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Occurrence, distribution and prey items of juvenile marbled sole *Pseudopleuronectes yokohamae* around a submarine groundwater seepage on a tidal flat in southwestern Japan

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ABSTRACT

Occurrence, distribution and prey items of juvenile marbled sole *Pseudopleuronectes yokohamae* were investigated around a submarine groundwater seepage on a tidal flat in southwestern Japan. Spatial distribution of radon-222 (^{222}Rn) concentration in water showed more submarine groundwater seepage in the offshore area. The lower salinities at offshore sampling stations corresponded with the highest ^{222}Rn concentrations. Juvenile marbled sole were collected from March through June with seasonal peak in April in 2013 and 2014. Mean abundance of juvenile marbled sole was highest at the second most offshore station where high submarine groundwater seepage was indicated. Major prey items in the stomachs of the marbled sole at the post-settlement stage (10–40 mm) were small crustaceans such as cumaceans and gammarids, which were partially replaced with polychaetes in larger juveniles (40–50 mm). Abundance of these major prey items was also higher at offshore stations. A negative correlation between gammarid abundance and salinity indicated a higher concentration of gammarids around the area of high submarine groundwater seepage, a pattern not observed for the other major prey organisms. Stable isotope analysis showed greater dependence of post-settlement stage marbled sole on the small crustaceans with low δ^{13}C indicating that nutrients of terrestrial origin contribute to production of the juvenile marbled sole on the tidal flat.

1. Introduction

Variability in freshwater supply affects biological production of aquatic ecosystems (e.g. Burnett et al., 2003; North and Houde, 2003; Valiela et al., 1990). Freshwater provided from terrestrial to coastal areas can be divided into surface water (river water) and groundwater. There have been far more studies on how the variability in surface water affects fisheries production in aquatic ecosystems than the groundwater supply (Hwang et al., 2005; Miller and Ullman, 2004; Sanders et al., 2011). In several recent studies, groundwater discharge has been estimated to approximate or even exceed 50% of total freshwater input to a bay (Valiela et al., 1990; Slomp and van Cappellen, 2004). In addition, in a temperate bay, a high contribution of nutrients (e.g. 65% of total dissolved inorganic phosphorus provided through all freshwater) was provided through submarine groundwater, which is higher in nutrients, especially phosphorus (Sugimoto et al., 2015). High levels of submarine groundwater seepage have been shown to correspond with elevated primary production in coastal waters of the world (Hwang et al., 2005; Miller and Ullman, 2004; Sanders et al., 2011; Sugimoto et al., 2015). To date, however, there is still limited information on the effects of submarine groundwater on higher trophic levels such as secondary consumers (Sanders et al., 2011).

Generally, migratory fishes are able to visit multiple ecosystems and/or areas for feeding and therefore it is difficult to quantify the relative contribution of each ecosystem or area to their productivity. Evaluation of the contribution of each ecosystem or area to fish production would be easier in fish species that are more localized in their distribution and/or feed only within one area.

The marbled sole *Pseudopleuronectes yokohamae* is widely distributed in coastal waters in the western North Pacific and is more dependent on shallow waters during the juvenile stage than other flatfish species in the region (Minami and Tanaka, 1992; Nakabo and Doiuchi, 2013). Juvenile marbled sole settle at about 10 mm total length (TL) in shallow waters (<10 m in depth) and feeds mainly on crustaceans and polychaetes for a couple of months before leaving for deeper waters at 80–100 mm in TL (Takahashi et al., 1987). High tolerance to low salinity conditions has been observed in a laboratory experiment (Wada et al., 2007, 2011) and aggregation around an area with submarine groundwater seepage has been reported in nature (Ito and Nakagawa, 2002). Therefore, dependence on organic and inorganic matter of terrestrial origin is expected to be highest during their early life history. However, there is

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no information on the occurrence, distribution and feeding habits of juvenile marbled sole around areas of submarine groundwater seepage.

In the present study, sampling for juvenile marbled sole was coupled with surveys of environmental conditions in order to identify an area with submarine groundwater seepage. The spatial distribution of juvenile marbled sole was examined in relation to that of the submarine groundwater seepage. Change in contribution of nutrients of terrestrial origin with size of juveniles was evaluated through analyses of juvenile stomach contents and stable isotope ratios.

2. Materials and methods

2.1. Field survey

Physical and biological surveys were conducted in shallow waters off Takehara City, Hiroshima, southwestern Japan (Fig. 1). Kamo River runs southward into the Seto Inland Sea. Tidal amplitude is approximately 4 m during spring tides in this area. In order to detect submarine groundwater seepage, spatial variability of Radon-222 (^{222}Rn) concentration was investigated in the survey area twice (on 24 Sep. 2013 and 23 May 2014) using the radon detector (RAD7, Durridge). Radon-222 (^{222}Rn) is a naturally occurring radioactive gas and a powerful tracer of groundwater inputs to oceans. The ^{222}Rn concentration is typically 2–3 orders of magnitude higher in groundwater than surface waters (Church, 1996; Kim et al., 2005). Therefore, high ^{222}Rn concentrations in coastal waters indicate relatively high groundwater seepage within a surveyed area.

We applied the multidetector method (Dulaiova et al., 2005) in 2013 and the dual-loop method (Dimova et al., 2009) in 2014 for continuous ^{222}Rn measurements at a ship velocity of about 1.0 knot during flood tide with water depths between 1.5 and 4.0 m with an interval of 2 min for each measurement, a depth of 1 m (from the surface) for water pumping, and a pumping rate of >5 L min^{-1}. Average values of the ^{222}Rn (in 2013 and 2014) and chlorophyll-a (only 2014) concentrations for every 120 s were calculated and then processed for mapping a contour plot. Count uncertainties of ^{222}Rn measurements in 2013 and 2014 were approximately 35% and 20%, respectively. Chlorophyll-a concentration was measured using a calibrated chlorophyll sensor (Cyclops-7, Tuner Designs). Temperature and salinity were simultaneously measured at 30 second intervals using the conductivity and temperature logger (INFINITY-CT, JFE Advantech).

Samples of juvenile marbled sole and their prey organisms were taken at intervals of about two weeks from 24 Mar to 26 May 2013 and 20 Feb to 11 July 2014. Juvenile marbled sole were collected with a scoop net (0.4 × 0.3 m mouth, 3 mm mesh) for stomach contents and stable isotope analysis in 2013 and 2014. Based on high ^{222}Rn concentrations associated with the initial survey for submarine groundwater seepage on 24 Sep 2013, six sampling stations were set at 50 m intervals in the western area outside the river mouth of the Kamo River (Fig. 1). In 2014, a push-net (1.5 m width, 0.3 m height and 3 mm mesh) was used to collect additional samples and estimate fish abundance. Juvenile sampling with the scoop net was conducted by four people for two hours around the low tide. The push-net was pushed at a velocity of 2.0 m s^{-1} for 50 m by two people at each sampling station during the two hours before and after low tide. In 2014, epibenthic invertebrates were sampled by towing a sledge-net (0.4 m width, 0.3 m height and 0.3 mm mesh) for 20 m at a velocity of 1.0 m s^{-1} and infaunal invertebrates were collected with a core sampler (15 cm diameter and 10 cm depth) at each station. Fish samplings were conducted prior to the invertebrate sampling in order to minimize sampling bias (effect on fish distribution).

Fish samples were preserved on ice, and the epibenthic and infaunal invertebrates were preserved in 10% seawater formalin. Water temperature and salinity were measured at each collection. All samples were taken during daytime while the water depth at each sampling station was 0.3–0.9 m. Additional samples for juveniles were collected by the

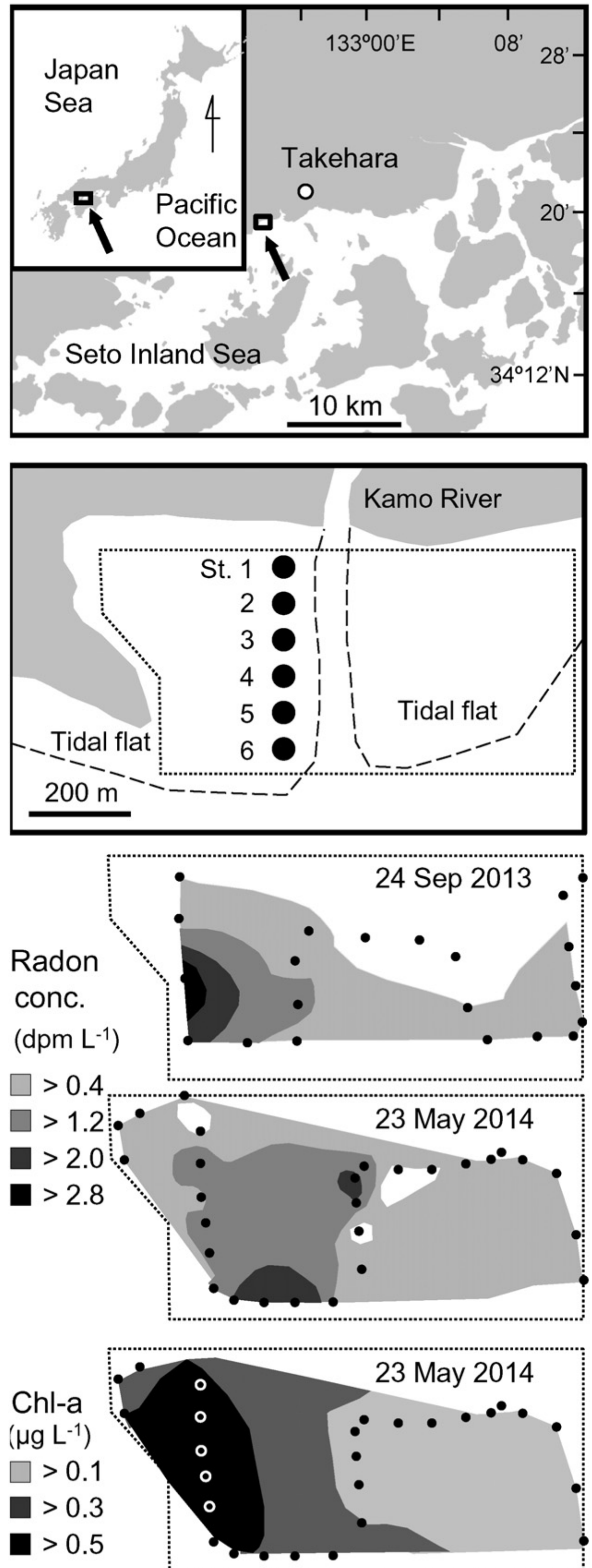

Fig. 1. Maps showing the location of the study site where physical and biological surveys were conducted in 2013 and 2014. Solid circles in the middle panel show the six sampling stations where juvenile fish and invertebrates were collected. Tidal flats are indicated by broken lines. Dotted lines show the area of survey for radon-222 (^{222}Rn) concentration. Lower panels are contour plots of the ^{222}Rn concentration observed on 24 September 2013 and 23 May 2014 and chlorophyll-a (Chl-a) concentration on 23 May 2014. Closed circles on the contour plots show locations where radon and chlorophyll concentrations were measured.