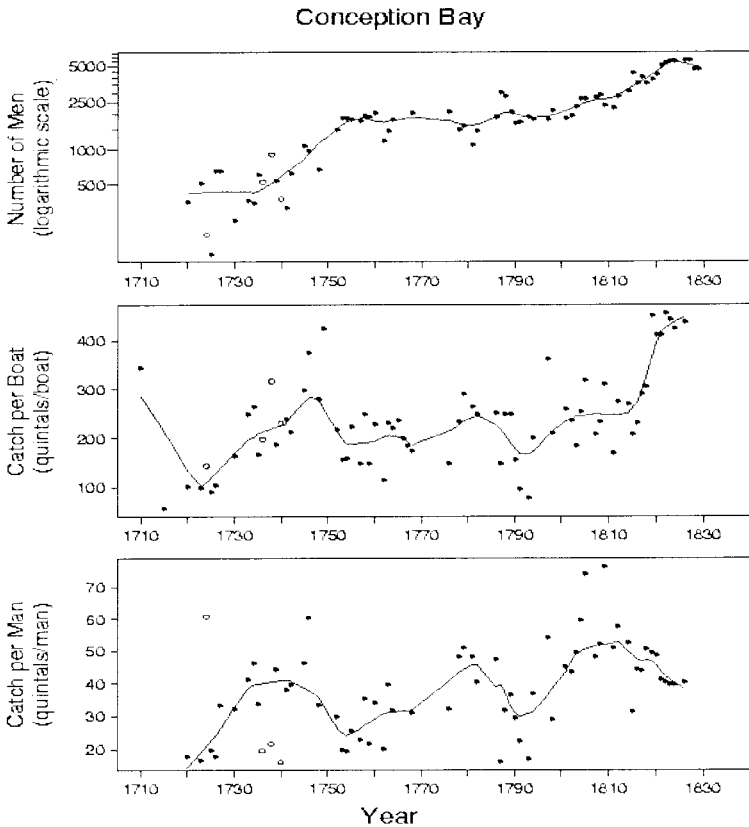
¹⁶B.F.J. Manly, *Randomization and Monte Carlo Methods in Biology* (New York, 1991).

¹⁷M.B. Priestley, *Spectral analysis and Time Series* (2 vols., London, 1981), I.

¹⁸K. Matthews, “A History of the West of England-Newfoundland Fishery” (Unpublished DPhil thesis, Oxford University, 1968).

1700s to over 1000 when the catch rates increased around 1740. Similar increases in catch rates and population size occurred in Conception Bay and St. John's to Cape Race. After 1750, catch rates fell to around 200 to 250 quintals per boat, and there was very little change in population for at least thirty years.

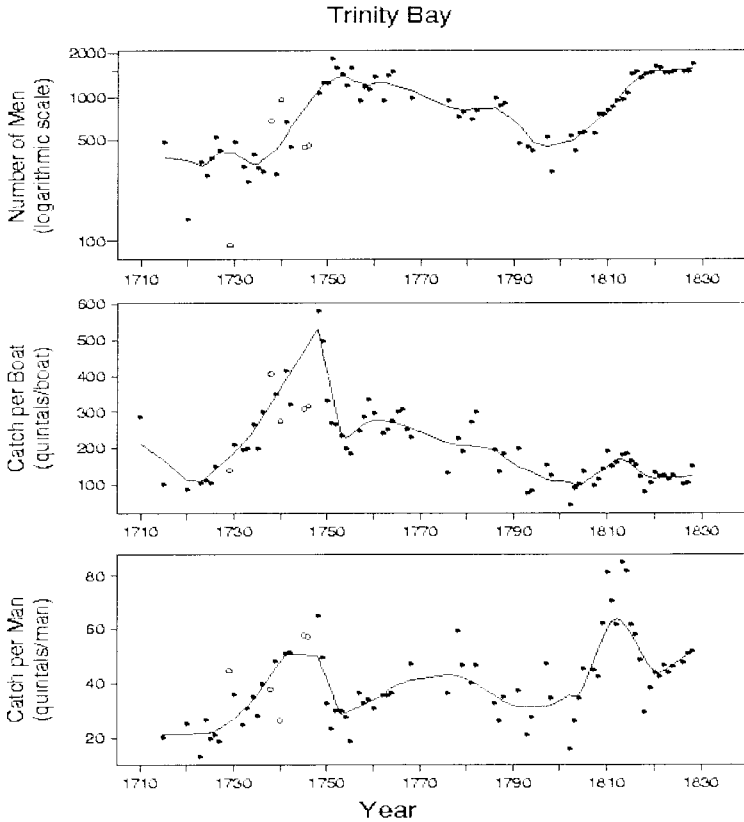
Figure 3
Number of Men, Catch Per Boat (Quintals/Boat) and
Catch Per Man (Quintals/Man) for Trinity Bay



Note: A lowess smoother with a window of fifteen years was used (solid line) and outliers in men per boat (figure 2) are shown as open circles.

Source: See text.

Figure 4
Number of Men, Catch Per Boat (Quintals/Boat) and
Catch Per Man (Quintals/Man) for Conception Bay



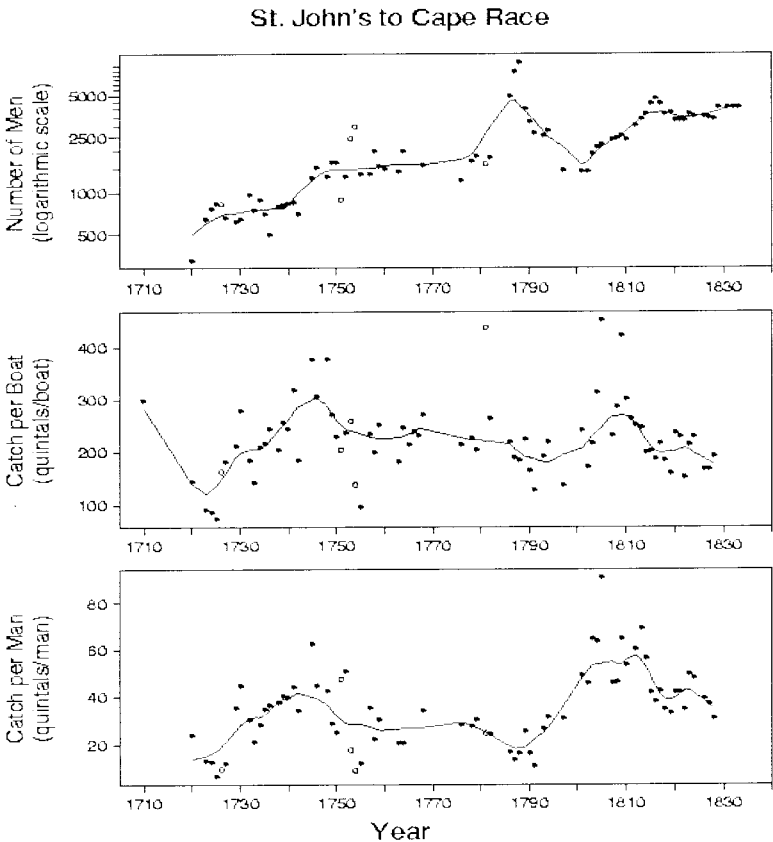
Note: See figure 3.

Source: See text.

After this time, however, there were significant differences among the regions. In Trinity Bay, population and catch per boat declined to 1800. Then about 1810, catch per boat, catch per man, and number of settlers increased. After 1820, the time series stabilized. In Trinity Bay, the correlation of the population growth rate with catch per man and catch per boat was 0.61 ($p=0.022$) and 0.48 ($p=0.38$), respectively.

In Conception Bay, there was a relatively constant increase in population from 1800 to 1820, which corresponded to a high catch rate per man. The catch per boat was about average until 1820, when it suddenly increased. In Conception Bay, the correlation of population growth rate with catch per man and catch per boat was 0.30 ($p=0.32$) and 0.31 ($p=0.32$), respectively.

Figure 5
Number of Men, Catch Per Boat (Quintals/Boat) and
Catch Per Man (Quintals/Man) for St. John's to Cape Race

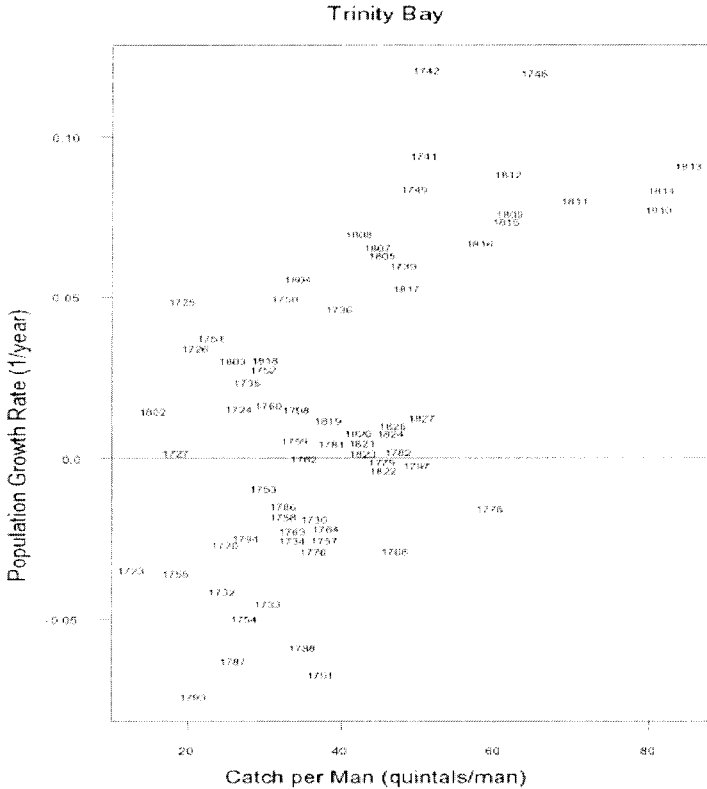


Note: See figure 3.

Source: See text.

From St. John's to Cape Race, the number of men increased suddenly around 1785, but this did not correspond to an increase in either catch rate. The decline in population from 1785 to 1800 corresponded to low catch rates, while the increase from 1800 to 1815 corresponded to high catch rates. The deviation around 1788 appears to have been caused by an overestimation of the number of fishermen in the source, but I was unable to verify this from the microfilm records. After 1815, the population and catch rates stabilized. From St. John's to Cape Race, the correlation of population growth rate with catch per man and catch per boat was 0.48 ($p=0.107$) and 0.46 ($p=0.114$), respectively.

Figure 6
Population Growth Rate in Trinity Bay, 1710-1833, and
Catch Per Man and Per Boat

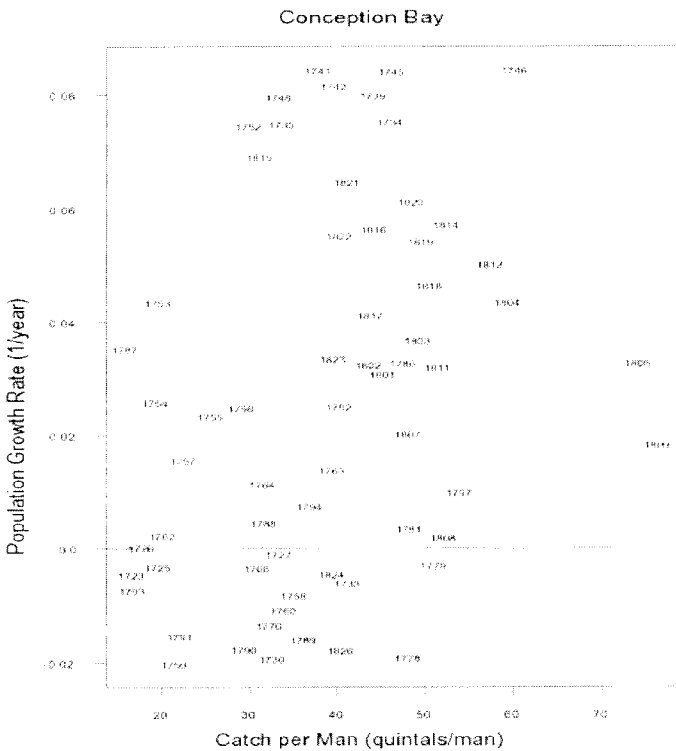


Note: A reference line at zero is given (dotted line).

Source: See text.

In all three regions, the population growth rate, $\frac{d(\log E)}{dt}$, was an increasing function of CPUE as measured by catch per man or per boat. The positive relationship was strongest for Trinity Bay (figure 6) and the St. John's to Cape Race region (figure 8). The relationship was still positive, but much less so, for Conception Bay (figure 7). The statistical significance of the results was low despite the relatively long time series because of strong auto-correlation in the data: there are relatively few true degrees of freedom. Nevertheless, the relationships are surprisingly consistent among regions.

Figure 7
Population Growth Rate in Conception Bay, 1710-1833, and
Catch Per Man and Per Boat

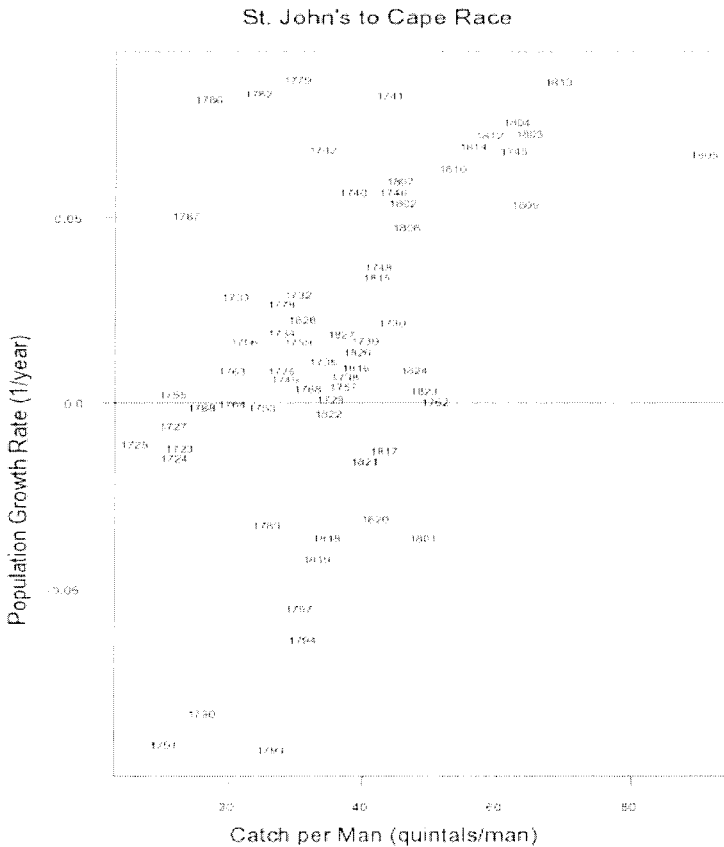


Note: See figure 6.

Source: See text.

I repeated the analysis using various modifications to test the robustness of the results. Different widths for the “window” were used to estimate the population growth rate. A width of ten or twenty years resulted in only a small modification. The analysis was also carried out without removing the outliers; the correlations between population growth rate and catch rate were reduced only slightly. In short, the results appear to be robust.

Figure 8
Population Growth Rate in St. John’s to Cape Race, 1710-1833, and
Catch Per Man and Per Boat



Note: See figure 6.

Source: See text.

A Comparison of Modern and Historic Catch Rates

The long-term catch in each region was about forty quintals per man, or about ten metric tonnes of fresh cod per year. This was also the approximate level where the derivative of population growth rate was positive when plotted against catch rate. That is, when the catch rate was above this level, on average the population increased, while when it was below this level population decreased.

The catch rate of about ten metric tonnes per person appears to be typical also of the catch rates in the seventeenth-century British fishery in Newfoundland and the French fishery in Placentia and Isle Royale (present-day Cape Breton).¹⁹ (Turgeon 1995). Remarkably, they are also typical of late twentieth-century Newfoundland catch rates. For example, in the 1980s the cod catch around Newfoundland was around 200,000 metric tonnes, while the number of cod fishermen was approximately 20,000. That is, catch per man in Newfoundland appears to have been the same for the last four centuries.

Discussion

It appears that the settlement of fishermen in Newfoundland from 1710 to 1833 can largely be explained by the CPUE. When catch rates were good, fishermen settled. While other factors, such as wars, colonial settlement policies and prices, may have affected settlement, the rational choice to settle in Newfoundland would have been made only if catch rates were good. There was little incentive to overwinter if they were poor.

It is not clear if wars had a large impact on settlement. For example, David Starkey has pointed out that the ratio of migratory to resident fishermen decreased during each war between 1698 to 1826.²⁰ But conflicts may not have been related as directly to the decision to settle as much as the ability to take part in the migratory fishery. Even during wars, many migrant fishermen came to Newfoundland, and they could have settled had they wanted to do so.

The results for the three study areas are consistent with the behaviour predicted by Gordon's model. This was true for alternative estimates of CPUE and alternative treatments of outliers, with consideration of reasonable lags. The relationship was strongest for Trinity Bay and the St. John's to Cape Race region,

¹⁹On the British fishery, see P. Pope, "Early Estimates: Assessment of Catches in the Newfoundland Cod Fishery, 1660-1690," in D. Vickers (ed.), *Marine Resources and Human Societies in the North Atlantic since 1500* (St. John's, 1995), 9-40. For the French experience, see L. Turgeon "Fluctuations in Cod and Whale Stocks in the North Atlantic during the Eighteenth Century," *ibid.*, 89-121.

²⁰D.J. Starkey, "Devonians and the Newfoundland Trade," in M. Duffy, *et al.* (eds.), *The New Maritime History of Devon* (2 vols., London, 1992), I, 163-171.

and weakest for Conception Bay. For all regions, settlement did not usually occur unless catch rates were good – around forty quintals of salted, dried cod per man per year, or around ten metric tonnes of fresh cod harvested. (ten tonnes of cod harvested per year per fisherman is the approximate average catch for the last 400 years.) These results appear to be robust and held up when alternative methods were used.

There are two general explanations as to why the CPUE changed over time. First, CPUE reflects changes in fish abundance or distribution caused by environmental changes. While environmental changes certainly influence cod populations, this is unlikely to be the full answer. The second general explanation is that fishing affected cod abundance as early as the 1700s.²¹ The catch in the British portion of eastern Newfoundland possibly was as high as 100,000 tonnes by the 1600s, a level that could certainly have caused the collapse of local cod populations.²² Analyses of historic tagging data have shown that the inshore fishery since 1945 was capable of causing very high mortality rates in fish stocks.²³ There is direct evidence of overfishing in the historic record as well. Laurier Turgeon has shown that the intensive British and French inshore fisheries in the eighteenth century were associated with a decline in the ratio of cod liver oil to dried fish produced, which indicates a decline in the average size of fish in the catch.²⁴ The analysis of catch rates presented here is consistent with the hypothesis that the inshore fishery was capable of causing very high fish mortalities.

One key factor may be changes in “catchability,” q , over time. As fishing technology changed, catch rates may have improved.²⁵ This would have led to increased settlement until the catch rates returned to their previous levels.

²¹Head, *Eighteenth Century Newfoundland*.

²²Pope, “Early Estimates.”

²³R.A. Myers, *et al.*, “The Collapse of Cod in Eastern Canada: The Evidence from Tagging Data,” *ICES Journal of Marine Sciences*, LIII, No. 3 (1996), 629-640; and R.A. Myers, N.J. Barrowman and J.A. Hutchings, “Inshore Exploitation of Newfoundland Atlantic Cod (*Gadus morhua*) since 1948 as Estimated from Mark-Recapture Data,” *Canadian Journal of Fisheries and Aquatic Sciences*, LIV, Supplement 1 (1997), 224-235.

²⁴Turgeon, “Fluctuations.”

²⁵J.A. Hutchings and R.A. Myers, “The Biological Collapse of Atlantic Cod off Newfoundland and Labrador: An Exploration of Historical Changes in Exploitation, Harvesting Technology and Management,” in R. Arnason and L. Felt (eds.), *The North Atlantic Fisheries: Successes, Failures and Challenges* (Charlottetown, 1995), 38-93.

One of the most surprising results of this analysis is that the fishery appears to have been close to bionomic equilibrium over the entire time period. The only time the fishery was not in this state was during periods of poor catches, such as the years around 1720, or when the time lag required for immigration created a temporary disequilibria. That is, the fishery appears to have been fully exploited for the type of gear and fishery practices used at the time, and by some definitions even over-exploited, from 1710 to 1833.

Open Questions

This paper only touches the surface of the vast archives of the colonial powers. Jeffrey Hutchings and I have compared environmental records with landings in Newfoundland from 1800 to 1995 and found no obvious link.²⁶ This analysis shows clear periods of low catch per unit effort in the inshore fishery; it would be interesting, given the slow recovery of cod stocks in the region from overfishing, to know if these periods of poor recruitment were associated with poor environmental conditions.

I have not included information on prices in this analysis. But a more sophisticated analysis should include such factors. A question of keen interest to fisheries ecologists is the total catch removed from the ecosystem. While Hutchings and I attempted to compile known estimates, most such analyses are badly flawed because they take no account of unreported catch. Peter Pope obtained much superior estimates for the period 1675-1698 using a ratio estimator, that is, by multiplying the number of fishermen by an average catch rate. His analysis shows that the catch per man fluctuated around forty quintals per man per year, with immigration occurring when catch rates were above that level and emigration occurring when they were below.²⁷ Thus, in the long term the catch man has been relatively constant. This general result may allow much better estimates of total catches to be estimated using modern mixed-effect and hierarchical Bayes methods.

²⁶J.A. Hutchings and R.A. Myers, "What Can Be Learned from the Collapse of a Renewable Resource? Atlantic Cod, *Gadus morhua*, of Newfoundland and Labrador," *Canadian Journal of Fisheries and Aquatic Sciences*, LI, No. 9 (1994), 2126-2146.

²⁷Pope, "Early Estimates."