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Higher species richness and abundance of fish and benthic invertebrates around submarine groundwater discharge in Obama Bay, Japan

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ABSTRACT

Study focus: There have been far more studies on how the variability in surface water discharge affects production of animal communities in aquatic ecosystems while less information has been accumulated on the mechanisms of how the groundwater supply works.
Study region: Physical and biological surveys were conducted to test the hypothesis that high level of submarine ground water discharge enhances species richness, abundance and biomass of fishes and invertebrates in coastal waters of Obama Bay, Japan, where a high contribution of nutrients (ca. 65% of phosphorus) to total provided through all freshwater has been reported. Survey for horizontal distribution of radon-222 (^{222}Rn) concentration showed high levels of submarine groundwater discharge in the west part of survey area. Fish and invertebrate communities were compared within a relatively small spatial scale (ca. 100 m) in relation to level of submarine groundwater discharge.
New hydrological insights: Species richness, abundance and biomass of fishes and abundance and biomass of turban snail and hermit crab were significantly higher in the area with high ^{222}Rn concentration. Abundance of gammarids, the most major prey item of the fishes, was 18 times higher in the area with high ^{222}Rn concentration. Since the turban snail, hermit crab and gammarids feed on producers (phytoplankton and benthic microalgae), submarine groundwater are concluded to increase species richness and production of fishes and invertebrates through providing nutrients and enhancing primary production.

1. Introduction

Increase in freshwater supply can enhance biological production and species diversity in coastal ecosystems though providing nutrients (Burnett et al., 2003; Crecco and Savoy, 1984; North and Houde, 2003; Okazaki et al., 2005; Shoji et al., 2006; Valiera et al., 1990). Freshwater which runs from the terrestrial area to coastal water is composed of surface water

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and groundwater. There have been far more studies on effects of the variability in surface water on biological production in aquatic ecosystems while information on the mechanisms of how the groundwater supply affects the production process is very limited (Hwang et al., 2005; Miller and Ullman 2004; Sanders et al., 2011; Valiera et al., 1990). In general, submarine groundwater is more abundant in nutrients than surface water. A recent study in a temperate bay in Japan showed a high contribution (ca. 65% of total) of phosphorus provided through submarine groundwater to total (provided through all freshwater: Sugimoto et al., 2015). In addition, temperature of submarine groundwater is more stable throughout year than waters in surrounding coastal area. Therefore, spatial and temporal variabilities in submarine groundwater discharge are expected to affect biological production and community structures of plants and animals in the coastal area. High levels of submarine groundwater discharge have been shown to correspond with elevated primary production in coastal waters of the world (Hwang et al., 2005; Sanders et al., 2011). However, there is still limited information on the effects of submarine groundwater on animals at higher trophic levels (primary and secondary consumers) in coastal ecosystems (Miller and Ullman, 2004). Biotic and abiotic properties of submarine groundwater such as nutrient concentrations and temperature would directly and indirectly influence distribution and abundance of primary and secondary consumers through effects on organisms at lower trophic levels. Clarifying the mechanism how submarine groundwater discharge affects biodiversity and biological production can contribute to comprehensive understanding of the interactions among the water and major ecosystem services such as food and energy (The water-food-energy nexus: Taniguchi et al., 2013) in coastal ecosystems that provide highest ecosystem services in the world's ecosystems (Costanza et al., 1997).

In the present study, physical and biological surveys were conducted in Obama Bay in order to test the hypothesis that submarine groundwater discharge increases species richness and production of fish and invertebrate community (primary and secondary consumers). Horizontal distribution of radon-222 (^{222}Rn) was examined to understand spatial variability of submarine groundwater discharge in the survey area. Two sampling stations were fixed according to results of the survey for horizontal distribution of ^{222}Rn for comparison of animal community in relation to submarine groundwater discharge within a fine spatial scale (about 100 m). Stomach contents analysis of fishes was conducted to understand the major trophic flows. Number of species, abundance and biomass of fishes and epibenthic invertebrates including the major prey items of the fishes were compared between the two stations.

2. Site description

Obama Bay is a semi-enclosed embayment located north coast of mid Japan (Fig. 1). The bay has a surface area of 58.7 km^2 and a volume of 0.74 km^3. Maximum depth of the bay is 35 m with a mean depth of about 13 m. The tidal range is <0.2 m (Isobe and Aihara, 1976). Annual precipitation around the region is >2000 mm, most of which occurs during the summer (rainy season) and winter (snowy season). There are abundant groundwater resources in the basin around Obama City, which contains more than 100 flowing artesian wells near the coast.

In 2013, survey for seasonal change in submarine groundwater discharge (SGD) and associated nutrient fluxes by the use of ^{222}Rn and salinity mass balance model was conducted. The SGD rates estimated show a large intra-annual variability of 0.05×10^6 to 0.77×10^6 m^3 d^{-1} (Sugimoto et al., 2015). The highest SGD fraction (>40%) in total terrestrial freshwater fluxes was estimated to occur in summer rainy season due to low discharge of surface river water. Nutrient fluxes from the SGD were about 42%, 65%, and 33% of all terrestrial fluxes of dissolved inorganic nitrogen, phosphorous, and silicate. Phosphorous-enriched nutrient transport through SGD is suggested to enhance biological production of Obama Bay since primary production is restricted by phosphorous (Sugimoto et al., 2015).

3. Methods

3.1. Radon-222 measurements

Physical and biological surveys were conducted in shallow waters in east part of Obama Bay (Fig. 1). Prior to biological survey, spatial variability of ^{222}Rn concentration was investigated at 13 stations on 22 July 2014 using the radon detector (RAD7, Durridge Co.) in order to detect submarine ground water discharge in the survey area. ^{222}Rn is a powerful tracer of groundwater inputs to oceans that is a naturally occurring radioactive gas and is typically 2 – 3 orders of magnitude higher in groundwater than surface waters (Church, 1996; Kim et al., 2005; Taniguchi et al., 2002). Glass bottles (3500 mL) of bottom water kept in an isothermal bath at 25 °C were aerated for 45 min via a closed-air loop using the Big-Bottle RAD H_2O system (Durridge Co.: De Simonea et al., 2015), an accessory for the RAD7 that allows higher-sensitivity ^{222}Rn measurement. After air-water equilibrium was established, the equilibrated air was measured by the RAD7 with at least six runs of 15 min, and the results were averaged. All samples were analyzed immediately after collection, and the decay effect was corrected using the ^{222}Rn decay constant ($\lambda_{222} = 0.181$ d^{-1}) and time elapsed after collection. Count uncertainty of ^{222}Rn measurements was less than 20%. According to the results from the ^{222}Rn measurements (see the results), two stations (sts. 1 and 2: Fig. 1) were fixed in order to compare species richness and abundance of fish and benthic invertebrates between areas with high and low submarine groundwater discharge within a relatively short distance (ca. 100 m).

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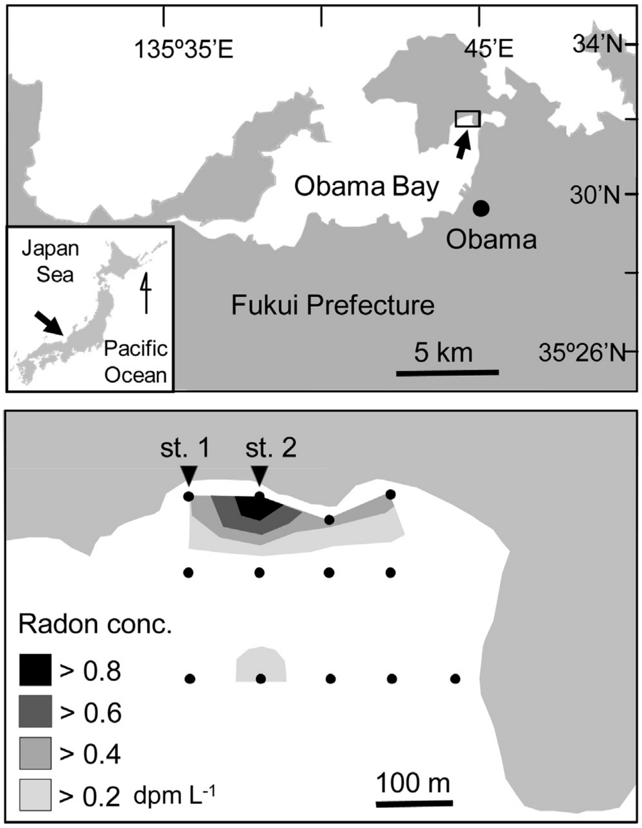

Fig. 1. Maps showing study site in eastern part of Obama Bay, Fukui Prefecture, mid Japan, where physical and biological surveys were conducted in 2014. Closed circles in the lower panel show the thirteen stations where radon-222 (^{222}Rn) concentration was measured on 22 July 2014, prior to biological survey. Contour plot shows results of the survey for ^{222}Rn concentration. Biological survey were conducted on 27 July 2014 at two stations (St. 1 and 2 with low and high ^{222}Rn concentration, respectively) to compare abundance of fish and benthic invertebrates between the two stations.

3.2. Biological survey

Sampling for fish and benthic invertebrates were conducted on 27 July 2015 at the two stations in the east part of Obama Bay. Fish were collected by a 15-m tow at a velocity of 1.0 m s^{-1} with a seine net (2.0 × 1.0 m, 2 mm mesh with 1 mm mesh cod-end). This net was towed at four separate locations around each sampling station.

Epibenthic invertebrates were sampled by a 20-m tow at a velocity of 1.0 m s^{-1} with a plankton net (0.4 m width, 0.3 m height and 0.3 mm mesh) at each station. In addition, larger shellfishes and hermit crabs were collected by the use of a quadrat (0.25 × 0.25 m). These epibenthic invertebrate samplings were conducted at four separate locations around each sampling station.

Fish and epibenthic invertebrate samples were preserved in 10% seawater formalin. Water temperature and salinity were measured at 15 min intervals from 11:00 to 15:00 with a multiple data logger (HOBO U-24-001, Onset Computer Coop.) equipped on sea bottom (water depth, 1 m) at each station.

3.3. Laboratory procedure

Fish were sorted and identified, then measured for total length to the nearest 0.1 mm and wet weight to the nearest 0.01 g. Fish abundance was expressed as number of individuals 30 m^{-2} based on the area covered by the seine net sampling. In order to understand the feeding habits, fish samples were processed for stomach content analysis. Stomach contents were removed from the fish body and were identified under a dissecting microscope. Body parts of the prey items were measured in order to estimate the dry weight according to length-weight equations for each prey species. Stomach content compositions (% in dry weight) were calculated for each fish species.

According to the results from the stomach content analysis, abundance of major prey items (gammarids and copepods) of the fishes was calculated as number of individuals 1 m^{-2} based on the area covered by the plankton net sampling. Among the larger epibenthic invertebrates, abundance and biomass (wet weight without shell part) of two dominant species (turban snail *Turbo coreensis*, a gastropod mollusk in the family Turbinidae and hermit crab *Pagurus filholi*, a decapod crustacean in the family Paguridae) were expressed as number of individuals 1 m^{-2} based on the area covered by quadrat sampling.

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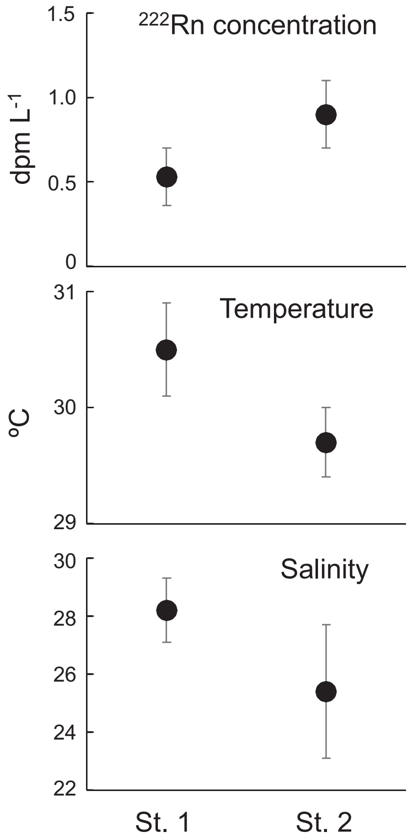

Fig. 2. Mean radon-222 (^{222}Rn) concentration (top), water temperature (middle) and salinity (bottom) at station 1 and 2 in the eastern part of Obama Bay. The ^{222}Rn concentration was measured on 22 July 2014 and temperature and salinity on 27 July 2014. Vertical bars show standard deviation.

In order to detect effects of submarine groundwater discharge on fish and epibenthic invertebrate communities, number of species, abundance and wet weight of fishes, abundance of the major prey items (gammarids and copepods), abundance and biomass of the larger epibenthic invertebrates were compared between the two sites by Mann–Whitney *U*-test.

4. Results

4.1. Physical properties in survey area

High ^{222}Rn concentration was observed in the west part of the coastal area (Fig. 1). Mean (SD) ^{222}Rn concentrations was 0.53 (0.17) at st. 1 and 0.90 (0.20) at st. 2 (Fig. 2). Mean water temperature was 30.5 (0.4) °C at st. 1 and 29.7 (0.3) °C at st. 2. Mean salinity was 28.2 (1.1) at st. 1 and 25.4 (2.3) at st. 2.

4.2. Fish community and feeding habits

Japanese temperate bass *Lateolabrax japonicas* and black sea bream *Acanthopagrus schlegelii* (Fig. 3) were dominant among the fishes collected. No fish was collected at st. 1. Number of fish species, fish abundance, fish biomass at st. 2 were significantly higher than those at st. 1 (Fig. 4: *U*-test, $p < 0.05$ for all comparisons).

All fishes except for one (gobiidae spp.) had fed. The dominant prey items were gammarids (*Pontogeneia* spp., *Melita* spp., *Pleusymtes* spp. and unidentified gammarids) and copepods (Table 1).

4.3. Epibenthic invertebrates

Mean (±SD) abundance of gammarids, the major prey item for the fishes, at st. 2 ($505.7 \pm 181.3\ m^{-2}$) was about 18 times higher than that at st. 1 ($28.3 \pm 41.3\ m^{-2}$). There was a significant difference between the two stations (*U*-test, $p < 0.05$: Fig. 5). Mean abundance of copepods, another major prey item, at st. 2 was slightly higher than that at st. 1 although the difference

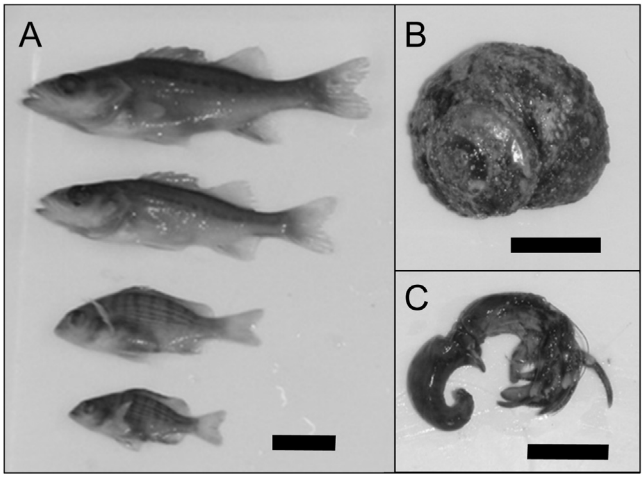

Fig. 3. Photographs of fish and benthic invertebrates which dominated animal community by weight at the sampling stations. A: Japanese temperate bass *Lateolabrax japonicus* (top) and black sea bream *Acanthopagrus schlegelii* (bottom); B: turban snail *Turbo coreensis* ; C: hermit crab *Pagurus filholi* . Scale bar shows 10 mm.

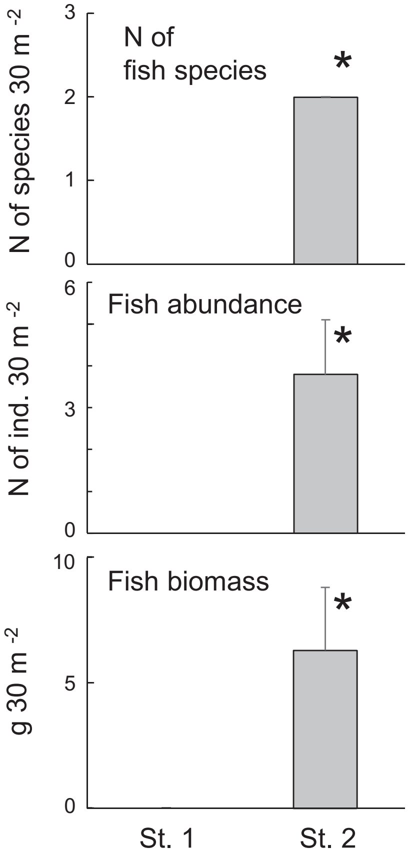

Fig. 4. Mean number of species, abundance, and biomass of fishes collected at stations 1 and 2 on 27 July 2014. Vertical bar shows standard deviation and asterisk significant difference between the sampling stations ($p < 0.05$).

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Table 1
Stomach contents of fishes collected during the biological survey on 27 July 2014. Number of fish examined, mean and range of total length were indicated for each fish taxonomic group. Stomach contents composition is expressed by% in weight.

Fish species	*Lateolabrax japonicus*	*Acanthopagrus schlegelii*	*Acentrogobius* spp.	*Tridentiger* sp.	*Gobiidae* sp.
No.fish examined	8	3	2	1	1
Total length (range, mm)	56.7–71.4	27.5–31.6	59.1–60.2	19.6	15.9
Total length (mean, mm)	64.0	33.7	59.7		
% of stomachs with prey	100	100	100	100	0
Stomach contents (W%)					
Gammarids					
Pontogeneia spp.	23.0		100	53.9	
Melita spp.	12.8	100			
Pleusymtes spp.	5.6				
Unidentified gammarids	15.7			46.1	
Caprellids	7.9				
Copepods	35.1				

was not significant (*U*-test, $p > 0.05$). Abundance and biomass of the larger epibenthic invertebrates (turban snail and hermit crab) at st. 2 were significantly higher than those at st. 1 (*U*-test, $p < 0.05$: Figs. 5 & 6).

5. Discussion

The high ^{222}Rn concentration revealed by horizontal survey indicates high submarine groundwater discharge in the west coastal part of the survey area in Obama Bay. Mean ^{222}Rn concentration differed between the two stations although the distance between the stations was within 100 m. Therefore, we conclude that location of the two sampling stations were suitable for comparison of fish and invertebrate communities in relation to submarine groundwater discharge within relatively a small spatial scale in Obama Bay.

Higher species richness, abundance and biomass of fishes, together with higher abundance of major prey item (gammarids) of the fishes and the larger invertebrates (turban snail and hermit crab) observed at st. 2 indicate submarine groundwater discharge affects distribution of fish and invertebrates within a small spatial scale of about 100 m. There seem to be two possible mechanisms through which the fish and invertebrate abundance increased at the area with high submarine groundwater discharge.

First, temperature would have affected distribution of the fishes and invertebrates in the survey area. Generally temperature of groundwater is more stable than sea water throughout year. Therefore difference in temperature between submarine groundwater discharge and surrounding seawater tends to be larger in summer and winter in temperate coastal waters.

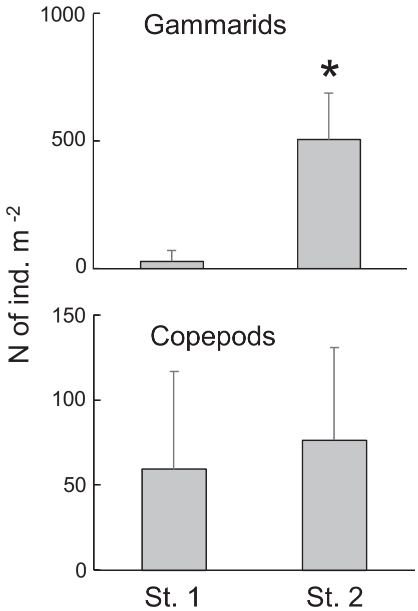

Fig. 5. Mean abundance of dominant crustaceans collected by the plankton net at stations 1 and 2 on 27 July 2014. Vertical bar shows standard deviation and asterisk significant difference between the sampling stations ($p < 0.05$).

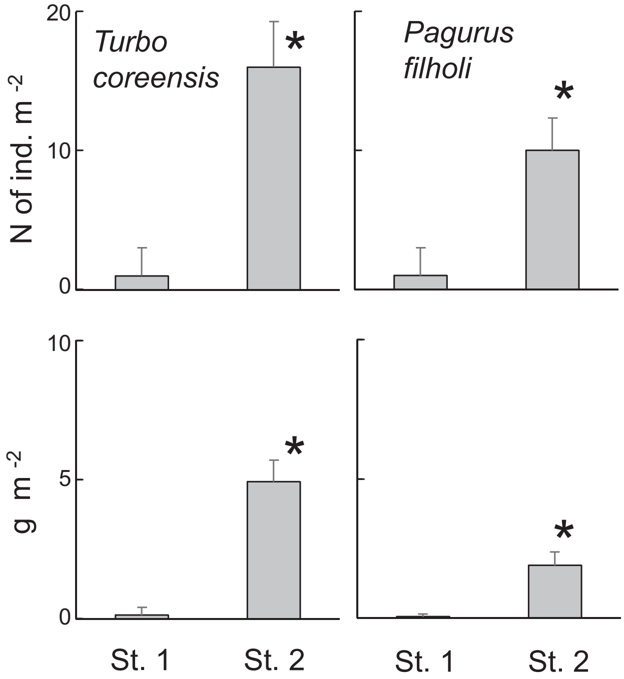

Fig. 6. Mean abundance (top) and biomass (bottom) of a dominant mollusk (turban snail *Turbo coreensis* : left) and crustacean (hermit crab *Pagurus filholi* : right) collected by the quadrat sampling at stations 1 and 2 on 27 July 2014. Vertical bar shows standard deviation and asterisk significant difference between the sampling stations ($p < 0.05$).

Aquatic animals have optimal temperature for their feeding, growth, metabolism and consequential survival rates (Takasuka et al., 2007). They can not be alive under extremely high and low temperatures. Poleward migrations of marine fish species under the global warming have been expected in a variety of marine animal species of the world (Rose, 2005; Shoji et al., 2011). At global scale, submarine groundwater can maintain growth, production and survival rates and decrease the speed of poleward movement of marine animals under the global warming through stabilizing the ambient temperatures. In the present study, submarine groundwater discharge seemed to have a significant effect of species richness and abundance of fishes and invertebrates although the difference in temperature between the two stations was less than 1.0 °C (30.5 °C at st. 1 with less groundwater discharge and 29.7 °C at st. 2 with more discharge). We suggest that at smaller spatial scales slight difference in temperature affects spatial distribution of fishes and invertebrates through their choice of habitat or location at a small spatial scale.

Second, nutrient transported through submarine groundwater is suggested to have increased the species richness and abundance of fishes and invertebrates through enhancing primary production. In Delaware Bay, US, elevation of benthic microalgae production was found around the area with submarine groundwater discharge (Miller and Ullman, 2004). In Obama Bay, nutrient fluxes from the SGD were estimated about 42%, 65%, and 33% of all terrestrial fluxes of dissolved inorganic nitrogen, phosphorous, and silicate (Sugimoto et al., 2015). Phosphorous-enriched nutrient transport through submarine groundwater discharge is suggested to enhance biological production in Obama Bay since primary production is restricted by phosphorous (Sugimoto et al., 2015).

The gammarids, one of the major prey items of fishes in the survey site, turban snail and hermit crab include herbivores which feed on phytoplankton and benthic micro algae (Sakurai and Yanai, 2006). Results of the stomach contents analysis showed gammarids were most important as prey sources for fishes collected around the submarine groundwater discharge. The extremely high abundance of gammarids 18 times higher at the station where more submarine groundwater discharge was indicated than at the other station, indicates that gammarids support fish production around the submarine groundwater discharge through connecting primary producers and fishes in the trophic flow. We conclude that nutrients transported by submarine groundwater discharge support fish and epibenthic invertebrate production through the trophic flow around the area with high levels of submarine groundwater discharge in Obama Bay.

6. Conclusion

Fish and invertebrate communities were compared within a relatively small spatial scale (ca. 100 m) in relation to level of submarine groundwater discharge. Survey for horizontal distribution of radon-222 (^{222}Rn) concentration showed high levels of submarine groundwater discharge in the west part of survey area. Species richness, abundance and biomass of

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fishes and abundance and biomass of turban snail and hermit crab were significantly higher at the station with higher ^{222}Rn concentration. Abundance of gammarids, the most major prey item of the fishes, was 18 times higher at the station with higher ^{222}Rn concentration. Since the turban snail, hermit crab and gammarids feed on producers (phytoplankton and benthic microalgae), nutrients provided through submarine groundwater are concluded to increase species richness and production of fishes and invertebrates through enhancing primary production. Results of the present study contribute to the comprehensive understanding of the water-food-energy nexus through providing scientific information on the interactions between water and food (fisheries resources) that is one of the major ecosystem services promoted by water in the coastal ecosystems.

Conflict of interest

There are no conflict of interests in relation to this manuscript.

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