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Effects of primary productivity and ecosystem size on food-chain length in Raohe River, China

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ABSTRACT

Food chains illustrate the fundamental relationship among different producers and consumers in the natural world. The length of a food chain describes the relationship from primary producers to top predators, and has long been a central concept in community ecology. Many different drivers, including productivity and ecosystem size, explain natural variations in the lengths of food chains. A significant amount of knowledge remains to be obtained about the roles of these various drivers in determining the lengths of food chains and the mechanisms by which they operate in river ecosystems. Raohe River in China is one of main rivers that flow into Lake Poyang. We examined the main channel and tributaries of Raohe River and collected the most common species in them. We found a total of 336 species belonging to 12 orders, 26 families, and 43 genera. We also collected 10 water samples. We conducted stable nitrogen isotope analysis of the consumers and used calculated nitrogen ratios ($\delta^{15}N$) to determine the lengths of the food chains at various sites in Raohe River. Subsequently, we examined the effects of primary productivity and ecosystem size on food-chain length. We used chlorophyll-*a* concentration obtained by analyzing filtered water samples to calculate the primary productivity of the river. The lengths of food chains in Raohe River ranged from 1.86 to 3.71. The longest food chains were at the Lake Poyang and Lianhu sample sites, and the shortest food chain (<2.0) was at Xiagang sample site. Results indicated that food chains in these rivers lengthened from the upper reaches to the lower reaches, reflecting an increased number of consumer species in the lower reaches. Significant positive correlations were observed between the lengths of the food chains in Raohe River and primary productivity ($y = 0.41x + 2.13$, $R^2 = 0.58$, $p < 0.01$) as well as ecosystem size (river width: $y = 0.61x + 1.28$, $R^2 = 0.43$, $p < 0.05$; catchment area: $y = 0.32x + 1.48$, $R^2 = 0.42$, $p < 0.05$). Together, these analyses tested the reliability of productive-space hypothesis, which is often applied to river ecosystems. Our data suggest that larger ecosystems result in longer food chains in rivers by integrating catchment area and river width through river networks, thereby enhancing environmental stability in river ecosystems.

Food chains, as the fundamental trophic structure in nature, can characterize linear features of food web structures in various types of ecosystems, and have a significant effect on the stability of ecosystem population structure, species density, and trophic relationship [1–3]. Research on food chain length (FCL) has consistently been a core topic in ecological science [4,5], which is significant to the study on the community structure of ecosystems, as well as processing and loading of pollutants [6].

Compared with the research on the FCL for lake and marine ecosystems, that on the FCL for river ecosystem is not fully understood [7]. In general, the FCL in the river ecosystem is shorter than that in the lake and marine ecosystems, and was estimated to be 1.5–3.0 [8]. Numerous factors determine the FCL in river ecosystems, including community structure, ecosystem size, resource availability, and interaction between predators and preys [6]. A number of researchers have developed a series of theoretical hypotheses on the effects of these aforementioned factors on the FCL. These hypotheses include Energy Hypothesis [9,10] and Productive-Space Hypothesis [6,11–13]. As one of the most important theories on the FCL in recent years, the Productive-Space Theory argued that primary productivity and ecosystem size were two key factors constraining the FCL. Post (2000) found that access of predators to food resources was mainly subject to the size of primary productivity [6], and richness of food resources determined the size of predators' population and affected the FCL of the lake. The study conducted by Vander Zanden and Fetzer (2007) revealed that globally, a

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positive correlation existed between ecosystem size and FCL [7]. Sabo et al. (2002) found that the FCL of rivers increased with the growth of river basin area, and the ecosystem size and primary productivity were positively correlated with the FCL [14]. Takimoto and Post (2012) also suggested through meta-analysis that primary productivity and ecosystem size had a significant effect on the FCL [15]. Most of these studies were focused on the lake ecosystem, but few were concentrated on the river ecosystem. In China, these studies on factors that affect the FCL were mainly conducted from the relationship between or among biodiversity, population structure features [16], spatial pattern [17], and river basin characteristics [18]. All studies indicated the presence of a significant correlation between population structure, quantitative features, and river basin characteristics (e.g., river basin area, length, and flow of main streams).

Over recent years, stable isotope technique has been widely applied in studies on food web structure of various types of ecosystems, and on the FCL [19]. The Raohe River basin, which is the study area, traverses through sub-tropical forest (upstream) to Poyang Lake wetlands (mouth of the estuary), where the upstream reaches are less affected by human beings, and receive only light urban effluent from small towns and agricultural activities. The middle and lower segments of the river are the most altered by Dexing copper mining activities, which is consequently the most heavy metal polluted because of acid mine drainage. The downstream, as floodplain, is dominated by agro-industrial activities associated with large-scale urban and wet rice cultivation. We used nitrogen stable isotope technique to study the FCL of the main streams (Le'an River and Changjiang River) and some tributaries of Raohe River, as well as to assess the relationship among primary productivity, ecosystem size, and the FCL of Raohe River to define the major factors that influence the FCL of the river system. The current study was mainly intended to test and verify the following hypotheses: (1) the FCL of a river grows with the increase of consumer types from the upper to the lower reaches of Raohe River; and (2) the FCL within the Raohe River basin is mainly constrained by the primary productivity and ecosystem size of the river.

1. Materials and methods

1.1. Study area

Raohe River is located between latitudes 28° 34′ N to 30° 02′ N and longitudes 116° 30′ E to 118° 13′ E, and is one of the five major rivers that flow into Poyang Lake. Raohe has a river basin area of 15,300 km^2. The river system consists of two main streams (i.e., Le'an River and Changjiang River) and several tributaries, including Jishui River. The Raohe River basin lies in moist sub-tropical mid-latitude climatic zone, with a mean annual air temperature of approximately 17.3 °C and average annual precipitation of 1850 mm. Precipitation is unevenly distributed within a year, and 69.1% of precipitation occurs from April to September. Average annual runoff of Raohe River is recorded at 16.56 billion m^3, 71.2% of which also occurs from April to September [20].

1.2. Sample collection

Because of hydrology of regime and size of tributaries between the upper, middle, and lower reaches of two main streams (i.e., Le'an River and Changjiang River) in Raohe River and the tributaries, the following sampling principles are observed in setting up sampling sites: (1) the sampling sites were set up at the upper, middle, and lower reaches of the main streams and lake inlet; (2) the sampling sites of tributaries are located in places that are far from the confluence with the main streams; (3) all sampling sites are set up near hydrological stations; (4) all sampling sites are located far from effluent discharge outlets of urban areas, villages, and industrial enterprises; and (5) because the middle reaches of Le'an River suffer from serious pollution of heavy metals from Dexing copper mine, which has significantly disturbed the food web of the river, the sampling sites are located off its surrounding areas.

A total of 10 sampling sites were set up, as shown in Fig. 1. Hydrological data of each sampling site mainly include river channel width, catchment area above the river section, and water temperature at the sampling site (Table 1).

Given the impact of river hydrological changes on fish communities, samples in the current study were collected during low-flow water level season of Raohe River, that is, November 2012. Water samples (1 L) from middle-level layer were collected at 1–2 m away from the river bank at each sampling site and filtered into two parts (500 mL for each part) with a filter membrane of pre-burnt Whatman GF/C (Ø = 47 mm) before being frozen and taken back to the laboratory. Consumer samples, including fish, were mainly captured 500 m along the river channel with netting gears and electric harpoons. After being treated (white muscles on the back of fish were sampled; abdominal muscles were tested from snails, which had been placed in clean water overnight; and abdominal segments were examined from shrimps after shell removal), all consumer samples were frozen and taken back to the laboratory for further treatment. After collection, the consumer samples were taken to identify their types, count their quantity, and measure their length and body weight.

1.3. Method

1.3.1. Content of chlorophyll-a

Chlorophyll-*a* concentration is a method of estimating primary production in rivers. A UV-2450 spectrophotometer was used to measure the content of chlorophyll *a* with hot-ethanol extraction method at Poyang Lake Wetland Ecosystem Research, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences [21]. The formula for calculating the content of chlorophyll-*a* is expressed as follows:

$$Chla = 27.9 \bullet V_{\text{ethanol}}[(E_{665} - E_{750}) - (A_{665} - A_{750})]/V_{\text{sample}} \quad (1)$$

where *Chla* is the concentration of chlorophyll-*a* (mg/L); V_{ethanol} is the constant volume of extracted liquid (mL); and V_{sample} is the volume of filtered water sample (L).

1.3.2. Stable isotope analysis and food chain length

Consumer samples that have been treated were placed in an Alpha 1–4 freeze dryer before they were ground into powder by using a mortar. Finally, analysis of nitrogen isotopes was conducted on approximately 1 mg of powder using a Finnegan MAT 253 (Thermo Scientific, USA) continuous-flow isotope ratio mass spectrometer coupled with a Flash Elemental Analyzer 1112 (Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences). Ratios of stable nitrogen isotope are expressed in parts per thousand (‰) deviation from international standards using the following equation:

$$\delta X = (\text{Rsample}/\text{R standard} - 1) \times 1000$$

where X = ^{15}N, and R = ratio of heavy/light isotope content ($^{15}N/^{14}N$). Reference standards were atmospheric N_2 for ^{15}N. Based on replicates of laboratory standards, analytical precision values were ±0.3‰ for ^{15}N. Lengths of food chain in different sampling sites are expressed as follows [22]:

$$\text{FCL} = (\delta^{15}N_{\text{top consumer}} - \delta^{15}N_{\text{base}})/\Delta + \lambda \quad (2)$$

where $\delta^{15}N_{\text{top consumer}}$ is the $\delta^{15}N$ value of top consumer, and Δ is the enrichment value of stable isotopes among various trophic levels.