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Food for Thought

Five centuries of cod catches in Eastern Canada

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The fishery for Northern Atlantic cod (*Gadus morhua*) off Newfoundland and Labrador, Eastern Canada, presents the most spectacular case of an exploited stock crashed in a few decades by an industrial bottom trawl fishery under a seemingly sophisticated management regime after half a millennium of sustainable fishing. The fishery, which had generated annual catches of 100000 to 200000 tonnes from the beginning of the 16th century to the 1950s, peaked in 1968 at 810000 tonnes, followed by a devastating collapse and closure 24 years later. Since then, stock recovery may have been hindered by premature openings, with vessels targeting the remains of the cod population. Previous research paid little attention towards using multicentury time series to inform sustainable catches and recovery plans. Here, we show that a simple stock assessment model can be used to model the cod population trajectory for the entire period from 1508 to 2019 for which catch estimates are available. The model suggests that if fishing effort and mortality had been stabilized in the 1980s, precautionary annual yields of about 200000 tonnes could have been sustained. Our analysis demonstrates the value of incorporating prior knowledge to counteract shifting baseline effects on reference points and contemporary perceptions of historical stock status.

Keywords: Atlantic cod, catch reconstruction, fisheries management, historical marine ecology, rebuilding, reference point, shifting baseline, stock assessment

Introduction

For millennia, the biodiversity of the ocean has supported pre-industrial fisheries, although they were already capable of extirpating easily accessible animals (Jackson *et al.*, 2001). The ascent of industrial fishing, i.e. the deployment of large vessels fuelled by fossil energy (first coal, then diesel), however, radically changed fisheries, and made it increasingly possible to target accumulations of any desirable fish species at any distance from coastlines, depth of occurrence or season, all factors which created areas and times where fishing was not before possible (Swartz *et al.*, 2010).

Thus, as industrial fishing spread across the world from the UK in the 1880s, global catch increased throughout most of the 20th century, and particularly after WWII, when bottom trawling became widespread. Although many coastal fish populations rapidly collapsed under the onslaught, this was long masked by the opening of new fishing grounds in hitherto unfished areas (Pauly *et al.*, 2002; Cardinale *et al.*, 2015). In the mid-1990s, however, the opening of new fisheries became unable to compensate for the over-exploitation of the "old" fishing grounds (Froese *et al.*, 2009), and the world catch peaked and began a decline which continues to this day (Pauly and Zeller, 2016; FAO, 2018), despite the increasing fishing effort and seafood demand. Recent intensive management efforts across the globe have started to show improvements in stock status for marine fish assessments that are based on science (Hilborn *et al.*, 2020).

We now have reached a point where the only way to increase—or even sustain present fisheries catches—must involve the rebuilding of fish populations earlier depleted by overfishing. This is best illustrated by the Northern cod of Eastern Canada, i.e. Atlantic cod (*Gadus morhua*). The stock defined by this assessment includes all cod caught within NAFO-delineated Divisions 2J3KL.

Previously considered one of the world's largest and most important fish stocks (Hutchings and Rangeley, 2011), Northern cod have played a fundamental role in shaping the history, economy and culture of Atlantic Canada since the late 15th century (Innis, 1940; Cell, 1982). In the 1960s, within a decade after European factory freezer trawlers began operation in Eastern Canada, catches peaked, and then plummeted. The declaration of a fishery exclusion zone in 1977, which largely eliminated foreign fishing, did not provide much of a respite, however, as Canada subsidised the building of a national fleet which continued overfishing. In 1992, the Canadian government declared a moratorium on Northern cod, as the stock had collapsed, followed in the next two years by cod moratoria in all eastern provinces of Canada, closing an entire economic sector.

The moratorium on directed commercial fishing was initially predicted by DFO to last two years to allow for sufficient stock recovery (Hutchings *et al.*, 1997). Other factors such as temperature and prey availability may have contributed additional pressure on the stock's ability to recover (Rose and O'Driscoll, 2002; Buren *et al.*, 2014). Almost 30 years later, all Canadian cod stocks remain in a critical state, their most recent estimates of population size being below their respective biomass limit reference points (all stock assessments for Canadian Atlantic cod are available through the Canadian Science Advisory Secretariat at https://www.dfo-mpo.gc.ca/csas-sccs/).

Applying a historical lens towards rebuilding

In order to estimate the full potential of an exploited resource, we must set our baseline near the start of its exploitation, and account for all withdrawals over time. Ignoring the past can lead to shifting baseline syndrome (Pauly, 1995), where we accept as baseline, a situation that does not account for the previous exploitation and its impact on stock size and dynamics. This can lead to underestimating fishing impacts and setting quotas too high, thus preventing a stock from rebuilding (Hutchings and Rangeley, 2011). The new discipline of historical marine ecology has emerged from attempts to counteract the shifting baseline syndrome, by demonstrating the value of recovering earlier abundance estimates and thus strengthening the management of marine populations (Jackson *et al.*, 2001).

The case study presented here has two goals: (i) to demonstrate the usefulness of a 500+ year record of Northern cod catches for the current setting of stock rebuilding targets and (ii) to demonstrate, using the newly developed CMSY stock assessment method (Froese *et al.*, 2017), that considering long time series does not necessarily require complex models with a multitude of free parameters.

Methods

Stock assessment

We used a new open source stock assessment tool (CMSY) (Froese *et al.*, 2017), which is based on surplus-production modelling (Schaefer, 1954, 1957). The CMSY tool (Froese *et al.*, 2017) includes two methods: the first (named CMSY, same as the overall tool) derives fisheries reference points from catch data and priors with a Monte Carlo approach, while the second (named BSM) is a Bayesian state-space implementation of a traditional surplus production model which derives its estimates from catch plus abundance or effort data, if available. Since the BSM assessment is based on more information, it usually produces narrower estimates of changes in population biomass trends over time. Overall, both methods show good agreement with more data-demanding assessments (Martell and Froese, 2013). The most recent CMSY R-code is available from http://oceanrep.geomar.de/33076/. The R-code used for this analysis is available in the supplementary material.

Equation (1) below describes how parameters for the intrinsic rate of population increase (r), carrying capacity (k), and biomass in a given year (B_t) and catch in the same year (C_t) can be used to determine biomass (B) in the subsequent year ($t + 1$). Bias-correcting lognormal errors (e^{s_1} *and* e^{s_2}) are assigned to surplus production and catch, respectively.

$$B_{t+1} = B_t + r\left(1 - \frac{B_t}{k}\right)B_t e^{s_1} - C_t e^{s_2} \qquad (1)$$

The above equation is modified (Equation 2) when a stock size is severely depleted (biomass below 0.25k or 0.5B/B$_{MSY}$) to account for depensation—the reduction of recruitment at a small stock size (Myers *et al.*, 1995; Maroto and Moran, 2014; Perälä and Kuparinen, 2017; Neuenhoff *et al.*, 2019). This differs from the latest assessment model (Cadigan, 2015) used by DFO (Brattey *et al.*, 2018), which does not consider depensatory population dynamics, but does report periods of very low productivity for the Northern cod stock after the collapse (Morgan, 2019).

$$B_{t+1} = B_t + \left(\frac{4rB_t}{k}\right)\left(1 - \frac{B_t}{k}\right)B_t e^{s_1} - C_t e^{s_2} | \frac{B_t}{k} < 0.25 \qquad (2)$$

Based on this theoretical framework, the CMSY method estimates likely biomass trajectories that correspond to the biomass reductions caused by fishing, the range for carrying capacity (k) and intrinsic rate of population increase (r). Uniform ranges for r and k were translated into prior densities with central values (Froese *et al.*, 2017). The most probable "viable" r-k pair is selected from the tip of a triangle-shaped bivariate plot of r vs. k (Froese *et al.*, 2017). When relative biomass data are known, an additional parameter (i.e. catchability or q) is estimated to convert *catch-per-unit-of-effort* into biomass. Each tentative biomass trajectory is compared with the available relative biomass trend, which usually results in narrower confidence intervals.

Selection of priors

In the present study, a reconstructed catch time series (Hutchings and Myers, 1995; Supplementary Information) starts in 1508 and was updated to 2017, using Northwest Atlantic Fisheries Organization (NAFO) annual reports (NAFO, 2021), and further updated to 2019 from the most recent DFO stock status update (DFO, 2021b) (Table 1).

Resilience corresponds to the intrinsic rate of population increase (r). We used a lower (Hutchings and Rangeley, 2011) bound of r set at 0.095 year^{-1} and an upper (Hutchings, 1999) bound set at 0.3 year^{-1}. Other studies also present the intrinsic rate of population increase within the chosen range (Myers *et al.*, 1997; Rose, 2004).

Independent prior knowledge about the reduction of biomass by fishing from the start of the fishery to the end of the time series was translated into broad ranges of biomass relative to unexploited biomass (Table 2). At the start of the time series with very little fishing in 1508, the biomass range relative to unexploited biomass

Table 1. Northern cod (*Gadus morhua*) catches from 1508 to 2019 based on a reconstruction from Hutchings and Myers (1995) updated to 2017, using NAFO annual reports (NAFO, 2021) for cod caught within Divisions 2J3KL, and further updated to 2019 from the DFO stock status update (DFO, 2021b).

Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)
1508	156	1582	3288	1655	5382	1729	26 904	1803	96 796	1877	158 000	1951	272 000
1509	203	1583	2190	1656	4370	1730	46 829	1804	97 200	1878	161 000	1952	265 000
1510	251	1584	657	1657	3358	1731	50 631	1805	92 400	1879	204 000	1953	238 000
1511	188	1585	10 301	1658	2346	1732	50 295	1806	110 800	1880	206 000	1954	315 843
1512	125	1586	8285	1659	1333	1733	50 570	1807	98 800	1881	220 000	1955	232 858
1513	125	1587	6268	1660	321	1734	49 738	1808	86 800	1882	206 000	1956	263 210
1514	125	1588	4252	1661	20 292	1735	49 561	1809	115 600	1883	223 000	1957	254 456
1515	125	1589	2235	1662	40 262	1736	46 229	1810	125 200	1884	222 000	1958	206 710
1516	125	1590	219	1663	643	1737	52 819	1811	130 000	1885	204 000	1959	359 572
1517	125	1591	219	1664	111 129	1738	59 410	1812	104 400	1886	216 000	1960	467 802
1518	251	1592	219	1665	46 705	1739	66 328	1813	126 000	1887	191 000	1961	505 105
1519	376	1593	219	1666	5797	1740	46 094	1814	133 200	1888	185 000	1962	507 026
1520	501	1594	219	1667	5476	1741	57 446	1815	150 000	1889	173 000	1963	509 209
1521	125	1595	219	1668	5476	1742	49 737	1816	145 200	1890	170 000	1964	602 651
1522	376	1596	22 140	1669	5476	1743	42 027	1817	142 800	1891	181 000	1965	545 035
1523	156	1597	219	1670	28 666	1744	44 130	1818	141 200	1892	163 000	1966	524 505
1524	125	1598	3726	1671	5476	1745	46 233	1819	130 800	1893	165 000	1967	611 764
1525	376	1599	4602	1672	5476	1746	48 422	1820	128 400	1894	170 000	1968	810 014
1526	627	1600	3891	1673	7730	1747	62 175	1821	128 400	1895	196 000	1969	753 690
1527	877	1601	20 621	1674	9985	1748	75 928	1822	126 000	1896	188 000	1970	520 226
1528	501	1602	23 878	1675	46 705	1749	88 793	1823	124 400	1897	190 000	1971	439 518
1529	125	1603	3249	1676	14 494	1750	80 790	1824	126 000	1898	200 000	1972	458 295
1530	376	1604	10 306	1677	12 560	1751	68 907	1825	138 000	1899	217 000	1973	354 509
1531	251	1605	17 363	1678	10 627	1752	89 496	1826	137 200	1900	206 000	1974	372 650
1532	125	1606	10 856	1679	9985	1753	72 965	1827	129 200	1901	219 000	1975	287 508
1533	251	1607	9764	1680	26 411	1754	73 654	1828	129 200	1902	222 000	1976	214 220
1534	125	1608	18 455	1681	52180	1755	60 362	1829	132 400	1903	211 000	1977	172 720
1535	376	1609	22 796	1682	38 653	1756	54 590	1830	135 600	1904	191 000	1978	138 559
1536	125	1610	31 477	1683	39 620	1757	48 819	1831	112 400	1905	222 000	1979	166 899
1537	1128	1611	24 961	1684	25 769	1758	55 736	1832	95 600	1906	216 000	1980	175 788
1538	376	1612	30 394	1685	52180	1759	62 652	1833	104 400	1907	234 000	1981	170 748
1539	376	1613	49 932	1686	46 383	1760	69 569	1834	119 600	1908	273 000	1982	229 774
1540	125	1614	37 993	1687	47 671	1761	76 485	1835	108 400	1909	261 000	1983	232 345
1541	9658	1615	18 455	1688	38 008	1762	83 401	1836	126 000	1910	238 000	1984	232 471
1542	752	1616	21 713	1689	14 745	1763	90 318	1837	118 000	1911	226 000	1985	231 293
1543	1505	1617	6507	1690	2768	1764	97 234	1838	110 800	1912	220 000	1986	266 713
1544	251	1618	10 856	1691	3864	1765	92 191	1839	128 400	1913	211 000	1987	239 924
1545	156	1619	14 287	1692	1604	1766	103 712	1840	134 800	1914	182 000	1988	268 677
1546	3011	1620	128 101	1693	8373	1767	104 951	1841	146 000	1915	215 000	1989	253 990
1547	1631	1621	16 280	1694	8051	1768	102 924	1842	146 000	1916	224 000	1990	219 452
1548	1631	1622	2903	1695	8373	1769	100 895	1843	138 000	1917	253 000	1991	172 012
1549	12 418	1623	10 856	1696	16 427	1770	112 469	1844	127 600	1918	236 000	1992	40 956
1550	156	1624	8681	1697	11 594	1771	111 192	1845	146 000	1919	265 000	1993	11 392
1551	219	1625	6507	1698	62 489	1772	130 617	1846	131 600	1920	222 000	1994	1314
1552	219	1626	81 959	1699	53 147	1773	132 966	1847	126 800	1921	250 000	1995	413
1553	657	1627	157 412	1700	27 570	1774	120 763	1848	137 200	1922	249 000	1996	1875
1554	219	1628	122 677	1701	24 765	1775	117 880	1849	168 400	1923	239 000	1997	877
1555	23 894	1629	13 022	1702	21 960	1776	96 301	1850	158 000	1924	223 000	1998	4507
1556	1752	1630	13 022	1703	19 674	1777	79 347	1851	125 000	1925	256 000	1999	8526
1557	2631	1631	13 022	1704	17 388	1778	62 394	1852	119 000	1926	289 000	2000	5430
1558	84	1632	13 022	1705	15 101	1779	66 672	1853	117 000	1927	278 000	2001	6969
1559	11 179	1633	13 022	1706	18 993	1780	70 949	1854	104 000	1928	250 000	2002	4249
1560	8330	1634	13 022	1707	22 884	1781	75 227	1855	131 000	1929	245 000	2003	994
1561	6794	1635	13 022	1708	25 651	1782	79 505	1856	151 000	1930	241 000	2004	649
1562	657	1636	29 311	1709	15 109	1783	83 783	1857	169 000	1931	216 000	2005	1331
1563	2409	1637	21 713	1710	23 679	1784	88 061	1858	134 000	1932	227 000	2006	2701
1564	10 741	1638	21 713	1711	19 776	1785	103 301	1859	154 000	1933	250 000	2007	2931
1565	26 084	1639	28 219	1712	11 694	1786	119 672	1860	166 000	1934	268 000	2008	3385
1566	876	1640	21 713	1713	20 522	1787	132 704	1861	156 000	1935	260 000	2009	3116

Table 1. Continued

Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)	Year	Catch (tonnes)
1567	745	1641	39 075	1714	21 590	1788	162 518	1862	158 000	1936	261 000	2010	2962
1568	613	1642	16 280	1715	17 378	1789	126 529	1863	130 000	1937	225 000	2011	3770
1569	482	1643	21 713	1716	15 209	1790	112 382	1864	130 000	1938	277 000	2012	3871
1570	350	1644	21 713	1717	26 153	1791	87 136	1865	126 000	1939	203 000	2013	4506
1571	219	1645	21 713	1718	21 303	1792	92 352	1866	117 000	1940	190 000	2014	4870
1572	3069	1646	26 053	1719	20 684	1793	92 756	1867	130 000	1941	184 000	2015	4436
1573	219	1647	21 167	1720	17 015	1794	93 160	1868	121 000	1942	165 000	2016	6916
1574	1314	1648	16 280	1721	19 206	1795	93 564	1869	130 000	1943	209 000	2017	13 013
1575	4164	1649	20 621	1722	21 397	1796	93 968	1870	144 000	1944	225 000	2018	11 000
1576	1533	1650	15 303	1723	23 589	1797	94 372	1871	155 000	1945	257 000	2019	10 559
1577	3726	1651	9985	1724	22 036	1798	94 776	1872	155 000	1946	252 000		
1578	2409	1652	8695	1725	23 136	1799	95 180	1873	152 000	1947	287 000		
1579	2409	1653	7406	1726	30 688	1800	95 584	1874	171 000	1948	268 000		
1580	3507	1653	7406	1727	29 675	1801	95 988	1875	222 000	1949	280 000		
1581	1314	1654	6394	1728	28 289	1802	96 392	1876	170 000	1950	272 000		

Table 2. Prior biomass ranges relative to the unexploited biomass (*B/k*) for years that were used as start, intermediate, and end points in the Northern cod (*Gadus morhua*) stock assessment.

Year	Biomass range
1508	0.9–1.0
1930	0.4–0.9
1970	0.2–0.6
1985	0.1–0.4
2019	0.01–0.2

Table 3. Total abundance from the autumn DFO fall RV bottom-trawl surveys of NAFO Divisions 2J3KL (DFO, 2021b, Table 2).

Year	Abundance Index	Year	Abundance Index
1983	2088958	2002	62371
1984	2198605	2003	42861
1985	1288360	2004	62576
1986	2502702	2005	61133
1987	1020462	2006	82735
1988	1223314	2007	128027
1989	2127417	2008	141297
1990	1627647	2009	174981
1991	1117670	2010	139350
1992	239740	2011	106374
1993	90709	2012	167270
1994	21797	2013	325654
1995	43240	2014	463376
1996	38698	2015	500413
1997	25223	2016	536091
1998	28702	2017	437705
1999	60663	2018	551383
2000	72300	2019	566968
2001	63292		

was set at 0.9–1.0 (very low depletion (Rose, 2004)). The end of the time series in 2019 corresponds to a biomass range of 0.01–0.20, as justified by expert knowledge that the stock's biomass is below critical levels (very strong depletion (Hilborn and Litzinger, 2009; Brattey *et al.*, 2018, DFO, 2021b)), but may be experiencing some recovery in sub-populations (Rose and Rowe, 2015). For the 1508–2019 analysis, the intermediate biomass range was set for 1930 at 0.4–0.9 (medium/low depletion). For the 1930–2019 analysis, the starting biomass was set at 0.4–0.9 (medium/low depletion) and an intermediate range was set for 1985 at 0.1–0.4 (strong depletion), since investigations at the time suggested the stock to be below B_{MSY} but not collapsed (Hutchings and Rangeley, 2011; Rose and Walters, 2019). For the 1970–2019 analysis, starting biomass was set at 0.2–0.6 (medium depletion (Rose and Walters, 2019)) and an intermediate range was set in 1985 at 0.1–0.4 (strong depletion (Hutchings and Rangeley, 2011; Rose and Walters, 2019)). A sensitivity analysis was conducted to test the use of priors in the 1970–2019 analysis by switching off the intermediate and end priors. The empirical built-in default priors gave similar ranges as the expert-based priors.

In addition, the BSM was informed by a time series of total abundance from the DFO fall Research Vessel (RV) bottom trawl surveys of NAFO Divisions 2J3KL (DFO, 2021b) (Table 3). The state-space model implementation of the BSM (Millar and Meyer, 2000) accounts for process error in population dynamics and observation error in measurement and sampling (Thorson *et al.*, 2012). The standard deviation of the process error is specified in the code as sigmaR with a default value of 0.1, which we varied, to evaluate sensitivity, between 0.1 and 0.4. The alternative values of the process error had minimal effect on the model output, thus the default value of 0.1 was used in the final analyses. Process error is sampled anew for every year of the time series, accounting for uncertainty in the modelled productivity. The code also models error in catch, with a lognormal distribution.

Assessment results

The CMSY analysis produces proxies for MSY, F_{MSY}, B_{MSY}, and indicators like stock size (B/B_{MSY}) and exploitation (F/F_{MSY}) (Table 4). The outputs of both CMSY and BSM analyses were similar for Northern cod (Table 4), thus building confidence in the results. Since BSM estimates are based on more data, they were used for the estimates presented in the text below (Figure 1). Analysing 512 years of catch data (Figure 1a) and 37 years of relative biomass data (Table 3) produced an estimate of the intrinsic rate of population increase (with 95% confidence intervals) of Northern cod

Table 4. Output parameters and reference points of the Northern cod (*Gadus morhua*) stock assessment with three time series with upper and lower confidence intervals. Results of reference points are based on BSM output. Units for *k*, MSY, and B_{MSY} are in millions of tonnes.

Time series	1508–2019	1930–2019	1970–2019
r (BSM)	0.25 (0.14–0.46)	0.29 (0.16–0.50)	0.34 (0.20–0.57)
r (CMSY)	0.16 (0.11–0.22)	0.15 (0.11–0.22)	0.16 (0.11–0.23)
k (BSM)	6.00 (4.03–8.93)	4.92 (3.09–7.84)	2.98 (2.02–4.39)
k (CMSY)	8.34 (6.72–10.4)	8.72 (6.44–11.8)	7.92 (5.20–12.1)
MSY (BSM)	0.38 (0.29–0.49)	0.35 (0.25–0.49)	0.25 (0.17–0.37)
MSY (CMSY)	0.32 (0.28–0.38)	0.33 (0.28–0.38)	0.31 (0.21–0.48)
B_{MSY}	3.00 (2.02–4.46)	2.46 (1.55–3.92)	1.49 (1.01–2.19)
B_{2019}/B_{MSY}	0.03 (0.02–0.10)	0.10 (0.03–0.30)	0.21 (0.09–0.38)
F_{MSY} (without depensation)	0.13 (0.07–0.23)	0.14 (0.08–0.25)	0.17 (0.10–0.28)
F_{MSY} (with depensation)	0.008 (0.004–0.014)	0.029 (0.017–0.051)	0.071 (0.042–0.119)
F_{2019}/F_{MSY} (with depensation)	14.3 (1.27–33.4)	1.49 (0.18–23.0)	0.50 (0.14–2.75)

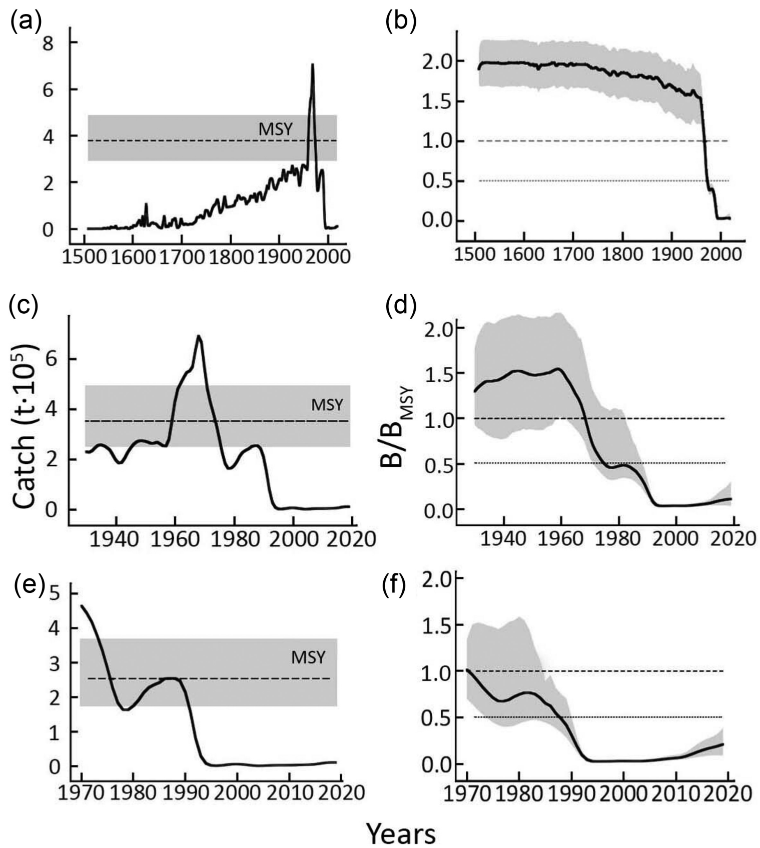

Figure 1. Catch and estimated biomass of Northern cod (*Gadus morhua*) off Eastern Canada from 1508 to 2019 (A, B), with emphasis on 1930 to 2019 (C, D) and 1970 to 2019 (E, F). The catch and relative biomass level compatible with Maximum Sustainable Yield are shown (dotted lines), along with the 95% confidence intervals.

of r = 0.25 $year^{-1}$ (0.14–0.46 $year^{-1}$) and a carrying capacity of $k = 6.0$ million tonnes (4.0–8.9 million tonnes). Maximum Sustainable Yield (MSY) can then be computed from $r{\cdot}k/4$, which yields 380000 $t{\cdot}year^{-1}$, (290000–490000 tonnes), while biomasses can be expressed relative to the biomass that can produce MSY (B/B_{MSY}; see Figure 1b).

Figure 1b shows that, for 200 years, the fishery for Northern cod impacted its biomass only lightly, and that it began to be noticeably reduced from 1700 on; however, it remained well over B_{MSY} and thus capable of producing MSY as well as fulfilling its ecosystem role as a major predator in the waters off what is now Eastern Canada. With catches increasing from the 18th to the middle of the 20th century, the biomass decline accelerated, but it was only in the 1960s, with the onset of the industrial trawl fishery, that Northern cod biomass precipitously declined below B_{MSY}, and specifically after 1968, when the peak reported catch of 810000 tonnes was extracted (Figure 1b).

Figure 1c and d show that the 1977 declaration of a fishery exclusion zone and the departure of foreign fleets led to a brief stabilization, at a suboptimal level, of the biomass of Northern cod in

Table 5. Comparison of Northern cod (*Gadus morhua*) stock assessments, including data-limited stock assessment methods CMSY and BSM with 95% confidence intervals. Units for MSY and B_{MSY} are in millions of tonnes.

Source	Reference points		
	MSY	B_{MSY}	F_{MSY}
BSM	0.38 (0.29–0.49)	3.00 (2.02–4.46)	0.13 (0.07–0.23)
CMSY	0.32 (0.28–0.38)	3.74 (3.10–4.50)	0.08 (0.06–0.11)
Logistic growth model (Hilborn and Litzinger, 2009)		2.8	
VPA (DFO, 2011)		2.6*	
Stock-recruitment model (Ricard *et al.*, 2012)		4*	0.1
Shelton model (Shelton, 1998)	0.13	2.4*	0.2

*Assumed a 4:1 ratio for total biomass to SSB according to DFO (2011) and Ricard *et al.* (2012).

the late 1970s and early 1980s. At this time, precautionary annual yields of around 200000 tonnes may have been sustained, but this opportunity to let the stock rebuild was not used. Rather, a newly built, heavily subsidized Canadian trawler fleet replaced the fishing mortalities previously exerted by foreign fleets, leading to a second collapse of catches (Figure 1e) and biomass, which fell below 1% of its original biomass (Figure 1f).

Remarkably, the 1992 fisheries "moratorium" did not lead to a cessation of the fishery. Rather, post-moratorium catches, ranging between 400 and 13000 tonnes per year, continued to be taken (DFO, 2021b), consisting of subsistence and recreational catches, by-catch, occasional 'sentinel surveys', and a stewardship fishery (i.e., small-scale commercial fisheries by any other name), and exerting just enough pressure to forestall a rebuilding of the population (Rose and Walters, 2019). The rebuilding plan, released in 2020, states that fishery removals are to be kept at the "lowest possible level" until stock biomass has grown above the critical zone (DFO, 2021a). This plan has been criticized for not restricting catches sufficiently and explicitly allowing increase in quotas before the stock has reached the limit reference point (Hutchings *et al.*, 2021).

In addition to the time series of catch, the BSM method used a relative index of abundance available from fisheries-independent surveys conducted by the Canadian Department of Fisheries and Oceans since 1983 (DFO, 2021b) (Table 3). The results of BSM are similar to published estimates of more data-intensive models (Table 5). The model estimates biomass in 2019 is 310 (131–570) kt. Although our estimate is lower than the 480 kt reported by DFO (2021b), it is consistent with Rose and Walters' (2019) estimates of 300 kt in 2015 declining to about 250 kt in 2017. As well, the intrinsic rate of population increase (r) estimated here is similar to that estimated in another long-term assessment of Northern cod, but which explicitly accounted for climate effects (Rose, 2004).

To explore changes in carrying capacity over the 512 years, we repeated the assessment for two recent periods, 1930–2019 and 1970–2019. The estimate of carrying capacity for the 1970–2019 period of 3.0 (2.0–4.4) million tonnes is lower than the estimate for the entire period of 6.0 (4.0–8.9) million tonnes, though the difference is not significant, with both estimates being included in their respective 95% confidence limits. This decline may indicate a true change in carrying capacity (Palomares *et al.*, 2018) or it may stem from non-consideration or under-reporting of previous catches and then present a case of a shifting baseline, where a rebuilding target such as B_{MSY} is underestimated because only recent data were included in the analysis (Préfontaine, 2009). For a lesser known stock, the shifting baseline syndrome (Pauly, 1995) may be more prevalent, especially if consecutive assessments selected more recent years without incorporating knowledge of past exploitation. For the case of Northern cod, the use of well-informed priors prevents or limits shifting baselines, as reflected by the limited shifts in reference points for the selected time periods (Table 4). The estimates of F_{MSY} in Table 4 (with and without depensation) are consistent with the hypothesis that Northern cod is not capable of sustaining levels of fishing mortality as high as those of other cod stocks (Myers *et al.*, 1996; Rose, 2019). These findings suggest that management strategies should strive to include historical data in order to provide realistic reference points as targets for rebuilding.

The broad confidence limits in our estimates of k reflect a legitimate challenge in estimating carrying capacity based on historical data. Although not statistically significant, we cannot discount the possibility that the changes in k are biologically informative and indicative of changing production regimes. One putative correlate of Northern cod productivity is water temperature (Lilly *et al.*, 2008). For example, citing Colonial Office export records, Innis (1940) reported low catches during the 1713–1720 and 1789–1792 periods, ostensibly because cold water had reduced the availability of cod to inshore fisheries. In contemporary times, water temperatures were colder in the 1970 to 2000 period when compared to the 1940 to 1970 period, and this might have contributed to lower productivity in the short term. But if one examines temperatures with a longer historical lens (as we have done with the catch data), the colder temperatures of the late 1980s and early 1990s were experienced by Northern cod from the 1850s to the 1930s (Hutchings and Myers, 1994; NCAR, 2021) with no discernably negative effects on catches.

Exploring the results of Table 4 further, the CMSY method produces lower estimates of r (closer to the prior) and consequently higher estimates of k (r and k are inversely related in the context of a Schaefer model). The observation that the CMSY output is closer to the r prior than the output from the BSM model stems from the fact that the CMSY model has no information on stock abundance. In other words, the higher r values estimated by BSM stem from the incorporation of highly informative CPUE data. We note, however, that the confidence limits of r from the CMSY and BSM outputs overlap, suggesting that the differences in r produced by the two methods are not substantial.

Our assessment suggests that the biomass of Northern cod is currently (in 2019) 2% of carrying capacity and less than 0.05 B_{MSY}. Independently of the accuracy of these quantitative estimates, the biomass of Northern cod is clearly far lower than the historical biomass that was capable of sustaining annual catches of 150000 to 200000 tonnes (Figure 1). There is a scientific consensus that the stock is currently well below its biomass limit reference point (0.48 B_{LIM}, according to DFO, 2021b) and that periodic inshore fisheries since the 1992 moratorium have had (Hutchings and Rangeley, 2011; Rose and Walters, 2019), and continue to have (DFO, 2021b), an inhibitory effect on stock rebuilding.

All else being equal, the smaller a population, the greater its susceptibility to stochastic environmental change, resulting in increased variability in mortality in fishes (Minto *et al.*, 2008); the greater the magnitude of population reduction, the longer and more uncertain the rebuilding period (Neubauer *et al.*, 2013). Such impairments to recovery can be caused by depensation or Allee effects (Perälä and Kuparinen, 2017; Neuenhoff *et al.*, 2019). Manifest by a decline in realized per capita population growth rate with declining population size, depensation in marine fish populations can be the result of declining recruits per spawner, increased natural mortality, or both (Maroto and Moran, 2014; Hutchings, 2015). Depensation is built into the principal Equation 2 of CMSY and reflected by a linear decline of curFmsy when biomass falls below 0.25k, a threshold consistent with previous estimates of where the Allee-effect threshold might exist for marine fishes, including cod (Hutchings, 2014, 2015). Our incorporation of depensation draws explicit attention to the possibility that per capita population growth, and consequently F_{MSY} (Table 4), declines with declining abundance at low population size, a caveat that is not reflected by current management strategies for Northern cod (Winter and Hutchings, 2020).

Conclusion

The CMSY tool may be useful to assess both data-limited stocks (those with only catch available) and data-rich stocks (e.g. Northern cod), as it can provide longer term estimates of stock status by incorporating past data-limited periods. Centuries-old catch data exist for several stocks, such as Bluefin tuna (*Thunnus thynnus*) in the Mediterranean (commercialized around the 8th century (Lleonart *et al.*, 1998; Addis *et al.*, 2009)), Atlantic herring (*Clupea harengus*) in the Baltic Sea (fishery started in the 13th century (MacKenzie *et al.*, 2002)), and Atlantic salmon (*Salmo salar*) in the Celtic Sea (fishery started in the 14th century (Manx Heritage Foundation, 1991)). By integrating historical data into stock assessments, we may better understand the total impact of fisheries on marine ecosystems and effectively manage marine populations for a long-term future.

Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

All data used in this paper can be found in the Supplementary Data. The full CMSY package developed by Froese *et al.* (2017) is available from: https://oceanrep.geomar.de/33076/.

Author contributions

RS performed model simulations, statistical analyses, co-wrote, and co-edited the paper. RF assisted in developing priors, designed and performed model simulations, co-wrote, and co-edited the paper. JAH provided the catch data, assisted in developing priors, co-wrote and co-edited the paper. DP conceived the study, co-wrote, and co-edited the paper.

Competing interest declaration

The authors declare no competing interest.

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