# Effects of Hypoxia on Principal Prey and Growth of Flathead Flounder Hippoglossoides dubius in Funka Bay, Japan

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Effects of hypoxia on principal prey and growth of flathead flounder *Hippoglossoides dubius* in Funka Bay, Japan

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ABSTRACT: Effects of hypoxia on the principal prey and growth of flathead flounder *Hippoglossoides dubius* were studied in Funka Bay. Of the three dominant year-classes that occurred in recent years, the 1995 year-class was small in total length at age ≥ 3 and low in condition factor at age ≥ 2. Ophiuroids (almost *Ophiura sarsi*), which were the dominant prey in the 1980s, were of little importance and instead, crustaceans such as mysids, natant decapods and pelagic amphipods, bivalves and fish were important prey items for *H. dubius* in 2000–2001. In addition, the feeding intensity of *H. dubius* in 2000–2001 was lower than that in the 1980s. These facts are closely related to a reduction of prey abundance, particularly ophiuroids. It seems that the hypoxia that occurred in the central part of the bay during the summer and autumn of 1995–1997 caused the poor food supply and low growth rate at ages 2–4 of the 1995 year-class.

KEY WORDS: condition factor, feeding, flathead flounder, Funka Bay, growth, *Hippoglossoides dubius*, hypoxia, ophiuroids.

INTRODUCTION

Hypoxic events affect the existence of many sea animals seriously.¹⁻³ Many studies have been conducted on the survival times of marine benthos under hypoxic conditions (e.g. Vetter et al.⁴). In recent years, the effects of hypoxia on growth, feeding and metabolism have been reported by several authors, for example in fish, Atlantic cod *Gadus morhua*,⁵ mudskippers *Boleophthalmus boddarti* and *Periophthalmodon schlosser*⁶,⁷ and sole *Solea solea*,⁸,⁹ and also in ophiuroid *Amphiura filiformis*,¹⁰,¹¹ bivalves *Crassostrea virginica*¹² and *Mytilus edulis*,¹³ white shrimp *Penaeus setiferus*¹⁴ and polychaete *Capitella sp.*¹⁵ These studies are based upon only the results of the laboratory experiments.

Some field studies (e.g. Imabayashi,¹⁶ Kikuchi,¹⁷ Pearson *et al.*,¹⁸ Josefson and Widbom,¹⁹ Furota*²⁰*) demonstrated the reductions of biomass and abundance in benthos assemblages in the areas with low oxygen concentrations. As for fish, Pihl,*²¹* and Baden* et al.*²⁴ reported that some demersal fish species left the areas with low oxygen concentrations and changed diet. However, there are few studies on a change in growth caused by reduced oxygen concentration.³

In Funka Bay, Hokkaido, bottom water with an oxygen concentration of ≤ 1.5 mL/L had not been observed until the 1980s.²⁰ However, severe hypoxia (0.6–1.1 mL/L) occurred in the central part of the bay during the summer and autumn of 1995–1997,²⁷ and the abundances of flathead flounder *Hippoglossoides dubius* and coonstripe shrimp *Pandalus hypsinotus* decreased drastically in the hypoxic area.²⁸

*Hippoglossoides dubius* is the main component in the demersal fish community and is an important fishery resource in Funka Bay. For this reason, many investigations have been conducted on distribution and annual life cycle,²⁹⁻³¹ food habits,²²,²³ age and growth,²⁴ food organisms,²³,²⁵ and annual change in year-class strength.²⁶ However, no information is available on the effects of hypoxia on the biological production of *H. dubius*. The purpose of the present paper is to estimate the effects of a hypoxic event on the principal prey and growth of *H. dubius* in Funka Bay.
MATERIALS AND METHODS

Study area

Funka Bay is located at the south-western part of Hokkaido, and is a semi-enclosed inner bay with a basin with a maximum depth of 96 m (Fig. 1). The characteristics of hydrographic conditions are as follows: in spring, the Oyashio Coastal Water (1–3°C, 33.0–33.3‰o) flows into the bay and stagnates during summer. The intrusion of the Tsugaru Warm Water (≥26°C, ≥33.8‰o) occurs in autumn and stagnates during winter. The annual bottom water temperatures in the basin range from 2°C to 10°C.36-39 The silt (Md< 6) accumulates in the greater part of the bay and the distribution of sand–gravel is limited to off Muroran.40 In recent years, the progress of eutrophication in the central part of the bay has been suggested.41

Sampling and data analysis

Sampling and data analysis

Samplings were conducted using R/V Ushio-Maru of Faculty of Fisheries, Hokkaido University in the daytime (09:00–16:30) from August 1993 to November 2001 in Funka Bay (Table 1; Fig. 1). Hippoglossoides dubius were collected with a 24-m otter trawl net (cod end liner of 12 mm mesh). The trawl net was towed at speeds of approximately 3 knots for 15 min on the sea bottom at each sampling station. Collections of benthic invertebrates were conducted with a sledge net using a 1-m x 1.5-m frame (cod end mesh of 3 mm) in June and October–November 2000 and May 2001. The sledge net was towed at speeds of approximately 2 knots for 1.5–5 min on the sea bottom. The samples were washed onto a 3-mm aperture sieve screen on the ship, and retained fractions were fixed in 10% buffered formalin seawater. After August 2000 the water samples at approximately 0.3 m above the

Table 1  Samples of Hippoglossoides dubius and benthic invertebrates

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Station no.</th>
<th>No. fish</th>
<th>Station no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 Aug.–2 Sep. 1993</td>
<td>22, 30</td>
<td>263</td>
<td>18, 24, 26, 27, 29, 30, 31, 33</td>
</tr>
<tr>
<td>3–5 Oct. 1994</td>
<td>29, 30</td>
<td>277</td>
<td>18, 24, 26, 27, 29, 30, 31, 33</td>
</tr>
<tr>
<td>29–30 Aug. 1995</td>
<td>29, 30</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>26–28 Aug. 1996</td>
<td>23, 24, 29, 30, 31</td>
<td>606</td>
<td></td>
</tr>
<tr>
<td>27–28 Aug. 1997</td>
<td>23, 24, 29, 30, 31</td>
<td>1051</td>
<td></td>
</tr>
<tr>
<td>26–27 Aug. 1998</td>
<td>24, 29, 30, 31</td>
<td>525</td>
<td></td>
</tr>
<tr>
<td>1 Sep. 1999</td>
<td>29, 30</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>29–30 June 2000</td>
<td>–</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>22–24 Aug. 2000</td>
<td>24, 29, 30, 31, 33</td>
<td>783</td>
<td>18, 23, 24, 26, 27, 29, 30, 31, 33</td>
</tr>
<tr>
<td>17 Oct.–2 Nov. 2000</td>
<td>24, 30, 31, 33</td>
<td>233</td>
<td>18, 23, 24, 26, 27, 29, 30, 31, 33</td>
</tr>
<tr>
<td>12–14 Mar. 2001</td>
<td>30, 33</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>28–30 May 2001</td>
<td>30, 33</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>31 Oct.–2 Nov. 2001</td>
<td>24, 30, 31, 33</td>
<td>930</td>
<td></td>
</tr>
</tbody>
</table>

1Sampled with an otter trawl net.  
2Sampled with a sledge net.
Effects of hypoxia on flathead flounder

The feeding intensity was estimated from stomach weight (g) and SCI, where SCI is the stomach contents weight (g) after thawing. The age was determined from the annuli of otolith, according to Nakatani et al. Stomachs of _H. dubius_ collected from August 2000 to May 2001 were excised and preserved in 10% buffered formalin solution. All food organisms in the stomachs and sledge net samples were identified to the lowest taxon possible, counted and wet weighed (nearest 0.01 g). For comparison of data by fish sizes, we divided the sampled _H. dubius_ into four length groups: ≤200 mm, 201–250 mm, 251–300 mm and ≥301 mm total length. Diets were analyzed in terms of numerical composition (%N), weight composition (%W) and frequency of occurrence (%F):

\[
\%N_i = n_i \times 10^2 / \sum_{i=1}^{n} n_i
\]

\[
\%W_i = w_i \times 10^2 / \sum_{i=1}^{n} w_i
\]

\[
\%F_i = f_i \times 10^2 / \sum_{i=1}^{n} f_i
\]

where \(n\) is the total number of prey items found in a unit, \(n_i\) and \(w_i\) are the number and total wet weight of prey items \(i\) in a unit, respectively, and \(f_i\) is the number of _H. dubius_ stomachs containing prey items \(i\) in a unit. Based on these indices, the percentage of index of relative importance (\(\%IRI\)) was calculated for each prey item as follows:

\[
\%IRI_i = (\%N_i + \%W_i) \times \%F_i
\]

\[
\%IRI_i = IRI_i \times 10^2 / \sum_{i=1}^{n} IRI_i
\]

Because the body weight of _H. dubius_ is approximately proportional to the third power of total length in both sexes, Fulton's condition factor (\(K\)) was calculated to estimate the nutritive conditions. The feeding intensity was estimated from stomach contents index (SCI):

\[
K = BW \times 10^5 / TL^3
\]

\[
SCI = SCW \times 10^2 / BW
\]

where TL is the total length (mm), BW is the body weight (g) and SCW is the stomach contents weight (g). The \(K\) was calculated for the samples collected from late August to early September in each year. Gonads of male and female _H. dubius_ during this period were approximately <1% of the body weight. The diet composition and feeding intensity were examined for the samples taken from the central part of the bay where hypoxia occurred in 1995–1997, and TL and \(K\) were examined for the samples from more extensive areas (Fig. 1). To compare the growths of each year-class, the samples collected chiefly from late August to early September were used. Although in 1994 and 2001 the samples collected in early October and late October–early November were used, respectively, no correction was conducted.

One-way ANOVA was used to test for significant differences in TL and \(K\) among year-classes. When a significant difference was found among three year-classes, multiple comparisons were made between two year-classes by Scheffe's test. Temporal and spatial changes in prey abundance were determined through a two-way ANOVA. Prey abundance data were log-transformed \([\log(x + 1)]\) prior to analysis.

### Results

The majority (89%) of 5697 _H. dubius_ collected from 1993 to 2001 were composed of three year-classes (1989, 1991 and 1995). The mean TL values of the 1995 year-class were significantly smaller than those of the 1989 and 1991 year-classes at ages 2–6 in both sexes (\(P<0.01\) in all cases; Fig. 2). However, its difference was approximately constant after age 4. Conversely, the mean TL values at age 2 of the 1995 year-class were significantly larger than those of the 1991 year-class (\(P<0.05\) for male, \(P<0.001\) for female). The mean condition factors (K-value) of the 1995 year-class were significantly lower than those of the other two year-classes at ages 2–5 in both sexes (\(P<0.01\) in all cases; Fig. 3).

The diet compositions of _H. dubius_ collected from August 2000 to May 2001 are shown in Fig. 4. The principal prey items of fish ≤200 mm TL varied among months, and the principal prey items were natant decapods (chiefly _Eualus macilenta_), fish (chiefly pricklyback _Antisarchus macrops_ and young walleye pollock _Theragra chalcogramma_), a bivalve _Portlandia japonica_ and a pelagic amphipod _Themisto japonica_. The \(\%IRI\) of fish and _P. japonica_ tended to increase with the size of _H. dubius_. The \(SCI\) was very low from August 2000 to May 2001 in both sexes (median value: 0–0.23 for male, 0–0.17 for female; Fig. 5).

Figure 6 shows the horizontal distributions of _Ophiura_ spp., _P. japonica_ and natant decapods from June 2000 to May 2001. The abundance of
**DISCUSSION**

The abundance of *H. dubius* in Funka Bay fluctuates remarkably among year-classes, and in recent years three dominant year-classes (1989, 1991 and 1995) occurred. Of these three year-classes, the fish born in 1995 when severe hypoxic water occurred were smallest in total length (Fig. 2) and lowest in condition factor (Fig. 3). The average size of American plaice *Hippoglossoides platessoides* in...
Grand Bank became smaller when the fish abundance increased.44 In the present study, however, the catch per unit effort (CPUE: the number of fish per 15-min tow) of *H. dubius* in 1993–2000 did not vary widely. Namely, the mean CPUE (±SD) in the central part of the bay and nearby waters from late August to early September was less variable, ranging from 126.8 ± 73.1 fish/tow in 1998 to 236.7 ± 208.4 fish/tow in 1993, except for 1995 (81.7 ± 126.1 fish/tow).28 In addition, the total length at age 2 of the 1995 year-class was larger than that of the other year-class (1991; Fig. 2). From these facts, it cannot be considered that the tardy growth of the 1995 year-class is due to the high population density of *H. dubius*.

According to Yokoyama et al. the *H. dubius* in Funka Bay consumed chiefly ophiuroids, fish, mysids and natant decapods in 1985–1986. In particular, ophiuroids were the most important prey for both the small- (<200 mm TL) and large-sized fish (>200 mm TL) through the year.33,35 A similar situation was observed in 1982–1983.45 However, *H. dubius* in 2000–2001 fed chiefly on mysids, fish, natant decapods, *T. japonica* and *E japonica*, and the relative importance of ophiuroids was very low except for fish of ~200 mm TL in May 2001 (Fig. 4; Table 2). In south-east Kattegat, Sweden, hypoxia changed the food supply for Atlantic cod and plaice *Pleuronectes platessa*, and their principal prey changed from crustaceans and molluscus to polychaetes and ophiuroids (chiefly *Amphiura filiformis*). This dietary shift decreased the nutritional value of the food taken and decreased the average size of fish.21 It is known that *A. filiformis* have high tolerance to hypoxia.46 In the present study the principal prey of *H. dubius* changed from ophiuroids (a low energy content)35 to crustaceans and bivalves (a high energy content).35,47 But the feeding intensity during the active feeding season (peak, May–July) in 2000–2001 was low compared with that in the 1980s. Namely, the proportion of *H. dubius* having a low SCI (<0.5) from mid-May to August was approximately 50% in 1985–1988 (sampling time: 10:00–15:00),31 while that in 2000–2001 were 65–77% for both sexes (Fig. 5). In addition, the mean SCI values in 2000–2001 (0.3–1.0, male; 0.8–0.9, female) were low as compared with those in 1985–1988 (0.5–0.9, male; 0.7–1.6, female).31 Yokoyama reported that most of the *Ophiura* spp. consumed by *H. dubius* was ≤7 mm in disk dia-

![Table 2 Comparisons of principal food of *Hippoglossoides dubius* in Funka Bay between 1985–1986 (Yokoyama et al.33) and 2000–2001](image-url)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct.–Nov.</td>
<td><em>Ophiura</em> spp. and Pisces</td>
<td>Mysidacea, Decapoda natantia and <em>Portlandia japonica</em></td>
</tr>
<tr>
<td>Feb.–Mar.</td>
<td><em>Ophiura</em> spp., Mysidacea and Decapoda natantia</td>
<td>Mysidacea and Pisces</td>
</tr>
<tr>
<td>May</td>
<td><em>Ophiura</em> spp. and Pisces</td>
<td><em>Ophiura</em> spp., <em>Themisto japonica</em> and <em>Portlandia japonica</em></td>
</tr>
</tbody>
</table>

Fig. 4 Diet compositions of *Hippoglossoides dubius*, by size group of fish and month, expressed as percentage of index of relative importance (%IRI) for prey items. *n*, number of stomachs examined.
Although the data of ophiuroids in 2001 contained all individuals collected, the abundance was very low in the central part of the bay and nearby waters. 28 The low condition factor at age 2 of the 1995 year-class (Fig. 3) is probably related to a dietary change from demersal plankton to benthos including ophiuroids in addition to habitat shift to the central part of the bay. As aforementioned, an apparent reduction of growth was not found in both the 1989 and 1991 year-classes after the hypoxic event in 1995. Although there is no available information on the diets of H. dubius in the 1990s, the majority of fish of the two aforementioned year-classes grew up to 200 mm TL or more at age 5, although the condition factors were low (Figs 2, 3). This indicates that the reduced abundance of benthic animals (chiefly ophiuroids) strongly affected the 2–4-year-old fish.

It is known that the abundances of ophiuroids and most of the crustaceans, gastropods and bivalves decrease drastically in hypoxic events. For example, in Amakusa-Tomoe Bay ophiuroids and sea urchin Echinocardium cordatum disappeared, and the number of species of bivalves and gastropods decreased. 17 Also, in Hiuchi Nada on the Seto Inland Sea, crustaceans such as gammarids decreased in the number of species and abundance. 16 A similar fact was also reported from Tokyo Bay: Crangon affinis and Ophiura kinbergi were not collected under oxygen concentration ≤1 mg/L (–0.7 mL/L). 20 Maita and Yanada reported that bottom water with oxygen concentration ≤2.0 mL/L did not occur in the bay from 1998 to 2001 (Table 3). 49–51 However, the abundance of ophiuroids was still low in 2000–2001, except for off Mori (Fig. 6). Most ophiuroids continue to grow for periods of 8 years at least, and probably for 10 or 15 years, and O. sarsi barely reach half their maximum size over a 2–4-year period. 22 It seems likely that the tardy recovery of ophiuroid abundance in the bay is related to their long life cycle.

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**Fig. 5** Frequency distributions and medians (▼) of stomach contents index (SCI) of Hippoglossoides dubius. E%, percentage of empty stomachs; n, number of stomachs examined.
Effects of hypoxia on flathead flounder

**FISHERIES SCIENCE**

May 2001

Abundance (inds./100m²)

- $\leq 10$
- 30
- 100
- 300
- 1000

**Fig. 6** Spacial distributions of *Ophiura* spp., *Portlandia japonica* and natant decapods collected with a sledge net.

**Table 3** Dissolved oxygen concentration (DO) near the bottom in the central part of Funka Bay

<table>
<thead>
<tr>
<th>Date</th>
<th>Station no.</th>
<th>DO (mL/L)$^t$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 July 1995</td>
<td>30</td>
<td>0.58</td>
<td>Maita$^{45}$</td>
</tr>
<tr>
<td>23 Aug. 1996</td>
<td>30</td>
<td>0.91</td>
<td>Maita$^{46}$</td>
</tr>
<tr>
<td>4 Oct. 1997</td>
<td>30</td>
<td>1.07</td>
<td>Maita$^{46}$</td>
</tr>
<tr>
<td>28 Aug. 1998</td>
<td>30</td>
<td>2.67</td>
<td>Maita$^{50}$</td>
</tr>
<tr>
<td>29 Sep. 1999</td>
<td>30</td>
<td>3.29</td>
<td>Maita$^{50}$</td>
</tr>
<tr>
<td>23 Aug. 2000</td>
<td>33</td>
<td>2.52</td>
<td>Present study</td>
</tr>
<tr>
<td>27 Aug. 2001</td>
<td>33</td>
<td>2.4</td>
<td>Yanada$^{51}$</td>
</tr>
</tbody>
</table>

$^t$Lowest values observed in each year are shown.

**ACKNOWLEDGMENTS**

We would like to thank the captain and crew of the R/V Usagi-Maru for their help with data collection. We also thank T Sekigawa, A Satou, Y Suzuki, H Izumi and Y Tanaka (Hokkaido University) for their cooperation during the field surveys and data processing. The present study was supported, in part, by The Hokusui Society Foundation.

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