1 **Long-term ecosystem change in the western North Pacific inferred from commercial fisheries**
2 **and top predator diet**

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31	

32 **ABSTRACT**

33 Assessment of the current status of marine ecosystems is necessary for the sustainable
34 utilization of ecosystem services through fisheries and other human activities under changing
35 environmental conditions. Understanding of historical changes in marine ecosystems can help us
36 to assess their current status. In this study, we analyzed Japanese commercial fishery catch data
37 and scientific survey data of the diet of northern fur seal (*Callorhinus ursinus*, NFS) to investigate
38 potential long-term ecosystem changes in the western North Pacific Ocean off northeastern Japan
39 over the past 60 years. Total commercial catches experienced peaks around 1960 and during the
40 1980s, decreasing to low levels around 1970 and after 1990. Catches were substantively
41 impacted by the Tohoku earthquake and tsunami in 2011. Species composition of the commercial
42 catch changed over time, resulting in changes in the mean trophic level (MTL) of the catches.
43 Trends in observed commercial catches were affected by many factors, including species
44 population fluctuations potentially related to large-scale environmental shifts, migration and
45 distribution patterns of species related to local oceanography, changes in fishing technology, and
46 the introduction of fishery management frameworks. The composition of NFS diet also changed
47 over time: although overall changes were small, MTL derived from NFS stomach contents declined
48 from the early 1970s to the late 1980s. This fall in the MTL of the diet of NFS is suggestive of a
49 shift in pelagic fish fauna from a “mackerel-dominant regime” to a “sardine-dominant regime”.
50 Inconsistencies between changes in species composition and MTLs of the commercial catch and
51 NFS diet resulted from differences in commercial fishing targeting and NFS foraging behavior
52 strategies. Although commercial catch is a valuable source of information for investigating
53 historical changes in fisheries, biological resources, and ecosystems, catch data should be
54 interpreted carefully and other relevant information available should also be considered.

55

56 **1. Introduction**

57 Recently, fisheries have attracted global attention because of their impacts on marine living
58 resources and ecosystems (Hilborn et al., 2005; Murawski et al. 2007; Myers and Worm, 2003;
59 Pauly et al., 2002; Worm et al., 2009). Global capture fisheries production remains to be stable,
60 however catch trends by country, fishing area or species have varied significantly through time
61 (FAO, 2014). To sustainably utilize fishery resources and maintain marine ecosystem function
62 and biodiversity, it is necessary to make sound assessments of the impacts of commercial fisheries
63 and other anthropogenic activities on marine ecosystems under shifting environmental conditions
64 (Botsford et al., 1997; FAO, 2003). Historical data provide valuable baseline information for
65 evaluating the current condition of ecosystems in light of past status (Lotze and Worm, 2009; Pauly,
66 1995; Tian et al., 2014). Catch data accumulated by commercial fisheries can offer some insights
67 into the status of fishery resources and the impact of fisheries activities on the broader marine
68 environment, although views differ on the effectiveness of catch data in assessing the health of fish
69 stocks (Hilborn and Branch, 2013; Hilborn and Hilborn, 2012; Myers and Worm 2003; Pauly
70 2013).

71 A comparison study carried out on fish communities and trophic structure of the Tsushima,
72 Kuroshio, and Oyashio currents ecosystems around Japan aimed at identifying variability
73 associated with climate regime shifts (Tian et al., 2014). This study demonstrated the efficacy of
74 historical data in understanding drivers of marine ecosystems variability. Commercial catch data
75 are affected by many factors including management regulation and socioeconomics (Maunder et al.,
76 2006; Murawski et al., 2007; Polacheck, 2006). With this in mind, the use of fishery-independent
77 data, such as those collected by scientific surveys (Branch et al., 2010) or studies on marine top
78 predators (Bowen et al., 1997; Piatt et al. 2007) may considerably improve the interpretation of
79 historical changes in marine ecosystems and impacts on fisheries based on catch data alone.

80 Northern fur seals (*Callorhinus ursinus*, NFS) are the most abundant in all otariid species

81 and are widely distributed in the subarctic waters of the North Pacific Ocean (Jefferson et al.,
82 2008). The waters adjacent to the Tohoku region in northeastern Japan provide a major wintering
83 and foraging area for NFS; approximately 100,000 seals, mostly adult females and juveniles,
84 migrate to this area from winter to early spring (Gentry, 1997). The main prey species of NFS in
85 this region consists of small schooling pelagic fishes (e.g. Japanese sardine, *Sardinops*
86 *melanostictus*, and chub mackerel, *Scomber japonicus*), mesopelagic micronektonic fishes
87 (myctophids), small schooling mesopelagic squid (e.g. sparkling enope squid, *Watasenia*
88 *scintillans*), and oceanic squids (e.g. boreal clubhook squid, *Onychoteuthis borealijaponica*) (Mori
89 et al., 2001; Yonezaki et al., 2003, 2008). Scientific efforts aimed at monitoring the reproductive
90 condition and feeding ecology of NFS were conducted by National Research Institute of Far Seas
91 Fisheries, Fisheries Research Agency, Japan (NRIFSF) under the auspices of the North Pacific Fur
92 Seal Commission (NPFSC) from the 1960s to the 1980s (NPFSC, 1962, 1969, 1971, 1975, 1980,
93 1984), and follow-up surveys were conducted by NRIFSF in the 1990s (Yonezaki et al., 2003).
94 These survey data comprise the Miho Collection, a long-term scientific archive of data that
95 provides valuable information on the ecology of NFS (Yonezaki et al., 2008; Yonezaki and Kiyota,
96 2014). These data also have the potential to provide information on marine ecosystem variability,
97 particularly because NFS is regarded to be an opportunistic predator on fish and squid that are most
98 available in their foraging habitat (Kajimura, 1984). The NFS diet data from this collection can
99 be considered as complementary to fishery catch data in providing insights into ecosystem
100 variability, because it includes species that are not recorded by commercial catch statistics (e.g.
101 mesopelagic micronekton) and the data are largely independent of factors influencing fisheries
102 catches such as socio-economics and management.

103 The Pacific Ocean adjacent to northeastern Japan is one of the most productive fishing
104 grounds in the world. This is largely because of the mixing of two ocean currents, the warm
105 Kuroshio Current and the cold Oyashio Current (Favorite et al., 1976; Fig. 1). Various coastal

106 and offshore fisheries operate in these waters targeting pelagic and demersal fishes, and shellfishes
107 (Kitagawa et al., 2008; Okutani, 2005). The commercial catches have been compiled by the
108 Miyagi Prefecture since 1952.

109 In this study, we assess commercial fishery catches and diet data compiled from scientific
110 surveys of NFS to investigate the potential for the long-term ecosystem changes in the western
111 North Pacific Ocean off northeastern Japan over approximately 60 years. The purposes of this
112 study were to i) examine changes in commercial catches across each of the fisheries operating in
113 the region, ii) explore temporal variability in the diet of NFS, and iii) investigate historical
114 variability in the mean trophic level (MTL) of commercial catches and NFS diet as an indicator of
115 potential fishing down of the food web (Pauly et al., 1998).

116

117 **2. Material and methods**

118 *2.1. Commercial fisheries and marine environment data*

119 We digitized commercial fishery catches (in tonnes) from an area adjacent to northeastern
120 Japan (Fig. 1) from data compiled by the prefectural government of Miyagi across the period 1952
121 - 2011 and reported by fishing companies registered in the Miyagi prefecture. We also compiled
122 fisheries effort (fishing days) data across the period 1957 - 2006, with the exception of the trap net
123 fishery. Since 2006, catch data of the surrounding net fishery were not available. Catch data for
124 Japanese sardines were available for the periods 1957 - 1985 and 2007 - 2011; catches of Japanese
125 sardine, Pacific round herring (*Etrumeus teres*), and Japanese anchovy (*Engraulis japonicus*) were
126 aggregated and reported as sardines during the period 1986 - 2006. Data derived from fisheries
127 that were likely to operate in offshore, distant waters (e.g. skipjack pole-and-line, distant waters
128 squid jigging, former distant-water trawl fisheries in the East China Sea, Yellow, and Bering Seas
129 and former high seas squid and salmon driftnet fisheries) were excluded from analyses. We
130 calculated total catches for each year identifying the major species caught by each fishery in each

131 year.

132

133 2.2. *Northern fur seal dietary data*

134 Dietary data from NFSs caught in the study area (Fig. 1) between January and April across
135 the period 1953 - 1988 were extracted from the Miho Collection. These data were derived from
136 7,104 adult female and juvenile NFSs. Collection of samples from NFS focused on areas of high
137 densities of individuals which primarily occurred on the shelf edge and continental slope regions of
138 the study area. Prey species were identified based on the external morphology of undigested and
139 partly digested diet derived from stomach contents and the percent wet weight (PWW) for each
140 species calculated. The PWW of prey species in the stomachs of NFS were pooled across all
141 samples in a given year. Because there were biases in the annual capture locations of NFS (for
142 details, see Yonezaki et al., 2008), PWW values for each species were then pooled across the 1950s,
143 1960s, 1970s, and 1980s to produce a total PWW for each decade.

144 The NFS samples in the Miho Collection could detect the long-term changes that were
145 ovaries, therefore we analyzed the ovary samples for trophic levels of NFS using stable isotope
146 technique. Usually, samples examined by stable isotope analysis for the characterization of diets
147 and trophic levels of marine mammals are derived from muscle, liver, skin and blood (Newsome et
148 al., 2010). Isotopic composition turnover rates vary among tissues according to protein metabolic
149 rate, and are relatively rapid, occurring across scales of a week to a month (Newsome et al., 2010).
150 Tissues such as blood and liver with have high rates of biochemical turnover provide dietary
151 information assimilated from recent feeding bouts, while tissues with slower turnovers such as
152 muscle and hair provide information from feeding bouts across extended periods of time (Tieszen
153 et al., 1983; Kurle and Worthy, 2002). In NFS, liver tissue has high protein turnover, with an
154 average protein half-life of ~ 1.9 to 6.7 days while, adipose tissue has a slower turnover, with an
155 average protein half-life of ~ 12.5 to 83.3 days (Kurle and Worthy, 2002). Ovary tissues are

considered to have a lower metabolic turnover than muscle tissue, and it would therefore be expected that the turnover of these tissues in NFS would be expected to occur over a few months. For the purposes of this study, it was assumed that $\delta^{15}\text{N}$ values in the ovaries of NFS females might reflect the diet of individuals in the year of capture.

Ovary samples from adult females NFS ($n = 444$) collected during 1969 - 1997 (1969: $n = 60$; 1970: $n = 61$; 1971: $n = 72$; 1972: $n = 58$; 1980: $n = 65$; 1987: $n = 54$; 1988: $n = 58$; 1997: $n = 16$) were analyzed for stable isotope ratio of nitrogen ($^{14}\text{N}/^{15}\text{N}$). Approximately 5 g of tissue was removed from ovaries, stored in 10 % formaldehyde, rinsed with distilled water, dried at 60 °C overnight and ground into a fine powder without lipid removal treatment. Stable isotope of $\delta^{15}\text{N}$ were determined from each sample using a mass spectrometer (MAT252, Finnigan MAT) coupled online, via a Finnigan ConFlo II interface, with an elemental analyzer (EA 1110, ThermoQuest). Isotope values were calculated as ‰ deviation from the standard according to the formula,

$$\delta^{15}\text{N}_{\text{NFS}} = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000 \quad (1)$$

where R_{sample} and R_{standard} were the ratios of ^{14}N to ^{15}N in the sample and the standard material, respectively. Atmospheric nitrogen was used as the nitrogen isotope standard.

171

2.3. Mean Trophic Level of commercial catch and NFS

Annual MTLs of species identified in commercial catches from the study area were calculated using trophic level (TL) values from FishBase (<http://www.fishbase.org/search.php>) and SeaLifeBase (<http://www.sealifebase.org/search.php>). For those species for which TL values were not available from FishBase and SeaLifeBase, values of related species were considered to provide a reasonable approximation of true TL values (Table 1).

The MTL of the commercial catch in year t was calculated as follows:

$$\text{MTL}_t = \sum_{i=1}^n \{(Catch_{i,t} / \text{Total catch}_t) \times TL_i\} \quad (2)$$

where $Catch_{i,t}$ is the catch of species i in year t , Total catch_t is the catch of all species in year t , and

181 TL_i is the TL value of species i as specified in Table 1.

182 The TL of individual NFS was calculated using stable isotope values and decadal values of
183 PWW. Trophic Level was calculated using ^{15}N isotope values following formula:

$$184 \quad TL_{\text{NFS}} = (\delta^{15}\text{N}_{\text{NFS}} - 5.4)/3.4 + 1 \quad (3)$$

185 where $\delta^{15}\text{N}_{\text{NFS}}$ is the stable nitrogen value of each individual, 5.4 (‰) is the value of $\delta^{15}\text{N}$ of
186 particulate organic matter (POM) from waters off northeastern Japan reported by Sugisaki et al.
187 (1991), and 3.4 is the concentration factor of nitrogen used in Minagawa and Wada (1984).
188 Values from individuals were pooled in each year and the mean calculated providing an average TL
189 value for each year. Mean TL calculated from diet data was calculated as follows:

$$190 \quad MTL_{\text{NFS}} = 1 + \sum PWW_i \times TL_i \quad (4)$$

191 where PWW_i is the percent wet weight of prey item i , TL_i is the trophic level of species i cited from
192 FishBase and SeaLifeBase (Table 1). The following TL values were used for non-commercial
193 species: TL = 2.68 for sparkling enope squid (TL was calculated from stable nitrogen isotope ratio
194 of this species (Yonezaki et al., unpublished data)), and TL = 3.13 for myctophids (TL was a
195 substitute for that of California headlightfish (*Diaphus theta*) from FishBase).

196

197 **3. Results**

198 *3.1. Trends in commercial catches and fishing effort*

199 Inter-annual fluctuations in total commercial catches in this study area were large (Fig. 2),
200 with catches demonstrating two distinct peaks in catches during the late 1950s/early 1960s (with
201 the exception of 1960) and from the late 1970s to the mid-1980s (with the exception of 1983).
202 During the period preceding the second peak in catches, total catch more than tripled from about
203 130,000 t in 1969 to 400,000 t in 1984. Declines in total catches from the mid 2000s are a result
204 of missing data from the surrounding net fishery and the sharp decline in catches in 2011, is
205 associated with the Tohoku earthquake and tsunami.

Decadal catch species composition also varied greatly (Fig. 3). Pacific saury (*Cololabis saira*) was the dominant species caught in the 1950s (1952 - 1959), gradually decreasing from 56 % of the total catch in the 1950s to 6 % in the 1980s before increasing again across the following three decades to 19 % in the 2000s. During the same period mackerels increased from 1 % of total catches in the 1950s to 34 % in the 1970s before declining to 10 % - 7 % across the 1980s - 2000s. Catches of mackerels consisted mostly chub mackerel, although also included blue mackerel (*Scomber australasicus*). Although contributing to a much smaller percentage of catches, walleye pollock (*Theragra chalcogramma*) demonstrated a similar pattern with percent contribution to overall catches increasing from 1950s to 1980s and the declining in following decades. Percentage of Japanese sardine in commercial catches increased from the 1950s to the 1980s after which they were aggregated with Pacific round herring and Japanese anchovy into a 'sardines' category with overall percentages of this category in the 1990s and 2000s declining. Percentage of Japanese flying squid (*Todarodes pacificus*) and Pacific krill (*Euphausia pacifica*) increased across 1990 - 2010, although catches of Pacific krill were included in an 'Others' category prior to 1980, so earlier catches are unknown. Skipjack tuna (*Katsuwonus pelamis*) contributed similar percentage to overall catches in the 1950s and 1960s after which their contribution to overall catches decreased in the 1970s and 1980s and then increased again in the 1990s and 2000s. Japanese sand lance (*Ammodytes personatus*) contributed less than 0.1 % to overall catches across all decades.

Major fisheries operating in the study region were the surrounding net, trawl, lift net, gillnet, trap net, and hook and line fisheries (Table 2). Values for annual catches and fishing effort associated with each of the main fisheries varied across the time series (Fig. 4). All fisheries except the gillnet fishery have reported substantial declines in fishing effort from initial values reported in the 1950s (effort data were not available for the trap net fishery). Although effort reported for the gillnet fishery was higher in the 2000s than that recorded in the 1950s, effort had

231 still declined from a peak in the 1980s. Overall catches in all fisheries except for the trap net
232 fishery have also declined from peaks that occurred either in the 1960s (lift net, hook and line),
233 1970s (gillnet) or 1980s (surrounding net, trawl). Catches in the trap net fishery, while varying
234 inter-annually, were relatively consistent during the 1950s to 1975, after which they increased to an
235 initial peak in the early 1980s, were relatively consistent against during the 1990s and increased
236 again in the second half of the 2000s. Catch species in the surrounding net fishery were
237 predominantly mackerels until the mid-1970s, after which sardines dominated catches until the
238 1990s when catches of sardines declined and skipjack tuna catches increased. Overall catches of
239 all three species and associated effort have been relatively stable since the mid-1990s, with effort at
240 approximately 2,000 fishing days (Fig. 4A). Catches in the trawl fishery have primarily
241 comprised walleye pollock up until the early 1990s after which, catches of Japanese flying squid
242 dominated catches. Japanese sand lance have contributed minor catches to the fishery throughout
243 the time series except for a period in the 1980s when catches approaches those of walleye pollock.
244 Annual catches have demonstrated two peaks, the first in 1966 after which catches declined to
245 20,000 t, in the early 1970s and the second in the early 1980s when catches reached 100,000 t.
246 Catches decreased throughout the 1980s and 1990s and have remained relatively consistent
247 throughout the 2000s. Overall effort has decreased over the time series from 6,000 fishing days
248 to 3,000 fishing days (Fig. 4B). Catches within the lift net fishery were primarily comprised of
249 Pacific saury. Annual catches were relatively high during the first decade of the fishery although
250 demonstrated inter-annual variability. Catches reduced quickly and substantially in the early
251 1970s, increasing again slightly in the early 1980s, and remaining low after. Annual catches of
252 Japanese sand lance approached those of Pacific saury throughout the 1980s before dropping to
253 below the levels of Pacific saury from the 1990s onwards. Annual efforts followed patterns in
254 catches, being relatively high in the first decade of the fishery before decreasing in the mid-1960s.
255 Effort increased again rapidly at the mid-1970s before decreasing again throughout the 1980s and

1990s. Effort has remained relatively consistent since the early 1990s (Fig. 4C). Catches within the gillnet fishery have shifted between Pacific herring (*Clupea pallasii*), cephalopods, albacore tuna (*Thunnus alalunga*), skipjack tuna, and salmons with variability annual catches reflecting shifts between species. Annual catches within the fishery were relatively low across the first two decades of catch records. Catches of Pacific herring increased rapidly in the late 1960s/early 1970s before declining rapidly again in the late 1970s. Catches within the fishery increased again in the late 1970s in association with catches of cephalopods before declining again in the early 1980s. Catches increased again throughout the 1980s associated with increases in catches of albacore and skipjack tuna before declining again in the early 1990s when catches of salmons increased. Catches have remained relatively constant at relatively low levels since. Over the period for which catch records were available, annual effort increased gradually through to the late 1980s, after which it decreased gradually before stabilizing in the mid-1990s, and has remained at approximately 70,000 fishing days since (Fig. 4D). Catches by trap net fishery were mostly comprised of sardines, mackerels, and Japanese anchovy with catches of all three species relatively low the mid-1970s. Catches increased in association with increased in sardines and mackerels catches decreased in the late 1970s and then increased again in the early 1980s in association with increases in sardines catches. Catches of mackerels increased in the 1990s before decreasing again in the late 2000s when Japanese anchovy catches increased (Fig. 4E). Associated data on effort was not available. The vast majority of catches and associated effort in the hook and line fishery which comprised sharks, bigeye tuna (*T. obesus*), yellowfin tuna (*T. albacares*), swordfishes, and Pacific cod (*Gadus macrocephalus*) occurred during the first decade of catch records. Catch and effort declined rapidly in the mid-1960s and have remained relatively low ever since (Fig. 4F).

3.2. Trends in the MTL of commercial catches and NFS

The estimated MTL of catches from all fisheries was relatively constant through the 1950s to

the 1970s decreasing slightly from a high of 3.60 in 1958 to 3.22 in 1980. Estimated MTL then rapidly decreased to a minimum of 2.86 in 1983 before rapidly increasing again to a value of 3.17 in 1986. Estimated MTL then gradually increased further to values of between 3.32 and 3.30 during 2000 - 2010, similar to values during early parts of the time series. While annual estimates of MTLs varied between years, this variability was low. If catches of Japanese sardine and sardines (which included Pacific round herring and Japanese anchovy as well as Japanese sardine) were excluded from the time series, estimated MTLs were almost identical to those MTLs including catches of Japanese sardine and sardines, however the rapid decrease and increase in estimated MTL observed in the time series during the late 1970s and most of the 1980s was not observed (Fig. 5A).

The estimated MTL of prey items recorded in NFS diet present in commercial catches (Pacific herring, Japanese sardine, Pacific round herring, Japanese anchovy, horse mackerels, mackerels, Pacific saury, Okhotsk atka mackerel (*Pleurogrammus azonus*), Pacific cod, walleye pollock, salmon, ocean perches, Japanese sand lance, Japanese flying squid, neon flying squid (*Ommastrephes bartramii*)) was slightly higher the estimated MTL of commercial catches with the exception of the period of the dramatic decrease and increase in the late 1970s and 1980s when it was slightly lower. Annual estimate of the three MTL time series demonstrated similar patterns in variability (Fig. 5A).

Annual estimated MTLs of NFS calculated from nitrogen stable isotopes of gonad tissues demonstrated a slight overall decline from higher mean values ≈ 3.9 in 1969, 1970, and 1971 to values of 3.7 in 1987 and 1988 (Fig. 5A and B).

3.3. Decadal changes in the diet of NFS from stomach contents

Major prey species in this study area from NFS stomach contents were Japanese sardine, mackerels, myctophid fishes, demersal fishes, oceanic squids, and sparkling enope squid. Species

present were dominated by myctophids during the 1950's with PWWs of sparkling enope squid and Japanese anchovy contributing less than 5 % and Japanese sardine, mackerels, and walleye pollock not present in stomachs. Dietary composition was similar during the 1960s with myctophids dominating NFS diet, although at lower PWWs. Mackerels and walleye pollock comprised small amounts to dietary samples during this period. Mackerels dominated the diet of NFS during the 1970s; myctophids were not present in the diet of NFS and PWWs of walleye pollock, sparkling enope squid and Japanese anchovy were similar to previous decades. During the 1980s contributions of mackerels, walleye pollock and Japanese anchovy all decreased, while PWW of Japanese sardine increased substantially, with the species dominating NFS diet. The contributions of sparkling enope squid to NFS stomach contents was similar to that in the 1970s and the PWW of myctophids increased slightly (Fig. 6). Decadal MTL of NFS calculated from prey PWW and TL was similar across the four decades, decreasing slightly between the 1960s and 1980s similarly to the annual MTL based on tissue stable isotopes (Figs. 5B and 6G).

319

320 4. Discussion

Commercial fishery catches in waters off the north-east of Japan demonstrated large-scale fluctuations across the 60 period examined in this study, reflecting high variability in effort within each fishery and species targeted by each of the fisheries in this region. Various types and scales of fisheries have been operating in these waters, and a wide range of species have been utilized by local fisherman including algae, benthic invertebrates, plankton, demersal and pelagic fishes and top predators such as tunas, sharks and marine mammals.

327

328 4.1. *Fluctuation of commercial catch and NFS diet in the Tohoku region*

The large increase in total commercial catches during the 1980s can be directly attributed to increased catches of Japanese sardine. The catch history of Japanese sardine and mackerels

331 appear to parallel a regime shift, a well-known phenomenon of decadal alternation in the
332 dominance of small pelagic fishes within pelagic ecosystems. In the western North Pacific, the
333 dominant small pelagic species shifted from mackerels in the 1970s (“mackerels-dominant
334 regime”) and Japanese sardine in the 1980s (“sardines-dominant regime”), to Japanese anchovy in
335 the 1990s and 2000s (“anchovy-dominant regime”) (Kawasaki, 1983, 2013; Yatsu et al., 2003).
336 This supported by the substantive decrease in MTL observed during the 1980s as demonstrated
337 when MTLs associated with catches of Japanese sardine were removed from the time series.
338 Japanese sardine feed on phytoplankton as well as zooplankton and have a lower TL value
339 compared to planktivorous fishes that feed solely on zooplankton (Yasue et al., 2014). As a result,
340 increase in catches of Japanese sardine and decrease in higher TL planktivorous fish would be
341 expected to lower overall MTLs. To what degree this is reflective of a true shift in the ecosystem
342 dynamics of small pelagic fishes in the region or a consequence of shifts in targeting practices by
343 the fishery, however is unknown. Moreover, Japanese anchovy did not become the major species
344 in the commercial catch of the water off the Tohoku region in north-eastern Japan because of the
345 lower availability of processing plants in Tohoku, but it has been a little catch by the trap net
346 fishery in the late 2000s.

347 The MTLs derive from NFS stomach content and ovary stable isotope analysis was relatively
348 stable across the time series demonstrating only a slight decline across the time series from the
349 1970s to the 1980s which may have been related to increased consumption of Japanese sardine in
350 the 1980s. Estimated MTL from NFS sampled in 1997 suggests that the MTL remained.
351 Previous analysis of NFS diet from the 1990s reported that stomach contents of NFS were
352 dominated by myctophids and sparkling enope squid and lacked evidence of Japanese sardine
353 consumption (Yonezaki et al., 2003), suggesting that the slight decline may not have been
354 associated with consumption of Japanese sardine, but variation in the consumption of other species.
355 However, when it was “anchovy-dominant regime” in the 1990s of the water off the Tohoku region

356 in north-eastern Japan, Japanese anchovy was not the major species in NFS diet. It is not certain
357 why NFS scarcely preyed on Japanese anchovy, although there are several possible reasons for the
358 low feeding rate of Japanese anchovy unproportional to the abundance. One possible reason is
359 the spatial segregation. Japanese anchovy is a warm water species that dominates during the
360 warm water regime (Kawasaki, 2013). Japanese anchovy is mainly distributed to in the Kuroshio
361 water up to the Kuroshio-Oyashio mixture zone (Takahashi et al., 2001), whereas NFSs mostly
362 remain in the colder side of mixture zone and intrude into the Kuroshio water infrequently (Wada,
363 1971). Another possible factor is the diet selection. Although NFS has been considered as a
364 typical opportunistic feeder that prey on most abundant foods in the foraging area (Kajimura, 1984),
365 there are some studies that indicate the possibility of diet preference and selection related to prey
366 size and intake efficiency in NFS (Sinclair et al., 1994; Ream et al., 2005; Kiyota et al., 2013).
367 Commercial fisheries in this study area catch Pacific saury actively, however Pacific saury in diets
368 of NFS in this study area was very minor prey species (Yonezaki et al., 2008). As in the case of
369 Japanese anchovy, the reasons for the low feeding rate of Pacific saury are the spatial segregation
370 and diet selection of NFS. Pacific saury in this study area was mainly caught from summer to
371 autumn (Ebisawa and Sunou, 1999). Mismatch of the distribution of Pacific saury and NFS in
372 this study area might be the main factor.

373

374 4.2. *Changes in fisheries and their management*

375 The surrounding net fishery was responsible for most of the catches of mackerels, sardines,
376 and skipjack tuna during the 1970s, 1980s, and 2000s, respectively while the trap net fishery was
377 responsible for most of the catches of mackerels, sardines, and Japanese anchovy during the 1970s,
378 1980s, and late 2000s, respectively. The surrounding net fishery is a type of fishing gear that is
379 actively deployed to catch fish while the trap net fishery primarily catches passively. Despite
380 differences in the mode of fish capture between the two fisheries, it is possible that the catch

381 compositions of the two fisheries were affected by the stock fluctuation of pelagic species.

382 Trends in catches through time are not only affected by natural fluctuations in stocks and the
383 marine environment, but are also affected by implementation and changes in fisheries management.
384 Limit catches of Pacific saury was introduced between 1980 and 1990 to maintain commercial
385 prices (Kodama, 2004; Nakagami et al., 2011). Similar regulation of catches and effort have been
386 introduced for the Japanese sand lance and Pacific krill fisheries (Nagashima, 2000; Taki, 2002).
387 Implementation of these management measures suggest that recent trends in catches may not be
388 representative of the stock. In addition, total allowable catches were introduced on species (e.g.
389 Pacific saury, walleye pollock, Japanese sardine, mackerels, and Japanese flying squid) that were
390 the major targets of coastal fisheries in Japan as part of measures introduced under the Act on
391 Preservation and Control of Living Marine Resources 1996 (Makino, 2011). In fisheries in waters
392 off north-eastern Japan, total allowable catches apply to stocks of Japanese sardine, Japanese
393 anchovy, chub mackerel, blue mackerel, Pacific saury, and walleye pollock. Recent catches of
394 these species have stabilized at lower levels, in part because of this form of fishery management.

395

396 4.3. *Detection of changes in the north-eastern Japan marine ecosystem*

397 Declining trends in commercial fisheries across the world have been attributed to overfishing
398 (Myers and Worm, 2003; Pauly 2013). Similarly, declines in estimated MTL of catches have also
399 been associated with human impacts, declining when predators collapse (“fishing down marine
400 food webs”) (Pauly et al., 1998) and when low-trophic-level fisheries expand (“fishing through
401 marine food webs”) (Essington et al., 2006). Estimated MTLs of commercial catches have been
402 found to be unreliable predicting changes in marine ecosystems, largely because MTL trends
403 associated with commercial fishery catches often diverge from ecosystem MTL trends obtained
404 from surveys and assessments (Branch et al., 2010).

405 In this study area, species population fluctuations potentially related to large-scale

environmental shifts affected trends in observed commercial catches and NFS diet mainly. The marine ecosystems around Japan have been strongly influenced by changes in the marine environment (especially climate regime shifts) (Tian et al., 2014; Yatsu et al., 2013).

Balanced harvesting would more effectively mitigate adverse ecological effects of fishing while supporting sustainable fisheries (Garcia et al., 2012). Moreover, in the Tohoku region, the marine resources of wide range of TL (low-TL: kelps, clams, Pacific krill etc., high-TL: marine mammals, sharks, tunas etc.) from past to present. It is considered that commercial fisheries around Japan is balanced harvesting activities that utilize the wide range of ecosystem services “unconsciously”. However, it is not possible to accept blindly the current status of the marine ecosystem around Japan. While being conscious of the practice of balanced harvesting, it is very important that monitoring of the marine ecosystem in strict view point has been continue to the future by making full use of any data (commercial fishery including socioeconomic factor, scientific survey data combining various TL species).

5. Conclusions

Long-term catch data from fisheries operating in waters off the Tohoku region in north-eastern Japan across approximately 60 years did not reveal a simple reduction of total biomass and MTL in line with the “fishing down” phenomenon of Pauly et al. (1998). Fisheries in this region are highly diverse, deploying many different types of fishing methods and in association, landing a variety of marine species spanning a wide range of trophic level. Assessment of commercial catches and MTL of these catches suggest that catches are affected by many factors, including stock fluctuations potentially related to large-scale environmental shifts, individual migration and distribution patterns related to local oceanographic conditions, changes in species targeting, and the introduction of fishery management. Dietary information of top predators helped us to interpret the ecosystem change suggested by fishery data and to characterize the behavioral differences

431 between fisheries and predators. Commercial catch data are a valuable source of information
432 allowing investigation of historical changes in fisheries, biological resources, and ecosystems,
433 although interpretation of catch data should be done with care while also using other relevant
434 information. To ensure sustainable utilization of marine ecosystems, it is important that any
435 monitoring of the marine ecosystem utilizes all data available, including fisheries socio-economic
436 and scientific survey data incorporating species across multiple trophic levels within the ecosystem.
437 Further assessment of historical knowledge on the ecosystems and fisheries in the waters off the
438 Tohoku region will be important for facilitating an evaluation of the impact of the 2011 Tohoku
439 earthquake and tsunami on the marine ecosystem and in association, planning for the
440 reconstruction of local fisheries.

441

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454

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613

614 **Figure captions**

615 **Fig. 1.** Schematic illustration showing the oceanographic structures in the western North Pacific
 616 northeastern Japan (off Tohoku). Shade area is fishing ground of the commercial fishery statistics
 617 in Miyagi Prefecture and sampling location of northern fur seals (*Callorhinus ursinus*).

618

619 **Fig. 2.** Annual total catch of commercial fisheries off Tohoku from 1952 to 2011 based in the
 620 fishery statistics of Miyagi Prefecture, northeastern Japan. The dotted line is a smooth spline
 621 curve fit by using R software with smoothing parameters estimated by ordinary cross validation.

622

623 **Fig. 3.** Decadal species composition of catch in commercial fisheries off Tohoku calculated from
 624 the fishery statistics of Miyagi Prefecture. Species compositions of 2010 and 2011 was a single
 625 year data.

626

627 **Fig. 4.** Annual major fishery species catch and fishing effort (fishing days; open circle line) by
 628 main fishery type; surrounding net fishery (A), trawl fishery (B), lift net fishery (C), gillnet fishery
 629 (D), trap net fishery (E), and hook and line fishery (F) off Tohoku calculated from the fishery
 630 statistics of Miyagi Prefecture. The catch data were available from 1952 to 2011, however the

631 catch data of the surrounding net fishery was available from 1952 to 2005. The effort data were
632 available from 1957 to 2006, however the effort data of the surrounding net fishery was available
633 from 1952 to 2005. The effort data of the trap net fishery was not available. During 1986 and
634 2006, sardines contained Pacific round herring (*Etrumeus teres*) and Japanese anchovy (*Engraulis*
635 *japonicus*) in addition to Japanese sardine (*Sardinops melanostictus*). Mackerels consisted of
636 mostly of chub mackerel (*Scomber japonicus*) and partly blue mackerel (*Scomber australasicus*).
637

638 **Fig. 5.** Annual mean trophic level (MTL) of whole catch, catch without Japanese sardine and
639 sardines, and northern fur seal (*Callorhinus ursinus*, NFS) prey items in commercial fisheries off
640 Tohoku (A) and female NFSs estimated from stable nitrogen isotope ratios of stored tissue samples
641 collected off Tohoku for scientific investigations (B). Vertical bars in the right panel indicate
642 standard deviations. Sample size of each year; 1969: n = 60; 1970: n = 61; 1971: n = 72; 1972: n
643 = 58; 1980: n = 65; 1987: n = 54; 1988: n = 58; 1997: n = 16.
644

645 **Fig. 6.** Decadal percentage wet weight (PWW) of major prey species (Japanese sardine
646 (*Sardinops melanostictus*): A, Japanese anchovy (*Engraulis japonicus*): B, mackerels: C,
647 myctophids: D, walleye pollock (*Theragra chalcogramma*): E, sparkling enope squid (*Watasenia*
648 *scintillans*): F) and mean trophic levels (MTLs) (G) in the stomach contents of northern fur seals
649 (*Callorhinus ursinus*, NFS) collected off Tohoku in the 1950s, 1960s, 1970s, and 1980s for
650 scientific investigations. Mackerels consisted of mostly of chub mackerel (*Scomber japonicus*)
651 and partly blue mackerel (*Scomber australasicus*).

Table 1. Species categories used in the Miyagi Prefecture fishery statistics with trophic level (TL) values calculated from FishBase, SeaLifeBase and other information. Values for TL are based on FishBase or SeaLifeBase values, unless stated otherwise.

Species group		TL value	Species aggregation and TL calculation
English name	Scientific name		
Pacific herring	<i>Clupea pallasii</i>	3.20	Species-specific catch data were available until 1985. Same as above.
Japanese sardine	<i>Sardinops melanostictus</i>	2.40	
Pacific round herring	<i>Etrumeus teres</i>	3.50	
Japanese anchovy	<i>Engraulis japonica</i>	2.60	
Sardines		2.83	
Horse mackerels		3.40	After 1985, catch data of Japanese sardine, Pacific round herring, and Japanese anchovy were aggregated as sardines. TL of sardines was calculated as the average value of the three species.
Mackerels		3.65	TL was calculated as the average of Japanese jack mackerel (<i>Trachurus japonicus</i>) and amberstripe scad (<i>Decapterus muroadsi</i>).
Pacific saury	<i>Cololabis saira</i>	3.70	TL calculated as the average chub mackerell (<i>Scomber japonicus</i>) and blue mackerel (<i>S. australasicus</i>).
Skipjack tuna	<i>Katsuwonus pelamis</i>	3.80	
Frigate tunas		4.20	TL was calculated as the average of frigate tuna (<i>Auxis thazard</i>) and bullet tuna (<i>A. rochei</i>).
Pacific bluefin tuna	<i>Thunnus orientalis</i>	4.20	TL was calculated as the average of Pacific bluefin tuna, albacore, bigeye tuna, and yellowfin tuna.
Albacore	<i>T. alalunga</i>	4.30	
Bigeye tuna	<i>T. obesus</i>	4.50	
Yellowfin tuna	<i>T. albacares</i>	4.30	
Tunas		4.30	
Striped marlin	<i>Tetrapturus audax</i>	4.60	TL of other marlins was calculated as the average value of Indo-Pacific blue marlin (<i>Makaira mazara</i>), and black marlin (<i>M. indica</i>).
Swordfish	<i>Xiphias gladius</i>	4.50	
Other marlins		4.50	
Other billfishes		4.50	TL was calculated as the average of Indo-Pacific sailfish (<i>Istiophorus platypterus</i>), and shortbill spearfish (<i>Tetrapturus angustirostris</i>).
Japanese amberjack	<i>Seriola quinqueradiata</i>	4.00	TL was calculated as the average of blue shark (<i>Prionace glauca</i>), picked dogfish (<i>Squalus acanthias</i>), salmon shark (<i>Lamna ditropis</i>), starspotted smooth-hound (<i>Mustelus manazo</i>), and spotless smooth-hound (<i>Mustelus griseus</i>).
Pacific cod	<i>Gadus macrocephalus</i>	4.00	
Walleye pollock	<i>Theragra chalcogramma</i>	3.50	
Sharks		4.02	
Red seabream	<i>Pagrus major</i>	3.70	TL was calculated as the average of red seabream, blackhead seabream, crimson seabream (<i>Erynnis japonica</i>), yellowback seabream (<i>Dentex tumifrons</i>), yellowfin seabream (<i>Acanthopagrus latus</i>), and goldlined seabream (<i>Rhabdosargus sarba</i>).
Blackhead seabream	<i>Acanthopagrus schlegelii</i>	3.20	
Seabreams		3.48	
Bastard halibut	<i>Paralichthys olivaceus</i>	4.40	TL was calculated as the average of yellow striped flounder (<i>Pleuronectes herzensteini</i>), Kamchatka flounder (<i>Atheresthes evermanni</i>), Sôhachi (<i>Hippoglossoides pinetorum</i>), ridged-eye flounder (<i>Pleuronichthys cornutus</i>), shotted halibut (<i>Eopsetta grigorjewi</i>), flathead flounder (<i>H. dubius</i>), slime flounder (<i>Microstomus achne</i>), marbled flounder (<i>Pleuronectes yokohamae</i>), stone flounder (<i>Kareius bicoloratus</i>), yellowfin sole (<i>Pleuronectes asper</i>), blackfin flounder (<i>Glyptocephalus stelleri</i>), and willow flounder (<i>Tanakius kitaharai</i>).
Flounders		3.42	
Spanish mackerels		4.48	TL was calculated as the average of Japanese Spanish mackerel (<i>Scomberomorus niphonius</i>), Chinese seerfish (<i>S. sinensis</i>), narrow-barred Spanish mackerel (<i>S. commerson</i>), and wahoo (<i>Acanthocybium solandri</i>).
Okhotsk atka mackerel	<i>Pleurogrammus azonus</i>	3.60	TL was calculated as the average value of Japanese flyingfish (<i>Cypselurus agoo</i>), <i>Cheilopogon pinnatibarbatatus japonicus</i> , and <i>Cheilopogon doederleinii</i> .
Flying fishes		3.40	
Mullets		2.30	TL was calculated as the average of flathead grey mullet (<i>Mugil cephalus</i>) and so-iny mullet (<i>Chelon haematocheilus</i>).

Table 1. *Continued.*

Species group		TL value	Species aggregation and TL calculation
English name	Scientific name		
Salmons		3.95	TL was calculated as the average value of chum salmon (<i>Oncorhynchus keta</i>), sockeye salmon (<i>O. nerka</i>), coho salmon (<i>O. kisutch</i>), and chinook salmon (<i>O. tshawytscha</i>).
Sea trouts		3.90	TL was calculated as the average of pink salmon (<i>O. gorbuscha</i>) and Masu salmon (<i>O. masou masou</i>).
Seabasses		3.45	TL was calculated as the average of Japanese seabass (<i>Lateolabrax japonicus</i>) and blackfin seabass (<i>L. latus</i>).
Rays		3.80	TL of rays was calculated as the average value of whip stingray (<i>Dasyatis akajei</i>), ocellate spot skate (<i>Raja kenoei</i>), and brown guitarfish (<i>Rhinobatos schlegelii</i>).
Ocean perches		3.70	TL was calculated as the average of <i>Sebastes matsubarae</i> , rougheye rockfish (<i>S. aleutianus</i>), Pacific ocean perch (<i>S. alutus</i>), <i>S. baramenue</i> , <i>S. flammeus</i> , and gray rockfish (<i>S. glaucus</i>).
Broadbanded thornyhead	<i>Sebastolobus macrochir</i>	3.30	
Dolphinfishes		4.45	TL was calculated as the average of common dolphinfish (<i>Coryphaena hippurus</i>) and pompano dolphinfish (<i>C. equiselis</i>).
Japanese sand lance	<i>Ammodytes personatus</i>	3.10	
Drums		3.54	TL was calculated as the average of honnibe croaker (<i>Nibea mitsukurii</i>), yellow drum (<i>N. albiflora</i>), silver croaker (<i>Pennahia argentata</i>), blackmouth croaker (<i>Atrubucca nibe</i>), and yellow croaker (<i>Pseudosciaena polyactis</i>).
Conger eels		4.00	TL was calculated as the average value of whitespotted conger (<i>Conger myriaster</i>) and beach conger (<i>C. japonicus</i>).
Other fishes		3.55	TL was calculated as the average of silver croaker (<i>Pennahia argentata</i>), spiny red gurnard (<i>Chelidonichthys spinosus</i>), <i>Lepidotrigla microptera</i> , Japanese sandfish (<i>Arctoscopus japonicus</i>), deep-sea smelt (<i>Glossanodon semifasciatus</i>), <i>Takifugu porphyreus</i> , <i>Takifugu pardalis</i> , <i>Lagocephalus gloveri</i> , <i>Hexagrammos otakii</i> , dotted gizzard shad (<i>Konosirus punctatus</i>), <i>Lophius litulon</i> , splendid alfonsino (<i>Beryx splendens</i>), Japanese halfbeak (<i>Hyporhamphus sajori</i>), <i>Sebastes inermis</i> , <i>S. ventriosus</i> , <i>S. cheni</i> , <i>S. thompsoni</i> , and <i>Thamnaconus modestus</i> .
Japanese flying squid	<i>Todarodes pacificus</i>	4.28	
Neon flying squid	<i>Ommastrephes bartramii</i>	4.00	TL was a substitute for that of neon flying squid with reference to Okamura (2004).
Other squids, Cuttlefishes, Octopuses		3.50	TL was calculated as the average value of golden cuttlefish (<i>Sepia esculenta</i>) and common octopus (<i>Octopus vulgaris</i>).
Sakhalin surf clam	<i>Pseudocardium sachalinense</i>	2.00	TL was estimated from stomach contents of sakhalin surf clam with reference to Sasaki et al. (2004).
Bloody clam	<i>Anadara broughtoni</i> , <i>Gomphina melanegis</i>	2.00	TL was estimated from stomach contents of sakhalin surf clam with reference to Sasaki et al. (2004).
Clams, Other shellfishes		2.00	TL was estimated from stomach contents of sakhalin surf clam with reference to Sasaki et al. (2004).
Abalones		2.00	TL was a substitute for that of black abalone (<i>Haliotis cracherodii</i>).
Crabs		3.08	TL was a substitute for that of tanner crab (<i>Chionoecetes bairdi</i>).
Pacific krill	<i>Euphausia pacifica</i>	1.72	TL was estimated from stable nitrogen isotope ratio of Pacific krill with reference to Mitani et al. (2006). Before 1980, Pacific krill catch data were aggregated as "Others". Species-specific catch data were available since 1981.
Shrimps		3.07	TL was a substitute for that of northern shrimp (<i>Pandalus borealis</i>).
Sea urchins		2.40	TL was a substitute for that of green sea urchin (<i>Strongylocentrotus droebachiensis</i>).
Sea cucumbers		2.10	TL was a substitute for that of <i>Stichopus fuscus</i> with reference to Okey et al. (2004).
Kelps, Brown algae, Gelidacean red algae, Other algae		1.00	These species were primary producers.
Marine Mammals		4.50	TL was a substitute for that of Dall's porpoise (<i>Phocoenoides dalli</i>).
Others		3.50	TL was a substitute for that of Japanese squillid mantis shrimp (<i>Oratosquilla oratoria</i>) with reference to Nakashima et al. (2007).

Table 2. Categories of commercial fisheries off Tohoku, Japan and their main target species used in the Miyagi Prefecture fishery statistics from 1952 to 2011. See Kaneda (2005) for detailed description of the Japanese fishing methods.

Fishery category	Method of fishing	Main target species
Surrounding net	Fish are encircled with netting gear and gradually tightens until they are bagged. Large and medium purse seine fishery are the main types of fishery in this category.	Mackerels, Japanese sardine, skipjack tuna, Yellowfin and other tunas, Japanese anchovy
Trawl	A trawl net is towed by vessels. Demersal Off-shore trawl and Small scale trawl are the main types of fishery in this category.	walleye pollock, Flounders, Japanese flying squid, Pacific cod, Broadbanded thornyhead
Boat seine	A seine net composed of two wing nets with a cod end towed by a vessel. Midwater Pulling net and demersal Drag net are the main types of fishery in this category.	Pacific krill, Japanese sand lance, Sakhalin surf clam, shrimps
Lift net	Square, round, trapezoid or bag-like nets are set in the sea and lifted carefully after fish schools are attracted into or above the nets by light. Saury stick-held dip net and Japanese sand lance dip net are the main types of fishery in this category.	Pacific saury, Japanese sand lance, Pacific krill
Gillnet	Fish are gilled or entangled in a long wall of net (nylon monofilament or multifilament net in recent years) set vertically in the water.	Pacific herring, squids, salmon
Trap net	A large net (pound net) fixed in a certain area of water. The net is equipped with fish herding and retaining devices.	Mackerels, Japanese sardine, salmon, Japanese anchovy
Hook and line	Angling gear with hooks and lines and attracts the fish by bites or lures. Skipjack pole and line and Squid jigging are the main types of fishery in this category.	skipjack tuna, Japanese flying squid, albacore, neon flying squid
Other	Other fisheries include harpoon fishery, hook fishery, spear fishery with water glass, beach seine fishery, brush weir fishery, trap fishery, diving apparatus fishery, clip and twist fishery etc. Some fisheries listed above were aggregated into this category in some years.	striped marlin, swordfish, horse mackerels, mullets, Japanese sand lance, octopuses, Dall's porpoise, abalones, Sakhalin surf clam, clams, sea cucumber, sea urchin, kelps, brown algae, gelidacean algae

Fig. 1.

Fig. 2

Fig.3

Fig. 4

Fig. 5

Fig. 6