The history of ocean resources: modeling cod biomass using historical records

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Managing the remnants of the ocean's resources is a critical issue worldwide, but evidence for what constitutes a healthy fish population remains controversial. Here, we use historical sources to understand ecosystem trends and establish a biomass estimate for a key marine species prior to the industrialization of fishing. Declining trajectories have been described for predatory fishes and complex coral reef systems globally, but few numerical estimates of past abundance exist. We combined historical research methods and population modeling to estimate the biomass of cod on Canada's Scotian Shelf in 1852. Mid 19th-century New England fishing logs offer geographically specific daily catch records, describing fleet activity on fishing grounds with negligible incentive to falsify records. Combined with ancillary fishery documents, these logs provide a solid, reliable basis for stock assessment. Based on these data we estimate a biomass for cod of 1.26 x 10^6 mt in 1852 – compared with less than 5 x 10^4 mt of total biomass today. In the current policy debate about rebuilding depleted fisheries and restoring marine ecosystems, it is important to recognize that fisheries for key commercial species like cod were far more productive in the past. As we attempt to rebuild these fisheries, our decisions should reflect real and realistic goals for management, not just recently observed catch levels.

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On the eve of the American Civil War, 43 schooners from Beverly, Massachusetts (Figure 1a), comprising 18.5% of the entire US fishing fleet in the Northwest Atlantic, wetting fewer than 1200 hooks in total, caught over 7800 metric tons (mt) of North Atlantic cod (*Gadus morhua*), on the Scotian Shelf, a collection of rich fishing banks located south of Nova Scotia (Figure 1b). By comparison, in 1999 the entire Canadian fishery landed 600 mt *fewer* cod from a larger area incorporating the Bay of Fundy as well as Nova Scotia's inshore banks (North Atlantic Fisheries Organization Statistical Divisions 4X4VsW, see Figure 2). Our figures are compiled from catch reported in fishing logs from the period, which describe a cod stock and a supporting marine ecosystem very different from that observed today. Understanding these differences is essential for any successful policy aimed at restoring the ocean environment and preserving the fishery.

Cod act as keystone predators in northern hemisphere marine ecosystems. As a marketable commodity in world trade, this species has been heavily exploited for centuries, particularly so in the last 50 years. Economic incentives, the politics of resource management, and a lack of strong conservation measures have encouraged unsustainable exploitation (Rosenberg *et al.* 1993; Rosenberg 2003 a,b). Governments across the North Atlantic are now struggling to rebuild depleted cod stocks.

Controversy over what constitutes a rebuilt fish stock and a healthy marine ecosystem can arise from the "shifting baselines syndrome" (Pauly 1995), whereby standards degrade through time. Fishing can fundamentally alter marine ecosystems (Pauly *et al.* 1998; Jackson *et al.* 2001; Tegner and Dayton 1999). Without a historical perspective, scientists, policy makers, and public constituents consistently underestimate the potential abundance and diversity of marine species and the productive capacity of ecosystems. In recent, controversial analyses, Myers and Worm (2003) and Pauly and McLean (2003) described large-scale depletion of predatory fishes in the North Atlantic and other oceans over the past 50 years, the period for which comprehensive statistical data exist. Here we contribute to this debate by employing very different sources and methodologies. We apply to historic

In a nutshell:

- Investigating the historic effects of fishing on marine ecosystems is essential to understanding the productivity of oceans today
- Historical sources, such as fishermen's logbooks, provide reliable, geographically specific data suitable for population assessment modeling
- Population abundance of commercially important fishing species today is a small remnant of past abundance
- Understanding long-term changes in ecosystem structure and productivity are essential to crafting policies aimed at restoring ocean productivity

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fisheries records a well-established population dynamics model of catch rates and total fishery removals from the stock, extending the view back an additional 100 years.

During the mid 19th century, fishing vessels from New England, Nova Scotia, and, for a short time, France, worked the productive Scotian Shelf banks (Figure 2) from early April to late November (Goode 1884–87; Innis 1954). A nearly complete run of detailed, geographically specific fishing logs from the port of Beverly, Massachusetts, exists for the period 1852–1859. Most Beverly vessels plied the Scotian Shelf, reporting catch and location in daily log entries. Our study is based on the analysis of logs collected from 236 Beverly vessels fishing solely on the Scotian Shelf, 90 Beverly vessels fishing part of the season there, and the estimated catch of 1313 vessels from other ports "spoken" (other vessels sighted and communicated with at sea) on those fishing grounds and noted in the log of the day's occurrences.

Nineteenth-century deep water codfishing was much more of a community activity than it is today (Vickers 1994). Family members from towns across New England and the Canadian Maritimes congregated and socialized each season on the grounds they fished regularly. Vessels assembled in loose groups to fish, and skippers knew that a fleet of vessels at anchor on the horizon was as good an indicator of cod as flocking seabirds or schooling baitfish. Logkeepers routinely recorded the "vessels spoken" in a consistent manner in daily entries. They often provided the spoken vessel's name, homeport, and a rough estimate of the cod caught to date. The following, for instance, are entries from the log of the Beverly schooner, *Belle*, while she fished at anchor in a crowd of Cape Ann vessels (square brackets contain explanatory text added by the authors):

> (8/4/1854)…at 4 PM sound [found the depth of the water on] Middle Ground [part of the Scotian Shelf], spk [spoke the] MECHANIC [from the port of] Beverly [with] 7000f[ish] and PULASKI Manchester 1000f [at] Lat 44°32' Long 59°32' (8/7)… MAYFLOWER Beverly 300f (8/8)… PILOT of Manchester 400f [we] found no fish, [we] caught 9 (8/9)… WH LOVETT of Beverly [with] 1700f (8/10)… FRIENDSHIP Manchester 14 000f, bound home (8/11)… ESSEX 600f, RICHMOND 1100f, MAYFLOWER 300f, Little Frank [FRANKLIN 1 from Beverly] 1700f, FRANKLIN [Capt.] Buck [FRANKLIN 2 from Beverly] 8000f. (Quote taken from Gentlee 1854).

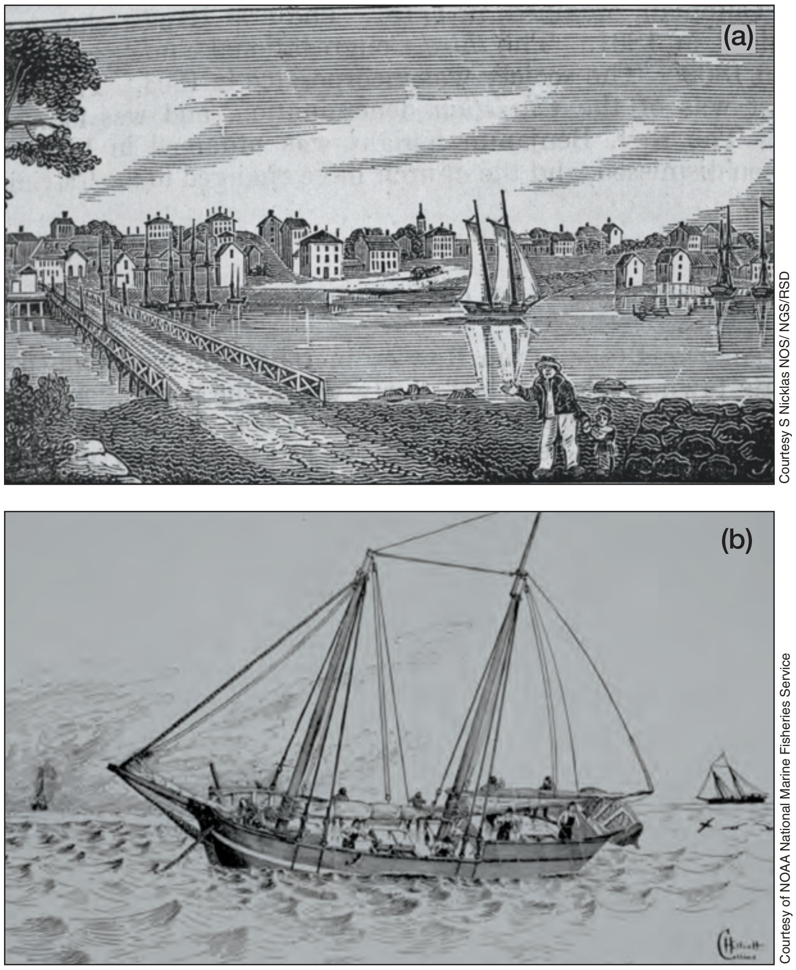

Figure 1. *(a) Beverly, Massachusetts, circa 1840, as seen from the southwest. (b) Schooners on the Scotian Shelf in the mid 19th century fished for cod with handlines (Goode 1884–87). This illustration from the 1880s shows fishermen lining the rails, each deploying two baited hooks in essentially the same manner as European fishermen had done off Newfoundland in the 1500s. Although some Beverly captains employed dories for handlining and a few experimented with tub trawls as catch per unit effort (CPUE) declined, handlining from the vessel remained prevalent in this fishery until the early 1860s.*

Daily entries in Beverly logs show that the spoken vessels were part of the Scotian Shelf fleet.

Using ancillary data we have inferred the fishing capacity of this fleet of vessels in order to estimate the total catch of the fishing fleet. No logs survive for the great majority of spoken vessels, but their names and homeports recorded in Beverly logs facilitate the compilation of a profile from manuscript and printed sources. Primary historical sources for the Scotian Shelf fleet are found in US Customs Records preserved in the National Archives Regional Administration, Waltham, MA, (NARA Waltham); the JD Phillips Library, Peabody Essex Museum, Salem, MA (PEM); and the Stephen Phillips Memorial Library, Penobscot Marine Museum, Searsport, ME (PMM). The Beverly logs used in this study are located at NARA Waltham, RG36, Boxes 8–13, 53–91, "Salem Beverly Fishing Journals".

The accuracy of the data in these logs is credible

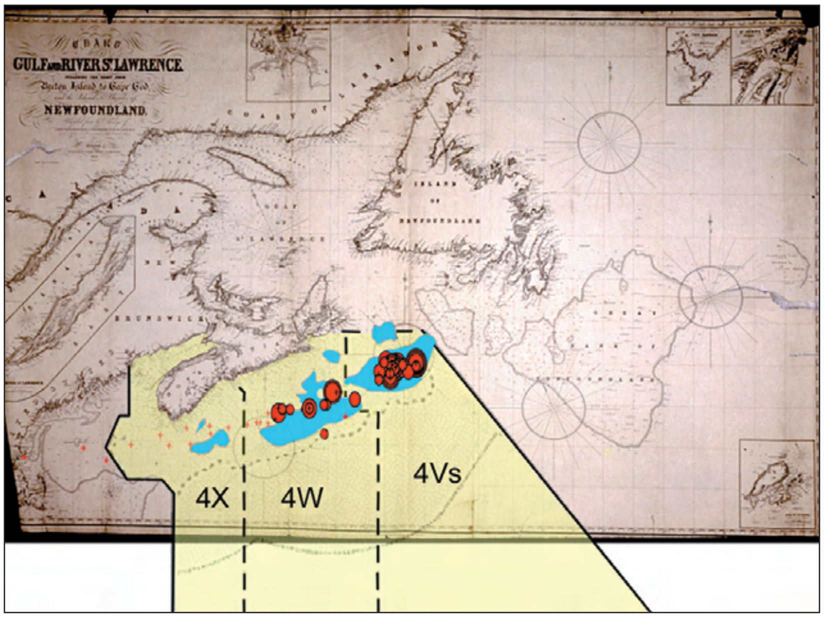

Figure 2. *Geographic distribution of 19th century fishing, with modern management divisions. The Scotian Shelf, highlighted in blue, featured prominently on this 1853 British Admiralty Chart of the Gulf and River St Lawrence (London: Bayfield, Holbrook and Bullock, 1853; courtesy PEM), along with other notable fishing grounds. Red crosses track the course of the Beverly fishing schooner,* Angler*, to the Scotian Shelf and back again during her spring, 1853 trip; red ovals indicate location and relative magnitude of daily catch. The voyage of the* Angler *is typical of Beverly schooners fishing on the Scotian Shelf in the 1850s. NAFO statistical management divisions, the geographical basis of modern population estimates, have been superimposed in yellow. Charts of NAFO management areas courtesy Northwest Atlantic Fisheries Organization.*

because of a system of internal checks. Each fisherman was paid at the end of the season by the number of fish he landed. Merchants, however, weighed the catch and bought it by dried weight, not number of fish. The cod bounty, a federal subsidy divided among owners and crew, was paid according to vessel size (tonnage), not by the total weight or numbers of fish caught. In addition, vessels fished in groups that constantly changed composition as some left and others arrived. They shared catch information and position when communicating with each other at sea, and the data mutually exchanged were recorded daily in the log entries. Historians with logs of two speaking vessels can easily check for accuracy. Redundant accounting and oversight left no incentive to falsify records.

Changing fishing patterns suggest that this handline fishery in sailing schooners depleted regional cod stocks (Figure 3). Between 1852 and 1857, close to 90% of the time Beverly vessels fished was spent on the Scotian Shelf, with a decline to 60% in 1859 as Beverly captains began to search farther afield for more economically profitable concentrations of cod. Some vessels left the Beverly fleet and may have left the cod fishery altogether, a familiar pattern in collapsing fisheries today. Catch per unit of fishing effort (CPUE in fish per day per ton of vessel]) declined by over 50% between 1852 and 1859. In the logs themselves, effort was measured in a good day's catch. On May 23, 1859, Gilbert Weston, captain of the *Dorado* on the Scotian Shelf's Banquereau Bank, noted in his log that they "had 1000 hooks out (on trawls) and (caught) 130 (cod) fish" (Weston 1859); but men who had fished in 1852 remembered good days when seven or eight handliners fishing two hooks apiece over the schooner's rail could each bring in more than 100 fish. George Gould's crew of eight on the *Betsy & Eliza* had four such good days in 1852, landing more than 1000 cod on one day in June (Gould 1852).

We analyzed catch data for the Beverly fishing fleet using a variation of the Chapman-DeLury fishery stock assessment methods (Chapman 1974). As with most stock assessment methods, abundance is scaled by the total removals from the population (catch). Catch taken from the Scotian Shelf in each year is the sum of: (a) the total catch from each Beverly vessel that spent the entire season on the Shelf; (b) a portion of the catch from each Beverly vessel that spent part of the season on the Shelf; and (c) some unknown amount of catch from each non-Beverly vessel "spoken" on the Scotian Shelf.

For those Beverly vessels that spent the entire season on the Shelf (a), or part of the season on the Shelf (b), logs and fishing agreements give catch in numbers of fish and weight of fish (in "quintals" weighing 112 lbs of dried fish), respectively. The logs from those vessels that spent the entire season on the Shelf provide catch in both numbers and weight, allowing us to estimate a weight-to-numbers conversion. This is then applied to those logs with catch only in weight, in order to estimate catch in numbers as required by the modified DeLury model. This weight-to-numbers conversion equals the average number of fish per pound and is estimated separately for each year internally in the model, so that uncertainty in the number of fish per pound is propagated through into the total biomass estimate.

For those Beverly vessels that spent only part of the season on the Shelf (b), we assume that only 25% of their catch in numbers of fish was derived from the Scotian Shelf. This is a conservative estimate, given that these vessels spent, on average, over 60% of their time on the Shelf, and will result in a conservative estimate of the removals due to these vessels and therefore of the overall estimated biomass. We test the sensitivity of our results to this assumption.

Rigorous historical investigation of license registries, enrollments, and contemporary newspapers established a profile for 571 of the "vessels spoken" (c), closely matching the profile of Beverly vessels. Tonnages of Beverly vessels fishing the entire season on the Scotian Shelf (average 78.3 tons ± 14.9 tons) were remarkably representative of the vessels spoken fleet (average 81.4 tons ± 15.1 tons). Since fishing grounds determined appropriate fishing patterns, vessels spoken on the Scotian Shelf were probably fishing the same way as the Beverly fleet, with comparable catch. We concluded that Beverly vessels fishing the entire season on the Scotian Shelf were representative of the entire Scotian Shelf fleet, and could be used as a proxy for the spoken vessels.

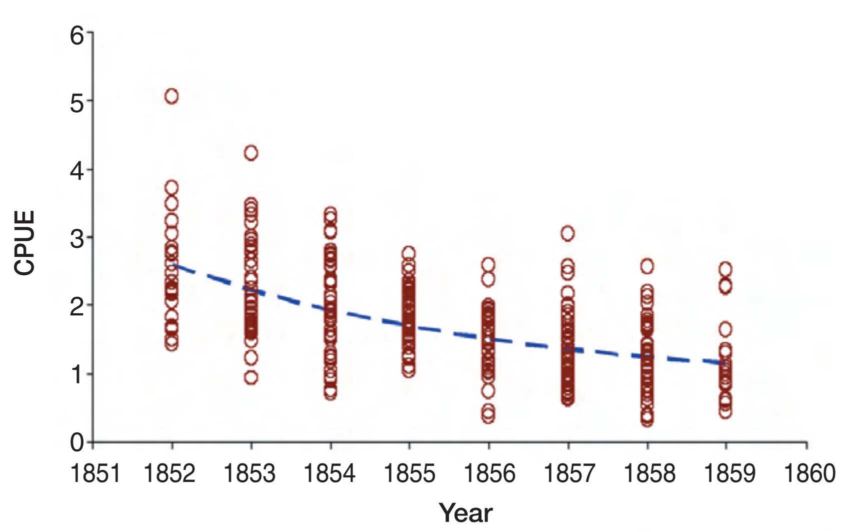

Figure 3. *Chapman-DeLury graph. Data and predictions of catch per unit effort (CPUE) for Beverly fishing schooners on the Scotian Shelf, 1852–1859. CPUE is in (hundreds of fish)/day*[ton of vessel]).*

Since 72.3% of the Beverly vessels fished the Scotian Shelf full time between 1852 and 1859, we assumed that 75% of the spoken vessels during those same years fished those banks full time and that a spoken vessel that fished the Scotian Shelf full time would catch the same number of fish as a Beverly vessel that fished the Shelf full time (a). This is a conservative assumption for estimating total catch from the spoken vessels (c), because no allowance was made for catch from spoken vessels that spent only part of the season on the Shelf. Since "part time" Beverly vessels passing through the Scotian Shelf to fish distant banks (b) still spent over 60% of their time there, the vessel spoken contribution to total catch may be higher than our initial estimates. Note again that this assumption relates to the scaling of subsequent biomass estimates: if the catch of the fleet of spoken vessels was higher than we inferred, the initial population biomass needed to support the larger catches and explain the decline in CPUE would be correspondingly larger.

We related the change in CPUE to the cumulative catch of the fleet as a whole over time, adjusted for assumed rates of natural mortality (M) and recruitment. In this model, we assumed that the recruitment rate equals the natural mortality rate. When an unfished population is in equilibrium, the annual instantaneous rate of recruitment should be approximately equal to the annual instantaneous rate of natural mortality. Over short time periods, the instantaneous rate of natural mortality may be considered constant, a condition likely to hold in this stage of the exploitation of cod.

We fit the population dynamics model to an index of abundance I_j with the following equation:

$$I_j = kN_0 - k\left(\sum_{i=1}^{j-i} C_i(1-M)^{j-i} - \frac{1}{2}C_j\right)$$

where N_0 is the initial abundance, C_i is the catch in year i, M is the instantaneous natural mortality rate, and k is constant of proportionality. We assumed M has a value of 0.2, a conventional value used for cod in many modern stock assessments, including those for the Scotian Shelf, but examined the sensitivity of our results to different values of M as well as the assumption that the recruitment equals M.

The index of abundance used here is CPUE only from those Beverly vessels that spent the entire season on the Scotian shelf and for which the logs give catch in terms of numbers of fish. Catch per unit effort equals the number of cod caught during a fare (one separate trip within an entire season) divided by the number of days spent fishing times the size of the vessel expressed as registered tonnage. The parameters of this model, including the annual average number of fish per pound, was estimated by robust regression techniques (eg Huber 1981) contained in the AUTODIFF language (Otter Research 1994) incorporated into AD Model Builder (Otter Research 2004). Full details of the robust regression technique used can be found in Otter Research (1994).

By estimating the parameters of the model, we can solve for the initial abundance, N_0. The total initial biomass can be calculated as N_0 times the estimated average weight of a fish caught in 1852, which is estimated internally in the model as described above. Average live weight is converted from the average weight of cleaned and dried cod using the multiplier employed by Pope (1995). There is uncertainty concerning this conversion factor, which may vary by fishing area and curing method, and changes in the conversion factor lead to proportional changes in estimated population size in terms of weight, but not numbers. We used the most recently derived estimate available to us.

The data and predictions are shown in Figure 3. Based on data from the American offshore fishery alone, we estimate the abundance of cod on the eastern and west-

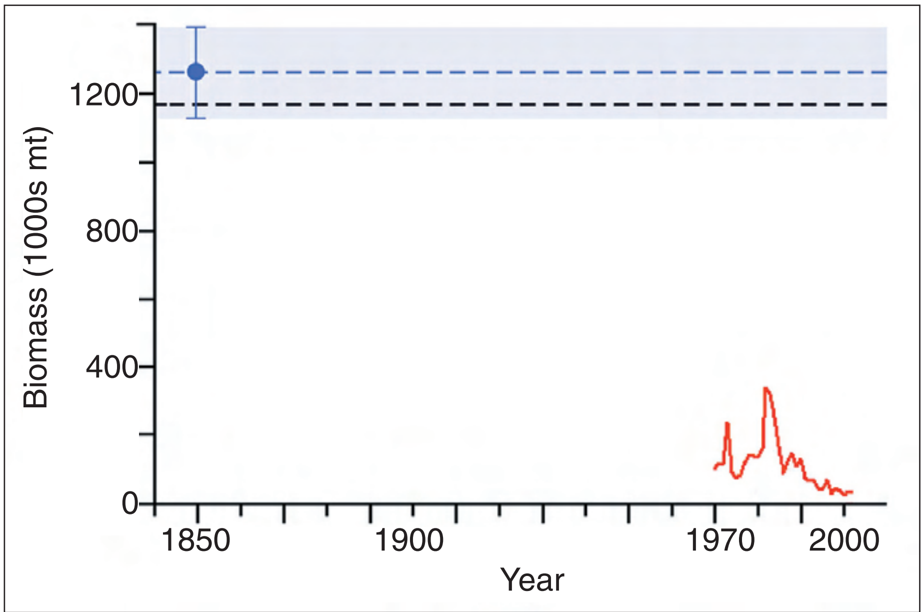

Figure 4. *Biomass estimates for Scotian Shelf Cod: ● this study, with confidence interval (1852); – – – estimated carrying capacity of this marine ecosystem from late 20th century data (Myers* et al. *2001); —— total biomass estimates from 1970 to 2000 for cod, 4X,4VsW (Mohn 1998; Canada DFO 2000; Fanning 2003).*

ern Scotian Shelf combined to be 1.26 million mt in 1852 (Figure 4). Completely ignoring the Beverly vessels that only fished part time on the Scotian Shelf lowers this estimate by only 4000 mt; assuming all their landings were taken from the Shelf raises the estimate by only 7000 mt. Higher estimates of the natural mortality rate (M) produce less than proportionally lower estimates for the 1852 biomass. For example, assuming M equals 0.3, a 50% increase, decreases the 1852 biomass by only 25%, to 947 000 mt. Similarly, smaller estimates of M produce less than proportionally larger estimates for the 1852 biomass. If we assume that the reproductive rate is greater than the instantaneous natural mortality rate, we get lower estimates for the 1852 biomass, and vice versa, though the relationship is not linear. For example, if we assume that the reproductive rate equals 125% of M, our estimate for the 1852 biomass decreases by 26%, but if we assume it equals 75% of M, our estimate increases by 54%.

Data from the mid-19th century Nova Scotian inshore fisheries are not included in this model because we know of no comparable historical records from that fishery. A biomass estimate based on catch from both the inshore and offshore fisheries would be higher. Furthermore, since prevalent hook sizes in this deepwater fishery made landing smaller juvenile cod very unlikely, comparing the results of this study with the current estimate of total cod biomass (adults and juveniles) is quite conservative.

Canada's Department of Fisheries and Oceans (DFO) has estimated from sequential population analysis that, in the 1980s, the combined peak total biomass for cod was nearly 300 000 mt in NAFO Divisions 4X and 4VsW (Mohn *et al.* 1998; Canada DFO 2002; Fanning *et al.* 2003; LP Fanning pers comm). These zones include the Scotian Shelf, but extend far beyond the banks fished by the Beverly fleet and others 150 years ago. For these combined stocks (4X and 4VsW) the current total biomass estimate (the sum of biomass estimates for statistical areas 4X and 4VsW from recent stock assessments, provided by LP Fanning) is less than 50 000 mt – about 4% of the adult biomass in 1852 (Figure 4). Furthermore, in 2002 adult biomass within these divisions was only about 3000 mt, or less than 0.3% of the biomass of adult cod in 1852 – a difference of three orders of magnitude. Despite stringent regulations for the last 6–10 years and a slight rebuilding of fish stocks, the best estimate of adult cod biomass on the Scotian Shelf today comprises a mere 38% of the catch brought home by 43 Beverly schooners in 1855. In other words, 16 small schooners from this mid 19th century fleet could contain all of the adult cod on the Scotian Shelf today.

Our estimates of biomass in 1852 correspond well with estimates of the potential biomass of unfished stocks derived from recent productivity data. Myers *et al.* (2001) estimated the carrying capacity of North Atlantic cod stocks based on a meta-analysis using Bayesian methods. They calculated the carrying capacity per unit area for cod for various regions. The carrying capacity of the western Scotian Shelf is 232 715 mt of cod and 917 789 mt for the eastern shelf, a total of 1.15 million mt. This ecological estimate is slightly less than our historically derived biomass estimate, but lies within the confidence interval (Figure 4). Carrying capacity estimates are based on data from the second half of the 20th century, in an area known to have been fished commercially since at least 1539. Neither the 1852 biomass estimates presented here, nor the carrying capacity calculated by Myers *et al.* (2001), can be said to represent the productivity of a pristine ecosystem.

Biomasses for many key marine species that are also valuable economic commodities probably follow the pattern we have estimated for this cod population. That is, biomass of commercially important species today is only a small fraction of what existed before industrialized exploitation. Jennings and Blanchard (2004) have recently published results showing similar levels of depletion for North Sea fish stocks using entirely different types of data and methods. This has important implications for ecological models. Either cod comprised a much larger fraction of the total ecosystem biomass 150 years ago or the marine ecosystem was far more productive then. An important, and often overlooked, scientific question raised by our historical analyses is, where has all this productivity gone? One obvious possibility is that other species are now far more productive than they were 150 years ago, when biomass accumulated in stocks of cod and other demersals (fish found on or near the seafloor) that were previously dominant components of the ecosystem. Alternatively, the marine ecosystem may now be far less productive than in the past, because of a variety of natural and anthropogenic changes. Put directly, has exploitation and overexploitation fundamentally altered the structure of the ecosystem and have primary ecosystem goods and services been lost because of these changes? Thinking historically about the role of human activity in marine ecosystems opens up new data sources and promising avenues of inquiry that may begin to address fundamental ecological questions about the nature and magnitude of productivity.

Current ecological models are greatly strengthened by incorporating long-term change due to human activities. By extending this chronological perspective back 150 years, we challenge current views and the "conventional wisdom" of what constitutes a rebuilt cod stock in a productive marine environment. This conventional wisdom often assumes that the most recently observed peak in biomass is indicative of a healthy, balanced ecosystem. In recent debates in New England over the management of George's Bank and Gulf of Maine cod stocks, many argued that 1980s stock levels should be considered fully rebuilt. This contradicted the evidence of basic cod biology, which suggested that cod stocks would only be rebuilt at higher levels (NEFSC 2002). Our historical analyses indicate that recent levels of biomass and catch may grossly under-represent the productive potential of commercially important species. Stock rebuilding programs should consider longer term, high biomass goals for full restoration.

The recently completed US Commission on Ocean Policy (2004) report and the Pew Oceans Commission (2003) report both call for a move toward ecosystem-based management of fisheries resources. In short, this means managing marine ecosystems in full consideration of each separate component and important interactions between components, in order to maintain healthy ecosystem function – including the production of goods and services that people value. An important point, frequently neglected, is that human activities are clearly part of the marine ecosystem today and have been throughout history. Ecosystem-based management planning must include a greater understanding of the enormous productive capacity of marine ecosystems, as well as acknowledging the fact that most of the ocean and coastal ecosystems we value have already been profoundly altered, even degraded. Our work on the Scotian Shelf codfishery from 1852–1859 revealed a fishery, a marine environment, and a cod population substantially different in size and structure from today's counterparts. As policy makers grapple with the global problems of overfishing and restoring ocean productivity, a historical perspective is needed to envision what oceans have produced in the past and what they might produce in the future.

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