ENVIRONMENTAL SCIENCE

Tambora and the mackerel year: Phenology and fisheries during an extreme climate event

Karen E. Alexander,[1]* William B. Leavenworth,[2] Theodore V. Willis,[3] Carolyn Hall,[4] Steven Mattocks,[1] Steven M. Bittner,[1] Emily Klein,[5,6] Michelle Staudinger,[1,7] Alexander Bryan,[7] Julianne Rosset,[1] Benjamin H. Carr,[8] Adrian Jordaan[1]

Global warming has increased the frequency of extreme climate events, yet responses of biological and human communities are poorly understood, particularly for aquatic ecosystems and fisheries. Retrospective analysis of known outcomes may provide insights into the nature of adaptations and trajectory of subsequent conditions. We consider the 1815 eruption of the Indonesian volcano Tambora and its impact on Gulf of Maine (GoM) coastal and riparian fisheries in 1816. Applying complex adaptive systems theory with historical methods, we analyzed fish export data and contemporary climate records to disclose human and piscine responses to Tambora's extreme weather at different spatial and temporal scales while also considering sociopolitical influences. Results identified a tipping point in GoM fisheries induced by concatenating social and biological responses to extreme weather. Abnormal daily temperatures selectively affected targeted fish species—alewives, shad, herring, and mackerel—according to their migration and spawning phenologies and temperature tolerances. First to arrive, alewives suffered the worst. Crop failure and incipient famine intensified fishing pressure, especially in heavily settled regions where dams already compromised watersheds. Insufficient alewife runs led fishers to target mackerel, the next species appearing in abundance along the coast; thus, 1816 became the "mackerel year." Critically, the shift from riparian to marine fisheries persisted and expanded after temperatures moderated and alewives recovered. We conclude that contingent human adaptations to extraordinary weather permanently altered this complex system. Understanding how adaptive responses to extreme events can trigger unintended consequences may advance long-term planning for resilience in an uncertain future.

INTRODUCTION

Global warming has fueled concerted research on recent, ongoing, and potential transformations of human and natural systems (*1*–*3*). However, gradual warming is not the proximate threat from climate change. Rising global temperatures have already increased the number and intensity of extreme climate events (*4*–*7*). Consequent human suffering and economic loss are well documented in public media, even as devastated coastlines and marine ecosystems, some in conservation areas and experimental field sites, increasingly appear in research (*8*–*10*). Because extreme events are erratic and damage can occur in many ways, assessing ecological and social impacts requires long-term monitoring capacity from appropriate baseline conditions (*11*–*13*), predicated on an understanding of local and regional variability (*14*–*16*). Disruption of marine food webs (*17*–*19*) and threats to fisheries (*20*–*22*) can be inferred from research linking climate oscillations to nonseasonal variability in fish abundance and distribution and to fisheries success or failure (*23*–*25*). Because adaptation and mutual influence are linked via feedback, fisheries are prime examples of coupled human and natural systems (CHANS), where conditions can evolve in complex and unexpected ways in different places over time (*26*, *27*). Coastal fisheries, ecosystems, and economies are particularly vulnerable to sudden climate events (*28*–*31*), yet long-term effects may be apparent only in retrospect (*32*).

Although they comprise only a small part of today's global economy, fisheries are important for local food security (*33*–*35*), particularly along densely populated shores and in developing countries with few sources of affordable protein (*36*–*38*). Historically, fisheries played an important role in national economies and foreign policies (*39*–*41*). Marine resource harvest generated wealth in trade (*40*–*42*), promoted transportation networks and infrastructure (*43*, *44*), and transmitted social and cultural traditions while providing a living to generations of fishers (*45*, *46*). Over time, as primary stocks declined in abundance and quality, a regular pattern of exploitation evolved (*47*–*49*). Marine resources were first harvested close to home and then at increasingly greater distances with greater effort, even as original, depleted targets were replaced by others that were still abundant and accessible (*49*–*51*). From prehistoric shell middens to sport fishing trophies, global evidence of marine resource harvest shows similar progressions (*52*–*55*). These patterns may disclose long-term processes underlying social-ecological change that, at present, can be difficult to identify (*56*).

Here, we turn to historical fisheries in the Gulf of Maine (GoM) to show how an extreme climatic event triggered adaptation and change within this coupled system. On 5 April 1815, the Indonesian volcano Tambora exploded in one of the most significant volcanic events in recorded history (*57*–*59*). With among the highest explosive indexes in 500 years, it ejected about 100 km^3 of ash into the stratosphere (*59*–*62*). Upper-level winds streaming northward from the equator swept its sulfate aerosols around the world, dropping global temperatures by 1° to 1.5°C (*59*) and generating extreme weather in the northern hemisphere. Unseasonable cold accompanied by droughts and floods characterized the period from the winter of 1815 to the spring of 1817 (*58*, *62*–*65*). Catastrophic weather conditions afflicted China (*64*). Floods and famine ravaged northwestern Europe, and starvation threatened the eastern United States and Canada (*58*, *62*, *63*, *65*). In

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[1]Department of Environmental Conservation, University of Massachusetts Amherst, Amherst, MA 01003–9285, USA. [2]Independent Researcher based in Maine. [3]University of Southern Maine, Portland, ME 04103, USA. [4]Alan Alda Center for Communicating Science, Stony Brook University, Stony Brook, NY 11794, USA. [5]Southwest Fisheries Science Center, La Jolla, CA 92037, USA. [6]Farallon Institute, Petaluma, CA 94952, USA. [7]Department of the Interior Northeast Climate Science Center, Amherst, MA 01003–9297, USA. [8]Marine Program, Boston University, Boston, MA 02215, USA.
*Corresponding author. Email: kalexander@umass.edu

southern New England, the months from May to September 1816 were several degrees colder than average, but spikes in temperature punctured the cold. Crop yields fell as much as 90% (*66*).

Unlike Tambora's documented effects on land, its influence on coastal ecology and fisheries has received little attention. However, in New England, 1816 was called not only the "year without a summer" and the "year of 1800-and-Froze-to-Death" but also the "mackerel year" [(*67*), p. 153], suggesting discernable effects on fisheries. We propose that the coldest summer in more than 200 years set within 19 months of wildly variable temperatures (*63*, *65*, *66*) interrupted fish attempting to feed or spawn in New England's freshwater and coastal ecosystems. In a year distinguished for widespread crop failure (*63*, *65*–*67*), fisheries failure could have further jeopardized human food supplies far more dependent on marine protein than today.

Tambora roughly coincided with the earliest, nearly complete time series of local fisheries data collected in the GoM: Fish inspectors' reports (FIRs) from Massachusetts (MA) (*68*) and Maine (ME) (*69*) began in 1804. Excepting an interruption in ME from 1820 to 1832 (following statehood), FIRs presented yearly quantities of brine-pickled fish inspected for export out of state from each town supporting commercial fisheries for most of the 19th century (total landings were not recorded systematically until 1889). Pickled alewives (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*) and salmon (*Salmo salar*), Atlantic herring (*Clupea harengus*), and American mackerel (*Scomber scombrus*) and menhaden (*Brevoortia tyrannus*) appear in inspection records before 1820, whereas dried fish such as Atlantic cod (*Gadus morhua*) do not. From 1804 to 1820, FIRs show that total pickled fish exported from the GoM fluctuated at first, but grew rapidly after 1814 (Fig. 1 and table S1). Historians have explained such rapid expansion as a response to the natural increase in the U.S. population, immigration, rapid industrialization, and westward expansion (*70*, *71*) that characterized the 19th century, that is, "progress" (*71*, *72*).

No fisheries effects from Tambora appear at these broad scales. However, when individual species export is graphed regionally, a complicated picture emerges (Fig. 2 and table S2). From north to south on six major watersheds (CACC, NCA, CB, KEN, PEN, and SC; Fig. 3), exports differed profoundly in magnitude and composition. For each species and over each watershed, export patterns were influenced by geophysical and oceanographic properties, geographic conformation, and the history of human settlement, as well as fish life history. Two major historical events during this period that are known to have suppressed trade—the War of 1812 and Jefferson's Embargo (Table 1)—likely explain the dips in Fig. 1 (*70*, *71*, *73*). However, complexity at smaller scales (Fig. 2) encouraged us to dig deeper.

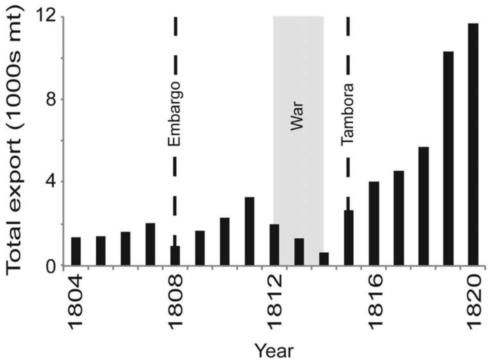

Fig. 1. Total export from the GoM, with historical events, 1804–1820 (Table 1 and table S1). A broadscale undulating pattern before 1814 gives way to rapid growth. Jefferson's Embargo (1808) and Tambora (1815) are marked in dashed lines. A gray band denotes the War of 1812 (ca. 1812–1814). The increasing export trend corresponds with industrial and territorial expansion and general optimism after the War of 1812, suggesting that national economic and technological progress may underlie fisheries expansion. mt, metric tons.

To explore complex interactions across different scales, we framed our analyses of GoM fish export using historical methods (*56*, *74*) informed by complex adaptive systems (CAS) theory. This synthetic approach emphasized the dynamic adaptive behavior of both people and fish (*75*). In CAS theory, system-level change results from the behavior of individual agents adapting to their ever-changing environment (*76*). This allows systems to be responsive and complex at many levels of organization, and promotes resilience and evolution over time (*77*–*79*). CAS theory has been used in a wide range of contemporary research from genetics to the social sciences. It can also contribute materially to historical studies, where understanding data organization at different levels may reveal obscure connections. Here, fisheries data reflected changing conditions in both human and aquatic systems across multiple scales of organization, and supported organization in CAS groups. We aimed to discover Tambora's climate effects and distinguish them from human impacts on targeted species, identify long-term contingencies that propagated through this CHANS, and explore the role of scale and rate in determining impact and resultant responses.

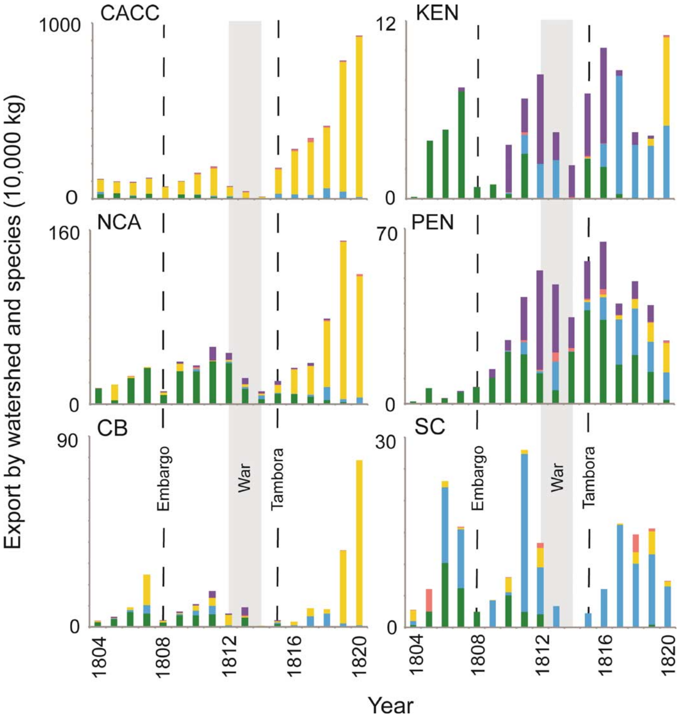

Fig. 2. Export of five species from six watersheds, with historical events, 1804–1820 (Table 1 and table S2). Species are, in alphabetical order from bottom to top, as follows: Alewives (green), Herring (blue), Mackerel (yellow), Salmon (pink), and Shad (purple). Watersheds are Cape Ann to Cape Cod (CACC), MA north of Cape Ann (NCA), Casco Bay (CB), Kennebec (KEN), Penobscot (PEN), and Saint Croix (SC). Jefferson's Embargo (1808) and Tambora (1815) are marked in dashed lines. A gray band denotes the War of 1812 (ca. 1812–1814). Considerable differences in quantity and species composition across all watersheds suggest an interplay of human and environmental factors at work. Before 1820, menhaden rarely appear in FIRs north of Cape Cod; thus, they were excluded from this graph.

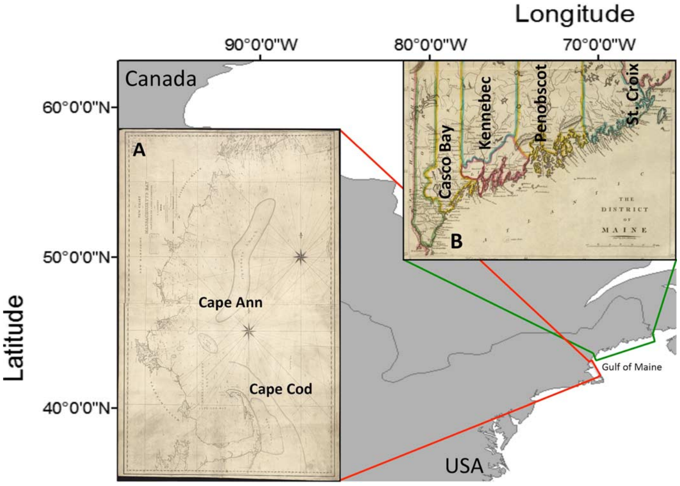

Fig. 3. 1812 maps of the MA and ME coasts. Superimposed on a geographic information systems (GIS) outline of the northeast U.S. coast, these maps show the extent of FIR coverage in the GoM. They also show how contemporary people viewed their world. (**A**) Lambert (*140*) follows the common navigational trope of putting west at the top of the map (left), the direction you sailed approaching Boston from Europe. (**B**) Warnicke's columnar counties (*141*) display ME's frontier character, fringe settlements along waterways, and an interior that was largely unknown. At that time, ME counties corresponded roughly, although not entirely, to principal watersheds.

Knowing general outcomes, we sought the interplay of causes and adaptations that led to these outcomes (*56*).

RESULTS

Grouping the following lines of data hierarchically to introduce scale as a variable, we examined the climate effects of Tambora and the consequences of human activity on fisheries export in the GoM. Table 1 presents a timeline of events keyed to the anthropogenic data we used. FIR export [for functional groups (Anadromous and Pelagic) and for individual species], human population pressure (*80*), towns reporting fish export (*68*, *69*), habitat obstruction due to dam building (*81*, *82*), and yearly temperature estimates (Yearly °C) (*83*) were grouped spatially (total GoM, and over the six different watersheds) and temporally (total timeline 1804–1820, and over three historical time periods: Embargo 1804–1809, War 1810–1815, and Tambora 1816–1820) (Table 1). Contemporary daily temperature readings (*84*) were analyzed within the general phenological parameters of our study species' migration and spawning behavior (*15*, *85*, *86*). Analytical methods and historical context differ in each case and will be explained with results.

Effects of anthropogenic pressures and Tambora on fish communities

We compared the effects of anthropogenic pressures with Tambora's extreme climate on fish export over the GoM. An equivalent investigation today would use fishing effort and total catch for stock assessment, and industry costs and prices realized for economic analyses of human behavior. However, before 1900, even snapshots of such data are rare and time series are exceptional (see section S1) (74). We are careful to present parsimonious results obtained from extant data that were evaluated within historical context.

Pairwise multivariate analyses (P) and Spearman's ρ tests (S) were performed on the data described above: Walsh and colleagues (*87*) informed our choice of simple parametric and nonparametric methods for analyzing these time series. Significant results are reported below, and full results are found in the tables. For reference, Fig. 4 presents Anadromous and Pelagic export (ln-transformed) for the GoM from 1804 to 1880. Overall, export exhibited a slight negative correlation ($S = -0.43$, $P = 0.0001$). Visual correspondence before 1815 and great disjuncture thereafter suggest that a significant shift in GoM fisheries occurred around that time.

Anthropogenic pressures.

We analyzed Anadromous and Pelagic export (ln-transformed; table S3), Dams, Towns, and Yearly °C (table S4) from 1804 to 1820 in search of system-wide influences that explained the trends in Fig. 4. Numbers of Dams and Towns were highly correlated ($S = 0.90$, $P < 0.0001$): New England town records attest that small mills were built early for essential services such as grinding flour and sawing lumber. Towns became a proxy for the spreading human footprint: yearly population growth, timber harvest, farming, and settlement sprawl near waterways. Pelagic export exhibited a moderate positive correlation with both Dams and Towns ($P_{\text{Dams}} = 0.63$, $P = 0.0065$; $S_{\text{Towns}} = 0.78$, $P = 0.0002$), and Dams showed a moderate negative correlation with Yearly °C ($P_{\text{Dams}} = -0.61$, $P = 0.0089$). No significant correlation existed between Anadromous export and anything else (table S5).

Performing the same tests at the species level showed similar results (table S4). Dams showed a moderate negative correlation with Alewives ($P_{\text{Dams}} = -0.62$, $P = 0.008$), but results were stronger and positive between Towns and Salmon ($P_{\text{Towns}} = 0.71$, $P = 0.0015$), Mackerel ($P_{\text{Towns}} = 0.75$, $P = 0.0004$), and Herring ($P_{\text{Towns}} = 0.70$, $P = 0.0017$). Yearly °C also moderately compromised Shad ($S = -0.62$, $P = 0.0086$) and Herring ($S = -0.51$, $P = 0.0366$), but otherwise average yearly temperature showed little significance (table S6). These results offered ambiguous support to anthropogenic explanations of export trends.

Data gaps discouraged similar analyses at the watershed level. However, in New England, long-term declines of anadromous species due to dams and other freshwater obstructions have been well documented (*81*, *82*, *88*–*90*). Today, most rivers and streams have been dammed to capacity, but in 1820, because of different settlement histories, dam distribution was lopsided: 268 dams were located on CACC, whereas CB and SC had only five dams each. Assuming no influence on marine fish, calculating Anadromous export/Dam for each watershed indicates the obstructive influence of its dam load, just as catch per unit effort indicates fishing pressure. Figure 5 graphs this metric for heavily dammed (Fig. 5A) and relatively free-flowing (Fig. 5B) watersheds. Obstructive effects differ in scale by an order of magnitude in favor of free-flowing streams. However, change in the dam load of each watershed (Fig. 5C, graphed as ln total dams) shows no correspondence with export fluctuations. Sharp dips in export/Dam on all watersheds around 1808 and 1813 suggest that broad geographic influences interacted with Dams over shorter time frames. Decline after 1816 resembles the trend in Fig. 4, indicating that significant disruption occurred that year.

Figure 5 also notes the mackerel jig, invented on Cape Ann (MA) around 1815, the only gear innovation in the GoM between 1804 and 1820. Adding a bit of polished metal to the shank of a regular hook made the hook shiny and more attractive to mackerel, and eventually revolutionized the fishery (*71*). Although we acknowledge its possible contribution to rising MA mackerel export after 1815, this cannot be proven: There is no evidence that the mackerel jig was widely used in MA until after 1820 [(*71*), pp. 88–105; (*91*), I, pp. 298–300].

Table 1. The timeline (1804–1820) and the spreading human footprint. Historical periods divide the timeline into roughly equal intervals and bracket dates of significant events: Embargo, 1804–1809 (*n* = 6); War, 1810–1815 (*n* = 6); and Tambora, 1816–1820 (*n* = 5). Watersheds from left to right run south to north [CACC, NCA, and CB (A) and KEN, PEN, and SC (B)], with area given in km^2. On each watershed, human factors that influence watershed quality (Dams, Census, and Towns) accumulate yearly from a baseline date of 1804—the spreading human footprint. Human population in 1800 and Dams in 1803 appear as baseline conditions in parentheses under appropriate headers. Towns are those that reported commercial export in the FIRs (*68*, *69*, *80*–*82*).

A	**Watershed**		**CACC (9,207 km^2)**			**NCA (13,590 km^2)**			**CB (2,448 km^2)**		
Time period	**Year 1800 (baseline)**	**Historical events**	**Dams (244)**	**Census (91,684)**	**Towns**	**Dams (92)**	**Census (33,241)**	**Towns**	**Dams (4)**	**Census (5,311)**	**Towns**
Embargo	1804	Fish inspection begins	0		7	1		6	0		1
	1805		0		9	2		5	0		1
	1806		1		7	2		5	0		1
	1807		1		7	2		4	0		1
	1808	Jefferson's Embargo	1		6	2		4	0		1
	1809		1		9	2		5	0		1
War of 1812	1810		2	118,785	8	2	44,486	8	0	9,353	1
	1811		5		8	2		7	0		1
	1812	War of 1812	13		8	2		6	0		1
	1813	War of 1812	14		8	2		7	0		1
	1814	War of 1812	16		6	4		8	0		1
	1815	Tambora; mackerel jig	17		9	4		5	0		1
Tambora	1816	Mackerel year	19		8	5		6	0		1
	1817		21		10	5		8	1		1
	1818		21		11	6		7	1		1
	1819		22		13	7		6	1		1
	1820	Mackerel jig widespread in MA	24	143,410	11	7	38,821	6	1	10,765	1

B	**Watershed**		**KEN (24,139 km^2)**			**PEN (22,196 km^2)**			**SC (3,885 km^2)**		
Time period	**Year 1800 (baseline)**	**Historical events**	**Dams (48)**	**Census (5,615)**	**Towns**	**Dams (30)**	**Census (8,520)**	**Towns**	**Dams (3)**	**Census (562)**	**Towns**
Embargo	1804	Fish inspection begins	3		1	1		1	1		1
	1805		3		2	1		1	1		1
	1806		3		1	1		1	1		1
	1807		3		2	1		1	2		2
	1808	Jefferson's Embargo	3		1	1		2	2		1
	1809		5		1	1		2	2		1

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B	Watershed		KEN (24,139 km^2)			PEN (22,196 km^2)			SC (3,885 km^2)		
Time period	Year 1800 (baseline)	Historical events	Dams (48)	Census (5,615)	Towns	Dams (30)	Census (8,520)	Towns	Dams (3)	Census (562)	Towns
War of 1812	1810		8	9,094	2	3	15,374	5	2	1,883	2
	1811		9		2	3		4	2		1
	1812	War of 1812	9		2	3		4	2		1
	1813	War of 1812	9		1	3		3	2		1
	1814	War of 1812	10		2	3		4	2		
	1815	Tambora; mackerel jig	10		3	3		6	2		1
Tambora	1816	Mackerel year	10		4	3		8	2		1
	1817		11		2	5		8	2		1
	1818		12		2	5		6	2		2
	1819		12		2	5		8	2		2
	1820	Mackerel jig widespread in MA	12	13,879	4	7	17,754	7	2	3,785	2

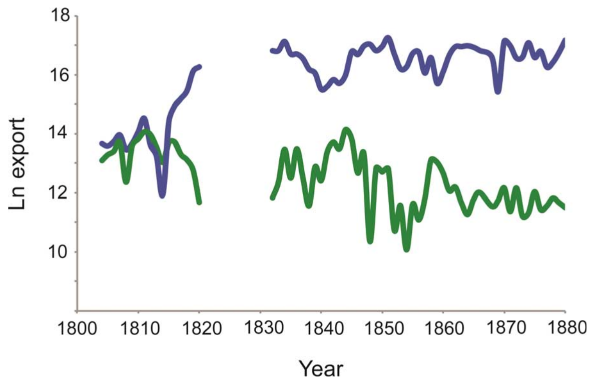

Fig. 4. GoM Anadromous and Pelagic export, 1804–1880 (table S3). Correspondence between anadromous (green) and pelagic (blue) export (ln-transformed) appears to be positive from 1804 to 1814, to be strongly negative from 1815 to 1820 (the period of rapid fisheries expansion in Fig. 2), and to fluctuate independently when regular inspection began again in the 1830s. The hiatus reflects a data gap after ME statehood.

Tambora's effects.

To distinguish Tambora's extreme climate effects from anthropogenic influences, we divided our timeline into roughly even time periods [each corresponding to one significant historical event that affected the entire North Atlantic: Jefferson's Embargo, 1804–1809 (Embargo); the War of 1812, 1810–1815 (War); and Tambora, 1816–1820 (Tambora) (Table 1)] and performed the same analyses described above for each time period. Our method differs from breakpoint analysis in that historical knowledge defined relevant periods, and analysis revealed how well that periodization explained known trends (*56*). Unlike earlier results, correlation of Anadromous and Pelagic export became strong and statistically significant during all time periods.

When Tambora erupted, the United States was just emerging from years of international conflict culminating in the War of 1812. The French Wars (1796–1815) created a great demand for New England fish, and Americans profited by smuggling fish products to both British and French markets in the Caribbean and Europe. Privateering, blockades, vessel confiscations, and embargoes often interfered with this dangerous commerce, but Jefferson's Embargo and the British Naval blockade of New England devastated export fisheries (*73*).

Embargo (1804–1809): To keep America out of the Napoleonic Wars and protect American seamen from British press gangs, Thomas Jefferson prohibited most oceanic commerce by American vessels. Fish exports were proscribed from January 1808 to March 1809. New England's mercantile interests protested so vehemently that the Embargo lasted barely a year.

War of 1812 (1810–1815): War between England and the United States opened American maritime commerce to British naval and privateering attacks and significantly reduced exports. In April 1814, the Royal Navy blockaded New England and briefly invaded PEN. British troops occupied SC on the disputed Canadian border until 1818, but fish inspections resumed there when the war ended in early 1815 [(*92*), II, p. 666].

Tambora (1816–1820): Volcanic winter altered the balance between export markets and local consumption. Crop failure was so extensive that farmers slaughtered livestock for want of fodder to keep them through the winter [(*93*), p. 204; (*94*), p. 155]. "In northern Vermont and New Hampshire, farmers fed their pigs with fish caught in local streams. Others had mackerel shipped in from New England seaports" [(*67*), p. 153]. Fish were likely caught and consumed locally in greater quantities, but this catch was not recorded.

For Embargo and War, correlation between Anadromous and Pelagic was positive because of termination of commerce (P_{Embargo} = 0.81, P = 0.0485; P_{War} = 0.88, P = 0.0198) (Table 2, A and B). Curtailed trade affected all export fisheries in similar ways, but fish populations probably benefited from reducing fishing pressure (*71*). When the crises ended, exports quickly resumed in roughly the same proportions.

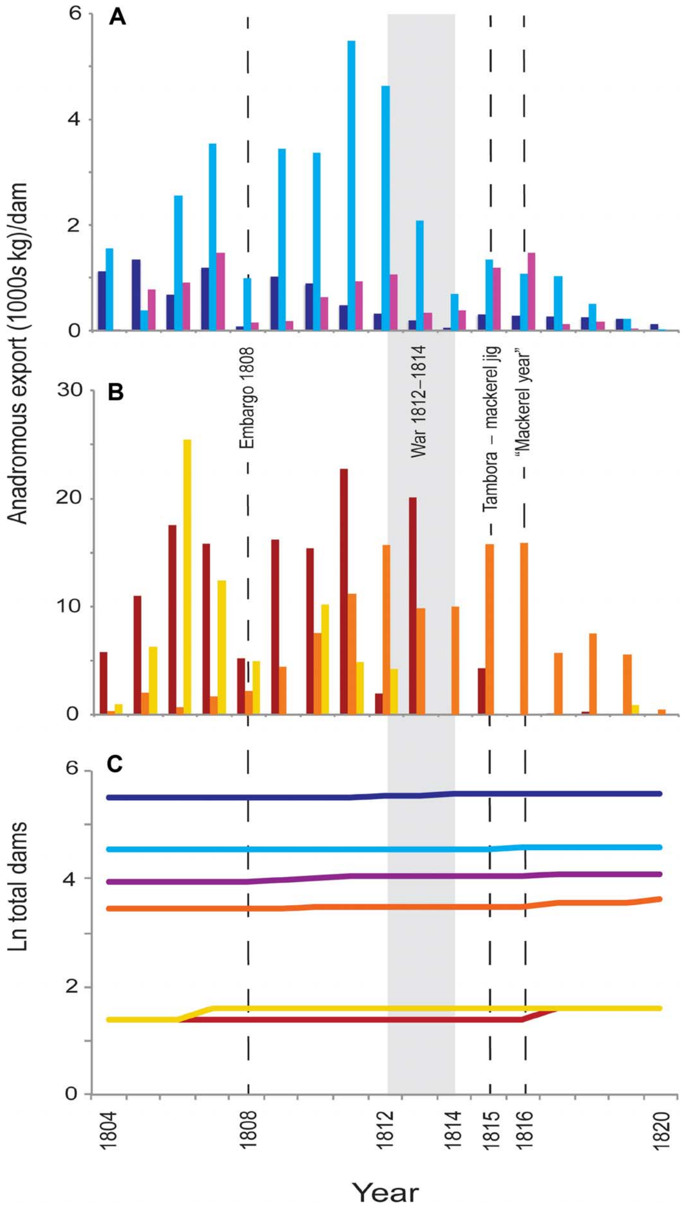

Fig. 5. Anadromous export per total Dams, and total Dams for each watershed, 1804–1820 (Table 1 and table S3). Anadromous export/Dam indicates obstructive influence on spawning fish by watershed: (**A**) watersheds with more than 50 dams in 1820 [CACC (dark blue), NCA (light blue), and KEN (purple)]; (**B**) relatively free-flowing watersheds with 30 dams or less in 1820 [CB (brown), PEN (orange), and SC (yellow). (**C**) Ln total Dams indicates corresponding change in dam load. Time periods and the invention of the mackerel jig are also noted. (A) and (B) exhibit similar fluctuations at different magnitudes, which show better correspondence with the events than with the dam load. Sharp dips during the Embargo and the War and decline after 1816 suggest the interaction of influences operating at different spatial and temporal scales.

Tambora was different. Correlation between Anadromous and Pelagic flipped to strongly negative (P_{Tambora} = −0.91, P = 0.0331) (Table 2C) and remained negative thereafter. Dams built during the Tambora period were also strongly correlated with Anadromous (P_{Tambora} = −0.93, P = 0.0206) and Pelagic export (P_{Tambora} = 0.93, P = 0.0218) (Table 2C). Yet, by themselves, Dams were unlikely to have caused this sudden change (Fig. 5).

In 1816, all living things in the GoM and elsewhere in the northern latitudes endured great fluctuations in temperature and weather, and long periods of bitter cold due to volcanic winter (*63–67*). Historical evidence suggests that weather-related fisheries failures may have occurred on PEN, which produced the most alewives in 1815 (372,222 kg) and 1816 (334,029 kg). Winter was so pronounced and prolonged there that, in 1815, 1816, and 1817, people could walk across the ice from Belfast to Castine [(*95*), p. 61]. Famine in 1816 forced the Penobscot Indians to sell most of their river bottomland for food [(*92*), II, pp. 640–657], which suggests that few fish could be caught in the river. The nearby town of Orrington failed to lease its weir rights in 1818 [(*91*), I, p. 712], implying that people had become skeptical of the weirs' profitability. Only during Tambora did Yearly °C seem consequential for fisheries [Anadromous (S_{Tambora} = −0.90, P = 0.0374) and Pelagic (S_{Tambora} = 0.90, P = 0.0374; P_{Tambora} = 0.9715, P = 0.0057) (Table 2C). We turned to daily temperatures in search of probable cause.

Fish, phenology, and Tambora

To find out whether Tambora could have affected the spawning and feeding of fish populations, we needed to know how its unseasonable temperatures interacted with the phenology and temperature tolerances of each species. Measurements are impossible to obtain, yet general dates of arrival and departure, and temperature tolerances for alewives, herring, mackerel, and shad can be found in the study by Bigelow and Welsh (*85*), the authority nearest to our time period. Augmented by Collette and Klein-MacPhee (*86*), these data were used in our analysis; menhaden and salmon were excluded because they were never more than 5% of yearly export (table S7).

Air temperature readings taken four times daily came from a meteorological journal kept at Salem, MA, from 1786 to 1829 by E. A. Holyoke, medical doctor and early president of the American Academy of Arts and Sciences (*84*). From Holyoke's daily measurements, we estimated values for temperature parameters key to habitat quality (*15*): daily averages, highs, lows, and daily temperature ranges (differentials). van der Schrier and Jones (*84*) determined that temperature variability in Holyoke's accounts was greater than it is today, and that his readings agreed with two contemporaneous sets of New England temperature records. Taking uncertainty into account, Berkeley Earth's monthly estimated averages for MA and ME (*83*) were not significantly different from Holyoke's monthly averages: Only 6% fell outside the confidence interval. However, these months were 3.6°C warmer, and two were July and October of 1816. Because Holyoke's observations were made in a coastal port, we assumed that his air temperatures approximated, with a short time lag, surface water temperatures in rivers (*96*) and nearshore areas (see fig. S1 and section S2).

Uncertainties in Holyoke's temperature readings, in substituting phenological generalizations made more than a century later for unobservable behaviors of fish, and variability in regional temperature distributions limited our analytical options. Therefore, we developed a historical likelihood scenario to assess the viability of each species, that is, a species' ability to function normally, within the daily temperature parameters that Holyoke recorded. From the timing and temperature ranges in table S7, we constructed "seasonal windows" representing the phenology and temperature tolerances of adult alewives, shad, mackerel, and herring during normal activities and during spawning events. Seasonal windows were overlaid on graphs of the daily temperature parameters calculated from Holyoke's readings: daily average

Table 2. Correlation of GoM Anadromous and Pelagic export, human influences, and yearly average temperatures over each time period. Pairwise multivariate analyses (*P*) and Spearman's ρ tests (*S*) were performed on five yearly variables [functional groups Anadromous and Pelagic (ln-transformed), Dams, Towns, and Yearly °C] over the time periods [Embargo 1804–1809 (A), War 1810–1815 (B), and Tambora 1816–1820 (C)]. Pairwise results are in the upper right-hand corner of each table, and Spearman's ρ results are in the lower left-hand corner. *n* = 6 for Embargo and War variables (A and B), and *n* = 5 for Tambora variables (C). Shaded blocks show significant correlations ($P < 0.05$). Significant positive correlations between Anadromous and Pelagic during Embargo and War become stronger and negative during Tambora.

A

		Embargo				
		Anadromous	**Pelagic**	**Dams**	**Towns**	**Yearly °C**
Anadromous	Correlation	1	**0.8144**	0.2144	0.6175	−0.59
	Signif prob.		**0.0485**	0.6834	0.1915	0.2177
	Spearman					
	Prob>					
Pelagic	Correlation		1	0.1051	0.1269	−0.5616
	Signif prob.			0.8429	0.8106	0.2416
	Spearman	**0.8857**				
	Prob>	**0.0188**				
Dams	Correlation			1	0.1188	**−0.8518**
	Signif prob.				0.8266	**0.0313**
	Spearman	0.4638	0.2319			
	Prob>	0.3542	0.6584			
Towns	Correlation				1	−0.2598
	Signif prob.					0.619
	Spearman	0.4414	0.1177	0.0149		
	Prob>	0.3809	0.8243	0.9776		
Yearly °C	Correlation					1
	Signif prob.					
	Spearman	−0.7143	−0.6571	**−0.8407**	−0.0294	
	Prob>	0.1108	0.1562	**0.0361**	0.9559	

B

		War of 1812				
		Anadromous	**Pelagic**	**Dams**	**Towns**	**Yearly °C**
Anadromous	Correlation	1	**0.8827**	−0.6079	0.4507	0.1714
	Signif prob.		**0.0198**	0.2004	0.3698	0.7454
	Spearman					
	Prob>					
Pelagic	Correlation		1	−0.485	0.6999	0.3125
	Signif prob.			0.3295	0.1216	0.5465
	Spearman	0.7714				
	Prob>	0.0724				

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B

		War of 1812				
		Anadromous	**Pelagic**	**Dams**	**Towns**	**Yearly °C**
Dams	Correlation			1	−0.4552	−0.7516
	Signif prob.				0.3679	0.0849
	Spearman	−0.6571	−0.3143			
	Prob>	0.1562	0.5411			
Towns	Correlation				1	−0.4565
	Signif prob.					0.0655
	Spearman	0.5218	0.7535	−0.4058		
	Prob>	0.2883	0.0835	0.4247		
Yearly °C	Correlation					1
	Signif prob.					
	Spearman	0.1429	0.2571	−0.6571	0.3479	
	Prob>	0.7872	0.6228	0.1562	0.4993	

C

		Tambora				
		Anadromous	**Pelagic**	**Dams**	**Towns**	**Yearly °C**
Anadromous	Correlation	1	**−0.9079**	**−0.933**	−0.6847	−0.8584
	Signif prob.		**0.0331**	**0.0206**	0.2022	0.0626
	Spearman					
	Prob>					
Pelagic	Correlation		1	**0.9305**	0.8644	**0.9715**
	Signif prob.			**0.0218**	0.0587	**0.0057**
	Spearman	**−1**				
	Prob>	**<0.0001**				
Dams	Correlation			1	0.7941	0.8392
	Signif prob.				0.1086	0.0755
	Spearman	**−1**	**1**			
	Prob>	**<0.0001**	**<0.0001**			
Towns	Correlation				1	0.7674
	Signif prob.					0.1299
	Spearman	−0.8	0.8	0.8		
	Prob>	0.1041	0.1041	0.1041		
Yearly °C	Correlation					1
	Signif prob.					
	Spearman	**−0.9**	**0.9**	**0.9**	0.6	
	Prob>	**0.0374**	**0.0374**	**0.0374**	0.2848	

temperatures (curving blue line) with highs, lows, and differentials (black drop lines) (Fig. 6 for in 1816). Numerical dates 91 (April 1) and 319 (November 15) bound seasonal periods when migrating fish became vulnerable to coastal fisheries and extreme weather, particularly during spawning events (Fig. 6B). Horizontal rails of the seasonal windows represent time periods (phenophase), whereas vertical stiles represent temperature ranges. Viable temperatures fall within the windows.

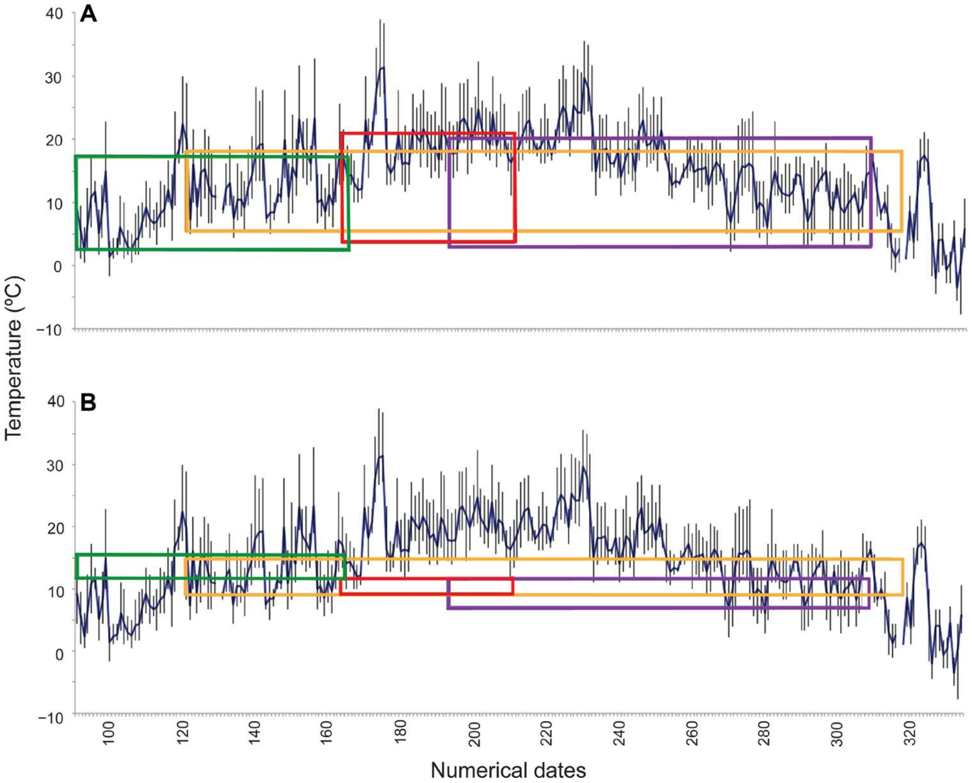

Fig. 6. Seasonal windows, 1816. This visualization depicts individual species' phenology and temperature tolerances against four daily air temperature parameters from 1 April 1816 to 1 December 1816. The four daily parameters—daily average temperatures (curving blue line), daily high, low, and temperature differential (black drop lines)—cover numerical dates 91 to 335. Boxes diagram the seasonal window for normal adult (**A**) and spawning (**B**) activities for the following (in order of arrival): alewives (green), mackerel (orange), shad (red), and herring (purple). The vertical lines of the boxes represent the phenophase; favorable air temperatures fall within the horizontal lines.

Because of the high temperature variability during this period (*84*), we chose the 5 years from 1814 to 1818 for analysis—1816 and its two nearest neighbors. Both average and extreme daily temperatures can potentially alter fish behavior by "changing the duration of time periods exceeding biological thresholds" (*15*), because rapid temperature fluctuations may disrupt biological processes that withstand slower fluctuation of the same magnitude (*15*, *97*). In 1816, daily average and low temperatures were more than 1 SD lower, and temperature differential was more than 1 SD higher when compared with the other years. Curiously, the highest temperature recorded during this period was on 23 June 1816 (table S8). Principal components analysis (PCA) confirmed that the four daily temperature parameters in 1816 were collectively different than their counterparts in 1814, 1815, 1817, and 1818. Table 3 quantifies the visualizations in Fig. 6 for all 5 years from 1814 to 1818 as suitability indices for adult (Fig. 6A) and spawning (Fig. 6B) fish each year. To compare relative effects of the temperature parameters, we ranked column categories from 1 (worst) to 4 (best) for each species-year and calculated the mean value. Table 4 displays the mean values for each species-year, thus comparing the relative viability of all species for each year (rows) and of each species over all years (columns). Yearly extremes counts the number of anomalies, which differ from row or column means by more than 1 SD.

In influence on fish phenology, 1816 was the anomalous year (Table 4). Phenological order plays a role in adaptive capacity. Alewives and mackerel arrive earlier when average temperatures are colder, whereas shad and herring arrive later when average temperatures are warmer. Earliest to arrive, alewives fared the worst. Both the coldest day and the warmest day fell within their seasonal window, and intervals suitable for normal activities were badly fragmented by unfavorable temperatures (Table 3). Seasonal movements and spawning behavior of adults may have been altered or delayed, and mortality at all life stages exacerbated (*98*, *99*). Alewives suffered significant adverse conditions in all categories ("Adult" and "Spawning"; "All conditions," "Daily averages," and "Daily extremes") with the overall lowest scores ("Daily averages"). Vulnerable in general due to higher temperature requirements, shad seemed to fare relatively better in 1816. It was a good year for mackerel and exceptional for herring. Thus, Tambora's daily temperatures likely penalized alewives but benefited shad, mackerel, and herring.

Human adaptation to Tambora

We used long-standing historical methods to analyze narrative evidence and reconstruct human responses to volcanic winter (*56*, *71*, *74*). According to a contemporary Maine newspaper, the *American Advocate and Kennebec Advertiser*, which covered North American manifestations of the catastrophe and responses to it, widespread famine afflicted Lower Canada and Newfoundland during the "mackerel year" of 1816 [(*100*), 1816]. Crop failures and the threat of famine in New England initiated imports of Midwestern foodstuffs sent down the Mississippi River to New Orleans and then by sea to Northeastern seaports [(*100*), 23 November 1816, 25 January 1817]. Potomac River ice was 63.5-cm-thick off Alexandria [(*100*), 1 March 1817], and on the New Jersey coast "immense

Table 3. Summary of the temperature parameters derived from Holyoke's daily measurements in relation to Adult (A) and Spawning (B) seasonal windows for Alewives, Mackerel, Shad, and Herring, 1814–1818. Four daily temperature parameters (in °C) [average and maximum range (differential) under Average daily temperatures, and high (max) and low (min) under Extreme daily temperatures] are evaluated within each species' phenophase and temperature range (Biological characteristics). Viability, is the amount of time each species has to perform necessary biological functions given the daily average and extreme temperature conditions common during this period. The remaining variables (Total residence, Longest interval, and Average interval length) present numbers of days. Values in each category were ranked worst to best (1 to 4) and the ranks were averaged to give a relative likelihood of success. Each category and its ranking is explained as follows. "Year" ranges from 1814 to1818, 1816, and its two nearest neighbors. "Biological characteristics" are determined by the phenology and life history of each fish species (table S7). "Species" are Alewives, Herring, Mackerel, and Shad. "Arrival" defines the numerical date of arrival on the coast, ranking lowest (1) to highest (4), because warmer temperatures generally benefited all species. "Spatial flexibility (rank)" ranks geographic dependence on spawning areas from 1 to 4. Spawning ground location influences exposure to adverse temperatures in shallower waters. Philopatric and anadromous alewives and shad are the least flexible (1) because they can become trapped in shallow fresh water. Marine spawners mackerel (4) and herring (3) have more freedom of movement, although bottom-spawning herring may be slightly disadvantaged. "Total residence" defines the vulnerable period in shallower fresh or coastal waters in number of days, ranking lowest (1) to highest (4), because more days within the seasonal window benefit spawning and feeding. "Average daily temperatures" summarize conditions within each seasonal window or year based on average temperature and greatest temperature range (table S8). "Average temperature" defines the mean daily temperature within the seasonal window, ranking lowest (1) to highest (4) and assuming that warmer temperatures were generally beneficial. "Maximum temperature differential" captures maximum daily fluctuation, ranking lowest (4) to highest (1), because temperature dips and spikes can move outside species' tolerances. "No. of suitable days" counts the number of days when average daily temperature falls within each species' seasonal window, ranking lowest (1) to highest (4). "No. of suitable intervals" indicates the degree of patchiness or fragmentation that occurs when dangerous temperatures break up suitable intervals, which are defined as periods of consecutive days when mean daily temperatures fall within a species' tolerance range. Number of intervals ranks lowest (4) to highest (1), because increased patchiness indicates greater likelihood of disrupted biological activities. "Longest interval" is the longest period of consecutive suitable days within the seasonal window, ranking lowest (1) to highest (4). "Average interval length" is the average length of all suitable intervals within each seasonal window, ranking lowest (1) to highest (4). "Extreme daily temperatures" consider daily temperature extremes that fall outside each seasonal window or year. "Minimum temperature" defines the lowest temperature within the seasonal window, ranking lowest (1) to highest (4) and assuming that very cold temperatures were more harmful. "Maximum temperature" defines the highest temperature within the seasonal window, ranking lowest (4) to highest (1), because every value exceeds the highest tolerable limit (22°C for shad). "No. of days < minimum tolerance" defines the number of days during which temperatures fall below the minimum temperature tolerance, ranking lowest (4) to highest (1). "No. of days > maximum tolerance" defines the number of days during which temperatures rise above the maximum temperature tolerance, ranking lowest (4) to highest (1). "No. of suitable days" counts the number of days for which all daily temperature parameters fall within the seasonal window, ranking lowest (1) to highest (4). "No. of suitable intervals" measures patchiness or fragmentation of the seasonal windows, ranking lowest (4) to highest (1). "Longest interval" is the longest period of consecutive days, with all temperatures falling within temperature tolerances, ranking lowest (1) to highest (4). "Average interval length" is the average length of all suitable intervals within each seasonal window, ranking lowest (1) to highest (4).

	Biological characteristics				Average daily temperatures						Extreme daily temperatures							
Year	Species	Arrival (date)	Spatial flexibility (rank)	Total residence	Average temperature (°C)	Maximum differential (°C)	No. of suitable days	No. of suitable intervals	Longest interval	Average interval length	Minimum temperature (°C)	Maximum temperature (°C)	No. of days < minimum tolerance	No. of days > maximum tolerance	No. of suitable days	No. of suitable intervals	Longest interval	Average interval length
A. Adult																		
1814	Alewives	91	1	75	13.84	18.34	51	6	23	8.5	1.11	33.89	2	9	32	10	9	3.2
1815	Alewives	91	1	75	11.3	15	56	7	24	8	−1.11	31.11	13	6	29	15	5	1.93
1816	Alewives	91	1	75	11.07	20.56	56	10	12	5.5	−1.67	32.78	13	3	33	13	9	2.54
1817	Alewives	91	1	75	11.82	20.56	61	7	20	8.57	−1.11	30.56	7	1	32	12	6	2.67
1818	Alewives	91	1	75	11.65	14.45	50	6	43	8.67	0	31.67	16	14	36	9	12	4
1814	Herring	196	3	109	17.52	16.11	58	11	17	5.27	−0.56	34.44	11	81	18	7	5	2.57
1815	Herring	196	3	109	17.18	18.89	49	13	22	3.77	−3.33	37.78	8	77	24	9	5	2.67
1816	Herring	196	3	109	16.58	16.67	62	7	52	8.86	2.22	35.56	6	75	29	11	7	2.64
1817	Herring	196	3	109	17.39	16.11	44	8	21	5.5	−3.33	36.67	11	81	18	10	5	1.8
1818	Herring	196	3	109	17.7	15	50	7	27	7.14	−1.11	34.44	7	84	19	12	4	1.55
1814	Mackerel	121	4	198	16.9	16.11	123	26	25	4.77	−3.89	34.44	27	114	61	22	15	2.77
1815	Mackerel	121	4	198	16.74	18.89	114	28	19	3.97	−5	37.78	36	120	49	23	6	2.13

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	Biological characteristics				Average daily temperatures						Extreme daily temperatures							
Year	Species	Arrival (date)	Spatial flexibility (rank)	Total residence	Average temperature (°C)	Maximum differential (°C)	No. of suitable days	No. of suitable intervals	Longest interval	Average interval length	Minimum temperature (°C)	Maximum temperature (°C)	No. of days < minimum tolerance	No. of days > maximum tolerance	No. of suitable days	No. of suitable intervals	Longest interval	Average interval length
1816	Mackerel	121	4	198	15.73	20.56	147	23	22	6.54	−1.11	38.89	38	104	63	29	7	2.14
1817	Mackerel	121	4	198	16.59	16.11	123	22	25	5.64	−3.33	36.67	36	120	47	22	7	2.14
1818	Mackerel	121	4	198	17.51	15	114	18	26	6.39	−1.11	37.78	25	123	58	27	5	2.15
1814	Shad	166	1	47	21.41	12.77	27	6	14	4.33	9.44	34.44	0	6	7	3	5	2.33
1815	Shad	166	1	47	24.01	18.89	15	7	5	2.29	13.89	37.78	0	17	5	5	1	1
1816	Shad	166	1	47	19.49	15	39	5	20	6.4	10	38.89	0	3	12	5	5	2.4
1817	Shad	166	1	47	21.07	14.44	29	8	11	4.25	8.89	36.67	0	5	5	3	2	1.67
1818	Shad	166	1	47	23.55	13.89	18	10	8	2	13.33	37.78	0	15	3	2	2	1.5
B. Spawning																		
1814	Alewives	91	1	75	13.84	18.34	48	10	17	4.80	1.11	33.89	36	1	20	9	10	2.22
1815	Alewives	91	1	75	11.30	15.00	36	11	12	3.27	−1.11	31.11	47	1	16	8	9	2.00
1816	Alewives	91	1	75	11.07	20.56	37	15	6	2.53	−1.67	32.78	59	0	13	11	2	1.18
1817	Alewives	91	1	75	11.82	20.56	46	8	18	5.88	−1.11	30.56	46	0	17	11	3	1.55
1818	Alewives	91	1	75	11.65	14.45	31	11	6	3.09	0.00	31.67	50	0	11	6	3	1.57
1814	Herring	196	3	109	17.52	16.11	69	11	28	6.27	9.44	34.44	28	56	11	13	5	2.08
1815	Herring	196	3	109	17.18	18.89	76	9	23	8.44	13.89	37.78	27	56	9	17	4	1.63
1816	Herring	196	3	109	16.58	16.67	79	12	22	6.42	10.00	38.89	27	50	12	14	12	2.64
1817	Herring	196	3	109	17.39	16.11	63	17	17	3.82	8.89	36.67	31	64	17	10	4	1.50
1818	Herring	196	3	109	17.70	15.00	76	12	32	6.33	13.33	37.78	27	60	12	13	5	2.17
1814	Mackerel	121	4	198	16.90	16.11	41	17	8	2.41	−3.89	34.44	35	167	6	6	1	1.00
1815	Mackerel	121	4	198	16.74	18.89	44	15	7	2.75	−5	37.78	45	158	4	3	1	1.00
1816	Mackerel	121	4	198	15.73	20.56	60	19	10	3.16	−1.11	38.89	46	160	11	9	2	1.22
1817	Mackerel	121	4	198	16.59	16.11	43	22	6	1.95	−3.33	36.67	43	161	5	5	1	1.00
1818	Mackerel	121	4	198	17.51	15.00	48	20	8	2.40	−1.11	37.78	37	171	5	4	2	1.25
1814	Shad	166	1	47	21.41	12.77	5	2	4	2.5	−0.56	34.44	4	29	0	0	0	0
1815	Shad	166	1	47	24.01	18.89	0	0	0	0.0	−3.33	37.78	0	40	0	0	0	0
1816	Shad	166	1	47	19.49	15.00	13	6	3	2.2	2.22	35.56	6	17	0	0	0	0
1817	Shad	166	1	47	21.07	14.44	4	3	2	1.3	−3.33	36.67	2	27	0	0	0	0
1818	Shad	166	1	47	23.55	13.89	3	2	2	1.5	−1.11	34.44	0	40	0	0	0	0

numbers of cod-fish [were] thrown up on the beach, dead" [(*100*), 8 March 1817]. Urban famine necessitated soup kitchens in Portland, ME, and in New York City [(*100*), 1 March 1817, 8 March 1817], where annual mortality rose to nearly 3% [(*100*), 15 February 1817; by comparison, the Center for Disease Control (*101*) calculated the 2013 U.S. death rate as 0.7%]. Catchable fish would have been a bulwark against starvation as soon as gear could go in the water; domestic consumption would have risen.

Tambora's effects lasted through the spring of 1817. Even as temperatures moderated, New England was still plagued with spring flooding, causing property destruction and agricultural losses, and a significant drought throughout northern New England lasted until late September (*65*). By that spring, little protein was left in New England except for spawning cohorts of fish arriving in local estuaries and streams, and marine predators following them inshore. Crops recovered somewhat in the summer of 1817 and famine abated [(*100*), 1817], but it likely took farmers several years to rebuild their livestock. Some did not bother to rebuild but left for the Northwest Territories, causing a CT minister to observe: "We had a great deal of moving this spring … our number rather diminishes …" (*62*). Thus, an unprecedented environmental and social crisis unfolded during the "mackerel year" and lingered into 1817. It caused the widespread redistribution of foodstuffs and stimulated emigration while enhancing the importance of marine fisheries as reliable sources of food.

Fisheries, phenology, and watersheds.

Timing is important to fisheries' success. Fixed gear and small boats must wait for migrating fish to come into catchable range. In consequence, the timing of different fish migrations generates different catch patterns. Each watershed's unique combination of human and natural factors shaped its fisheries. Long rivers in NCA, KEN, and PEN supported rich estuaries, whereas in CACC and CB, large bays drained short rivers and, in SC, fisheries soon clustered on Passamaquoddy Bay away from the river. MA watersheds were highly settled and industrialized, whereas ME watersheds were lightly populated frontiers (Table 1). Latitude played a role: Southern fisheries caught more mackerel (arriving in early May) than herring (arriving in October) (Fig. 2), whereas on lightly populated northern watersheds more resilient anadromous populations may have supported fisheries longer (see section S3). Thus, local characteristics shaped the options of fishermen. Alewife runs likely faltered in 1816, as climate stress and intense fishing pressure took their toll. Under continued stress in 1817, they buckled. As harvest failure and famine forced New Englanders to look to coastal seas for sustenance, the only fish available in large quantities near commercial distribution centers was mackerel.

DISCUSSION

To begin, we consider causation. It is plausible that severe cold and rapidly fluctuating extreme daily temperatures in 1816, compounded by anthropogenic influences, selectively penalized alewives, the earliest export species arriving on the coast (*15*, *102*). Disruption and decline of alewife runs likely persisted in 1817, as cold gave way slowly to floods and drought. Food scarcity due to agriculture failure compounded pressure on aquatic resources and drove radical changes in fisheries. Thus, Tambora elicited both social and ecological responses. In CAS theory, adaptive responses of agents to system-wide changes are the key analytical component (*103*–*105*). Both fish and fishermen are agents whose adaptive responses are jointly reflected in the FIRs. We consider the fish first.

Fish have limited responses. In marine habitat, they adjust to uncomfortable temperatures by moving onshore or offshore, or up and down the water column to areas where temperatures are buffered. Extreme conditions can shift phenology or migratory ranges in adaptations that may be temporary or permanent (*29*, *106*). Anadromous fish are more vulnerable to extreme weather conditions given the smaller volume of lakes and streams in which they spawn. Particularly in northern New England, lakes and streams often freeze, and annual spring freshets can make difficult natural features temporarily impassable (*85*, *86*, *107*). In the wake of Tambora, anadromous spawning populations confronted inhospitable shallow water temperatures. Some spawning may have occurred, but most suitable intervals would have lasted only a few days (Table 3B). GoM alewives can spawn a few hundred meters from shore or swim 100 km up river to natal grounds (*81*, *108*, *109*), making long-distance swimmers disproportionately vulnerable to temperature perturbations. Recent research has shown higher variability in alewife spawning behavior on the grounds than previously documented (*98*, *110*), which could indicate greater adaptive capacity (*89*). Adult alewives that spawned in estuaries or skipped spawning in 1816 likely survived to reproduce in later years as temperatures moderated. However, eggs, larvae, and juvenile fish could not evade dangerous temperatures. Mortality likely rose for all life stages during a time of greatly increased fishing pressure. Drought in 1817 (*65*) may have compounded these losses by blocking fish passage downstream. Subsequent declines were reflected in export, which fell from more than 500,000 kg in 1816 to about 45,000 kg in 1820.

The same was true for shad. Less common but more valuable than alewives or mackerel, some shad populations also swim long distances to natal grounds, but they have difficulty surmounting low obstructions and would have avoided rudimentary 19th century fish passes (*85*, *86*, *107*). Any benefit shad received in 1816 (Table 4) was marginalized thereafter by poor weather, habitat degradation, and high demand in the marketplace. From almost 280,000 kg in 1816, less than 8000 kg of shad were exported from the GoM in 1820. In contrast, marine fish could respond to inhospitable coastal temperatures by moving offshore. Atlantic herring would have encountered fewer barriers to successful reproduction, although their large eggs must be deposited on suitable bottom (*109*), and spawning mackerel probably fared well because of their long period of residence in the GoM. Thus, Tambora's volcanic winter may have temporarily altered community composition and food webs in estuaries and nearshore in favor of marine spawners.

Scale plays a role in causation. Dam building and other anthropogenic factors contributed to anadromous species decline at the watershed scale (Fig. 5). In highly settled regions (CACC and NCA), dam building and land clearing likely compounded Tambora's effects more than on Maine's frontier watersheds. Yet, the fish were resilient, and they adapted. Anadromous export rebounded in the GoM after 1830. After main stem dams blocked most New England rivers and much forested land had been clear-cut, anadromous export reached its highest level in 1844 (250,000 kg of shad and 975,000 kg of alewives, mostly from CACC). Nevertheless, pelagic export still exceeded it by an order of magnitude (Fig. 4).

In 1880 in KEN, we know that 87.5% of total alewife catch was consumed locally [(*91*), I, pp. 667–690]. If modest rates of local consumption rose to that level in 1816, stocks already stressed by extreme climate and other factors may have been devastated by intense fishing pressure in a grim example of short-term feedback. We can only speculate on the likely response of the fish in Tambora's aftermath, but historical records suggest

Table 4. Relative influence of temperature parameters on fish populations. Values in each category in Table 3 were ranked worst to best (1 to 4), and then rank scores were averaged to yield relative overall likelihood of success for each species each year. Average yearly ranks for adults and spawning Alewives, Mackerel, Shad, and Herring are presented for all conditions, daily average, and daily extreme temperatures for each year. Comparing each value to the row mean shows the relative success of that species compared to the others that year. Comparing each value to the column mean shows the relative success that year for each species compared to other years. Values greater than 1 SD above the mean are significantly better (blue), and values greater than 1 SD below the mean are significantly worse (red), with row significance indicated by block color and column significance by numeral colored. The number of significant differences each year is summed as total extremes. In terms of relative influence on fish populations, 1816 was more extreme than the other years. Weather apparently affected adult activity more than spawning activity in 1816, whereas in 1815 the reverse seems true.

	Adult temperature tolerances						Spawning temperature tolerances					
	Year	Alewives	Shad	Mackerel	Herring	Number of extremes	Year	Alewives	Shad	Mackerel	Herring	Number of extremes
All conditions (daily averages and extremes)	1814	2.41	2.29	2.41	2.41	1	1814	2.53	2.06	2.06	2.94	2
	1815	2.47	2.12	2.29	2.53	1	1815	2.59	**1.65**	2.24	2.88	4
	1816	**1.94**	2.47	2.24	**3.00**	5	1816	2.00	2.06	2.35	**3.12**	4
	1817	2.47	2.12	2.53	2.29	1	1817	2.53	1.88	2.18	2.94	2
	1818	**2.82**	2.18	2.24	2.53	2	1818	2.35	2.00	2.24	3.06	1
Daily averages	1814	2.00	2.00	2.78	2.78	0	1814	2.00	2.33	2.33	3.22	2
	1815	2.33	**1.78**	2.56	2.56	3	1815	2.00	**1.56**	2.44	3.33	3
	1816	**1.33**	2.33	2.67	**3.22**	5	1816	**1.56**	2.11	2.56	3.33	4
	1817	2.00	1.89	**2.89**	2.67	2	1817	2.22	2.11	2.33	3.00	3
	1818	2.44	2.00	2.44	2.89	3	1818	1.89	2.11	2.44	3.11	1
Daily extremes	1814	2.33	**2.42**	2.33	2.33	2	1814	2.50	1.92	2.25	2.75	2
	1815	2.25	2.17	2.25	2.58	2	1815	2.67	**1.67**	2.25	2.50	4
	1816	2.17	2.42	2.08	**2.83**	5	1816	2.08	2.00	2.33	2.92	2
	1817	2.42	2.25	2.42	2.25	1	1817	2.33	1.75	2.33	2.92	2
	1818	**2.67**	2.25	2.25	2.33	2	1818	2.42	1.92	2.25	2.92	2

that desperate people turned to mackerel in extremis because mackerel were available early and in great numbers when other species were not. Mackerel became both a lucrative commercial product and a utilitarian fish that fed livestock, farm families, and upstream villagers as alewives once had. Fishery expansion likely encouraged the spread of the mackerel jig and nudged fishing offshore, but it would not have depressed the alewife fishery. Although not the sole cause, Tambora's extreme event triggered the precise sequence of changes evident in the historical record.

Next, we consider contingencies and unexpected consequences. History chronicles how defeating the British in 1815 opened up new territories in the American West. New roads and navigation aids released waves of settlers into these frontier regions [(*111*), pp. 76–77]. Widespread famine in the Northeast also contributed to emigration (*62*, *63*, *66*) and to the development of new transportation routes and infrastructure, which substantially increased fish markets (*70*). A long-term feedback mechanism was in place.

The climate emergency caused by Tambora triggered a rapid, regional "resource switching," or "moving on" response from GoM fishermen (*47*), who redirected their efforts farther offshore toward schooling pelagic fish. Although weather conditions moderated in 1818, many inland communities had already abandoned commercial export fisheries. ME soon followed MA into pelagic fisheries, although north of the Kennebec, herring were targeted instead of mackerel (Fig. 2B). In the European Middle Ages and Renaissance, moving from river to coastal fisheries appears as a gradual process taking many decades or centuries (*112*, *113*). In the GoM after Tambora, the same sort of shift took place in 5 years. It would have occurred anyway. However, we assert, the shift occurred rapidly, at that time, and in that way because of the contingent adaptive responses of fish and fishermen to this climate disaster. Adaptations became permanent not because of permanent environmental damage and lack of natural resilience, nor of long-term planning and economic imperative, but because contingent human responses to the immediate threat created a new range of adaptive opportunities that were transformative.

Last, we consider scale and rate. In our study, varying scale and level of inquiry disclosed information hidden within the nested structure of this complex system. Using historical methods to group and order data in a CAS framework sharpened research signals by eliminating noise and helped identify potential relationships among known factors. Periodization selected, isolated, and refined influences. A similar approach might be useful in other data-poor situations, where context may partially counter deficiencies via grouping and ordering.

The role of rate is also complicated. In ecological terms, both resource switching and phenological mismatch stimulate predators to change targets, geographic ranges, and seasonal timing or suffer decline.

In the context of our study, resource switching can be constructed as a sociological response to phenological mismatch that occurs at a rate greatly exceeding the adaptive rates of biological organisms. Within an ecosystem, mismatched rates of adaptation have received less attention than biological timing or range shifts, but consequences may be fundamental and long-lasting (*114*). This insight encourages simultaneous examination of social and biological mismatch to find patterns, determine rates and scales of disruption, and identify potential consequences. It becomes equally crucial to understand the role of rate and scale in well-synchronized phenologies of resilient systems (*115*).

Two hundred years ago, anadromous fish populations recovered from Tambora in a few decades, whereas rapid cultural adaptation catapulted people far past the nexus in space and time where mere resilience was possible. People evolved new fishing gear, canal systems, railroads, and factories along with new market and social structures, thereby altering fisheries, fish, and ecosystems. This implies that ecological communities may recover if populations have time to adapt to altered conditions, but technology evolves so fast that regime shifts occurring in CHANS may be difficult or impossible to reverse.

Parallels between Tambora's abrupt climate event and the extreme weather occurring today are many and obvious. We need not point out the potential for widespread famine; the difficulty in forecasting local effects of global climate changes; the increasing devastation from storms, floods, and drought; or the uncertainty of what might ameliorate situations that fall far outside the realm of experience and expectation. More than future trends, extreme events demand immediate attention (*7*) as we negotiate what increasingly seems like an uncontrolled experiment. However, the past can be a laboratory, where outcomes of similar experiments may yield novel insights. Two hundred years ago, societal responses to a natural disaster, born of necessity, shifted cultural memory and expectations, transforming coastal communities, human and aquatic, from one dynamic social and ecological regime into another in ways Tambora never could have done alone. Complex systems elude simple explanations. Understanding how CHANS are governed by rate, scale, order, and group organization, and how thresholds are approached and crossed, may help advance human resilience by strengthening resilience in the natural world.

MATERIALS AND METHODS

Study design

Historical ecology is a forensic pursuit (*116*), where evidence from many sources is gathered and examined, and hypothetical explanations are eliminated to deduce probable cause. Subject to inevitable gaps, inaccuracies, and uncertainties, historical records nevertheless provide a reasonably accurate account of events and conditions as interpreted by the people who experienced and recorded them (*56*, *74*, *84*). Inevitably, such information rarely conforms to a priori experimental designs, which often generate structured data for particular analytical models. Using prior knowledge as context, researchers explore the nature of found evidence before deciding upon analytical methods, structuring data for modeling when it is possible or developing new approaches when it is not.

Our immediate goals were to discover Tambora's climate effects on targeted fish species and human communities, identify long-term consequences of contingent adaptations to volcanic winter, and explore the role of scale and rate in determining impact and response. Working backwards to discover the interplay of causes and adaptations characteristic of a complex system (*56*), we chose simple statistical methods to interrogate small data sets, where every point was valuable. Integrating historical analysis with CAS theory proved essential in assessing different drivers working simultaneously at different rates and scales. For phenological analysis, our seasonal windows method used known life histories of targeted fish populations and daily weather temperature parameters.

Data acquisition and organization

Fisheries export data from MA and ME FIRs were photographed in State archives, digitized using Adobe Acrobat software, and transcribed on Microsoft Excel spreadsheets. Dams and Towns were mapped in ESRI ArcGIS v.10.2 (*117*) GIS software for assignment to appropriate watersheds.

CAS theory

CAS structure permitted analyzing the adaptive behaviors of fish and human populations across varying scales and levels of hierarchical organization (*76*, *118*, *119*). Adaptive behaviors may be learned or genetically encoded, and agents that share behaviors can be grouped together. Within a group, variations among individuals cause subtly different responses to local conditions, and groups differentiate over time as local environmental adaptations accumulate (*120*). Groups sharing behavior patterns become subgroups within larger, more generalized groups at higher levels, thus providing scale to organizational structure (*121*). In CAS theory, hierarchical organization regulates the transfer of information and improves group fitness (*122*). This implies that organizational structure and spatial and temporal scale factor in adaptive capacity.

The same population may be divided into different hierarchical groups according to different characteristics. For example, American fishermen may be grouped by region, time period, fishery, age, and gender, whereas fish within a coastal community may be grouped by species, functional group, habitat, diet, and phenology. Aggregating and analyzing groups across different types and levels reveals the interplay of these characteristics (*123*) and isolates statistically significant correlations across multiple levels of interaction. We varied group levels to investigate different scales of resolution.

Statistical analyses

Pairwise multivariate analyses (P) and Spearman's ρ tests (S) performed on yearly time series, and PCA of the four temperature parameters from Holyoke's records, were done using JMP statistical software v.11.0.0 (*124*).

Historical context of New England fisheries

The historical context of GoM fisheries is important not only as metadata that informed data choice and usage but also as a form of analysis in its own right (*74*) that compliments and is complimented by quantitative methods. We presented historical context for time series used in our analyses (and explained why other data sets were not used in section S1). Assumptions about these data can be substantially different from contemporary assumptions in similar circumstances. Thus, history helps orient the reader in the past, as in an unfamiliar country.

Fish export (see section S1 for "Fishing effort" and "Market prices")

FIR data.

New England coastal and inland fisheries produced luxury foods such as salmon and shad, market staples such as mackerel, and utilitarian fish such as alewives, Atlantic herring, and menhaden. Unlike dried salt cod, these fish were caught in dip nets, bag nets, weirs, or shore "haul" seines, or from small boats hugging the coast, cleaned, and shipped pickled in brine or smoked in casks or boxes [(*91*), I]. All but menhaden were regularly consumed as food. Fish were inspected to ensure quality [(*90*), pp. 114–115]. Expensive fish like salmon and shad found markets in Boston, New York, and Philadelphia (*125*, *126*). Mackerel was widely sold in Europe and America, whereas cheap alewives and herring went to poorer urban and rural folks and to slaves in the Caribbean and American South. At this time, menhaden were primarily bought as bait for other local fisheries or as fertilizer to improve poor New England soil [(*91*), I, pp. 327–415]. Salmon, shad, alewives, mackerel, herring, and menhaden made up 98% of all FIR exports during this period.

Fishing was also important to farming communities and contributed materially to the social and economic fabric of the hinterland. Away from the sea, the arrival of alewives and shad in the spring offered windfall benefits to farmers and laborers who sometimes traveled far from home to dip fish from the rivers. Alewives were often pickled or smoked for use at home, but more valuable shad could be bartered and sometimes became a seasonal currency in cash-poor regions. At staging areas where many fishermen worked, traders provided food and rum, and a festival atmosphere sometimes ensued (*126*). In 1880, from 50 to 87% of alewives [(*91*), I, pp. 667–690] and as much as 66% of the mackerel [(*127*), I, p. 48] were kept for local consumption.

FIRs recorded only fish inspected for commercial sale out of state; therefore, they provide only a portion of total catch and are a conservative proxy for fish catch in the GoM during the early decades of the 19th century. Because no consistent catch or export data exist before 1804, we take that year as a baseline from which to measure change. Quantities of processed fish in casks (tierces, barrels, boxes, etc.) were converted to weight (in kilograms) using standard conversions (*128*, *129*) and ln-transformed for statistical analysis.

Fish life histories.

Information on general behavior came from authorities mentioned above (*85*, *86*, *107*–*109*, *125*) and from our own recent field and laboratory work (*81*, *82*, *98*, *111*, *130*). All fish spawned in the GoM at seasons determined by latitude and water temperature. Excepting adult salmon and mackerel, all consumed plankton and other tiny invertebrates and transferred productivity up the food web to apex predators.

Anadromous salmon, shad, and alewives once frequented virtually every watershed in coastal New England. Alewives and shad appeared in seasonal spawning runs to ascend major rivers such as the Connecticut, Merrimac, Kennebec, and Penobscot by the millions, and many smaller rivers by tens or hundreds of thousands (*107*–*109*). During the rest of the year, they moved offshore and schooled with Atlantic herring and menhaden (*130*). In the early 1800s, salmon still spawned in GoM tributaries (*125*). Smaller species, especially out-migrating young-of-the-year alewives, provided prey buffering for juvenile salmon (*131*) and forage for mackerel and groundfish nearshore [(*107*, p. 588; (*132*)].

Inshore waters were also essential habitat for schooling pelagics. From earliest settlement through the 19th century, herring spawned on all suitable nearshore bottom from the Bay of Fundy to Massachusetts Bay [(*133*), p. 387–442]. In estuarine environments, vast spawning cohorts beset the shoreline: On Grand Manan, herring eggs washed onto beaches were removed with shovels [(*134*), p. 46]. Adult mackerel also fed on juvenile alewives and herring. Cold-sensitive, lipid-rich menhaden were more common south of Cape Cod. However, in 1819, one menhaden school transected by a Rhode Island coasting schooner near Casco Bay, ME, was 3.2 km wide and more than 64 km long [(*135*), p. 79].

At the time of Tambora, alewife, shad, and salmon populations had already declined in MA and were considered species of concern by contemporary citizens and governments (*90*), yet by modern standards, GoM watersheds still supported thriving fisheries. Salmon from the Merrimack River still supplied Boston markets in 1822, just as the Boston Manufacturing Company began their great textile mill with its impassable dam at Lowell [(*125*), p. 426]. Alewives were exported from the Charles River in 1839, and shad from the Merrimack and the smaller rivers feeding Massachusetts Bay filled markets during the 1830s [(*125*), pp. 440, 442].

Watersheds

Between northern Cape Cod and the St. Croix River, 72 towns reporting fish export were georeferenced and assigned to a watershed. These fishing communities were shaped by harvestable forest and farmland and also by watershed conformation, coastal topography, and oceanographic factors. Fish migrations were shaped by freshwater outflow as well as coastal topography and oceanographic factors. We divided MA towns into two coastal watersheds: 41 MA towns reported export for CACC and NCA (*136*). Four ME watersheds were chosen for analysis, with 31 towns reporting (see section S3 for watershed descriptions) (*137*).

The spreading human footprint

Towns.

Census records from 1800, 1810, and 1820 provide decennial populations of all 72 towns (*80*). Summing individual town populations for each watershed gave an estimate of the total human population of fishing communities. CACC's population was consistently an order of magnitude greater than the populations of the other watersheds and two orders of magnitude greater than that of SC, even though SC's population trebled over 20 years (Table 1).

Dams.

Dams have been built on New England rivers since the 1630s. Today, dams have almost entirely blocked natural access to essential spawning habitat and are considered the leading obstacles to restoring anadromous populations (*88*). However, dams erected before 1820 were structurally different from industrial main stem dams built just a decade later. Simple log crib and stone freshet dams were constructed on tributaries, built with local materials by local workmen with oxen and axes, and vulnerable to destruction at ice-out in the spring (*138*). Some dams only partially blocked water flow, and simple fishways had been required by law on more permanent structures since 1740 [(*139*), pp. 70–71, 100–101, 129]. However, dams blocked the passage of spawning fish, of spent adults returning to the sea, and of juvenile fish transitioning from fresh to coastal waters. Thus, dam proliferation increasingly interrupted anadromous life cycles. By 1800, existing structures on MA watersheds had reduced available spawning habitat for anadromous fish by 45% (*82*), whereas spawning habitat in ME had been reduced by more than 50% (*81*). After 1820, many low freshet dams were replaced by insurmountable dams as industry came to rival agriculture and fisheries in economic importance.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/1/e1601635/DC1

section S1. Excluded data sets

section S2. Comparison of contemporary shore air temperatures with coastal sea surface temperatures

section S3. Watershed descriptions
fig. S1. Recent comparisons of average air and sea surface temperatures, 2002–2014 (*142*, *143*).
table S1. Yearly amounts of single species and total export (kg) for the GoM, 1804–1820 (*68*, *69*).
table S2. Yearly amounts of single species export for each watershed, 1804–1820 (*68*, *69*).
table S3. Original and ln values of Anadromous and Pelagic export for the GoM, 1804–1880 (*68*, *69*).
table S4. Ln of single species export values for the GoM, 1804–1820 (*68*, *69*), with numbers of Dams (*81*, *82*), Towns (*68*, *69*), and temperature (Yearly ºC) (*83*).
table S5. Correlation of GoM Anadromous and Pelagic export, human influences, and yearly average temperature, 1804–1820.
table S6. Correlation of GoM single species export, human influences, and yearly average temperature, 1804–1820.
table S7. Numerical dates of arrival, departure, and temperature tolerances (ºC) for adult and spawning activities of alewives, shad, Atlantic herring, and mackerel (*85*, *86*).
table S8. Table of four temperature parameters (*15*) for the spring, summer, and fall months from 1814 to 1818 derived from Holyoke's temperature readings (*84*).
References (*144*–*150*)

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