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Study of aquatic ecological regions using fish fauna and geographic archipelago factors

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ABSTRACT

An evaluation of ecological integrity is required for ecosystem conservation and restoration. The ecological region, or "ecoregion", has been adopted as a unit of geological area to enable a comparison of the ecological integrity of different regions. The delineation of an ecological region is difficult in countries in East Asia, including Japan because of complex topographies (i.e., several peninsulas and islands) and fauna that are very finely delineated based on climate or geology. Therefore, it is important to appropriately determine the ecoregions when determining their biological integrity and comparing it among that of other ecoregions. I attempted to delineate an ecological region of the Japanese archipelago based on the similarities among fish fauna by integrating the information on fish fauna that was collected by the researchers and the national government and local governments. In addition, quantitative analyses to investigate the relationship between fish fauna classification and meteorological and geographical factors were conducted to discuss the factors that influence fish fauna classifications. The archipelago was classified into 15 fish fauna groups, and the results of these grouped classifications were closely related to the process by which the Japanese archipelago was formed, the ocean current in its coastal waters, and the connection of the water system to the glacial age. Our findings suggest that rivers within geographical areas that are different from those within the Japanese archipelago might have different fish fauna classifications based on our results and potential fish fauna depending on the characteristics of the watershed, such as the scale of the floodplain, river conflicts, or river formation process. By applying the results of our fish fauna classification, we are able to make a comparison of the biological integrity of fish fauna among different watersheds for managing the river environments or establishing conservation policies.

1. Introduction

Freshwater habitats cover only ~0.8% of the Earth's surface; however, approximately 100,000 species account for 6% of all recorded species living in these habitats (Gleick, 1996; Hawksworth and Kalin-Arroyo, 1995; Dudgeon et al., 2006). An inventory of freshwater animals (Lévêque et al., 2005) or freshwater "ecoregions" of the world (Abell et al., 2008) was provided to enable scientists to better understand integrative conservation of aquatic biodiversity. The evaluation of ecological integrity is necessary to better conserve and restore our ecosystems, and the ecoregion was adopted as a unit of geological or climatic area by which to compare ecological integrity across geographic areas. Ecoregions are areas in which ecosystems, including the type, quality, and quantity of environmental resources, are generally similar (Omernik, 1987; Bailey, 2004; McDonald et al., 2005). They serve as a spatial framework for studying, assessing, managing, and monitoring ecosystems and their components (Omernik, 1987). In North America, ecoregions were established as levels I–V according to the geographical scale, and have been used to, among other applications, develop regional biological criteria and water quality standards, set management goals for nonpoint-source pollution, assess land cover trends, report on ecosystem carbon sequestration, and frame wildlife conservation research (Omernik and Griffith, 2014). For Europe, Illies (1978) classified 25 ecoregions using the endism of freshwater fish and benthic invertebrates, and subsequently, on the basis of this classification, more ecoregion subdivisions were established in Slovenia (Urbanic, 2008), northern Europe (Ecoregion form Nordic Council of Ministers 1984), and the southern Balkans (Zogaris et al., 2009). In recent years, ecoregions have been established in China using fish fauna or environmental factors of individual catchment areas (Kong et al., 2013; Gao et al., 2011; Wang et al., 2015). In contrast to ecoregion research on a continental scale, as mentioned, research is also being conducted on relatively small islands, and the effectiveness of delineating ecoregions in these smaller areas has been confirmed. The South Island of New Zealand is an ecoregion classified using the following six indicators: climatic region, rainfall, relief vegetation, soils,

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and geology. The classification results were found to be similar to those of the ecoregion classification using terrestrial Oligochaeta (Lee, 1959; Harding and Winterbourn, 1997).

Many researches evaluating ecological integrity or analyzing relationships between biota and the physical environment were conducted based on the ecoregion concept. Studies have been conducted using phytoplankton (Beaver et al., 2012), diatomaceous (Chen et al., 2008) and benthic animals (King and Richardson, 2003; Ogren and Huckins, 2014; Feld and Hering, 2007; Butcher et al., 2003), fish (Krause et al., 2013, Ferreira et al., 2007; Ellender et al., 2017; Mehner et al., 2007), and multiple taxonomic groups (Pace et al., 2012; Wang et al., 2007; Simboura et al., 2005; Johnson et al., 2007). The ecoregion is also used in studies as an indicator by which the spatial scale affecting community structure can be identified (Johnson and Goedkoop, 2002; Uzarski et al., 2005; Sandin and Johnson, 2004). The concept of the ecoregion was adopted to evaluate abiotic factors, and a reference nutrient condition was determined for lakes within the same ecoregion in China (Huo et al., 2015, 2013; Zhang et al., 2014). In addition, the ecoregion has been used for analyzing the invasion route of non-native species (Bajer et al., 2015). Hering et al. (2009) analyzed the sensitivity of European Trichoptera species to climate change and revealed that there was a high percentage of potentially endangered species in southern European ecoregions. Furthermore, the concept of the ecoregion was applied not only to land and freshwater areas but also to coastal and marine areas, and studies have been conducted to determine reference conditions (Lucena-Moya et al., 2009), evaluate biodiversity (Simboura and Reizopoulou, 2008; Barnes et al., 2011; Easton et al., 2017), and assess conservation plans (Giakoumi et al., 2013). Most of the research on how to determine ecoregions were conducted in North American or Europe; whereas, despite the abundant biodiversity in East Asia, including Japan (Allen, 2008; De Silva et al., 2007; Lopes-Lima et al., 2014), the concept of an ecological region within these areas is rarely clear. The delineation of an ecological region is difficult in countries within the Asian monsoon region because of complex topographies (i.e., several peninsulas and islands) and fauna that are very finely delineated based on climate. In particular, the Japanese archipelago is a biodiversity hotspot because of its location and complex geological history, including that it traverses multiple biomes and comprises an intense diastrophism formed by the collision of four large tectonic plates (i.e., the Pacific, Philippine Sea, Asian, and North American). On the other hand, the biota is regionally subdivided; therefore, it is important to appropriately determine the ecoregions when determining their biological integrity and comparing it among that of other ecoregions.

Research on fish fauna within the Japanese archipelago has been conducted from the perspective of phylogeny or biology. Research on the geographical distribution pattern of fish fauna has been conducted based on their similarities (Lindberg, 1972; Nakajima et al., 2006; Yodo et al., 2001; Hirayama and Nakagoshi, 2003) or the mechanism by which the distribution area was formed from the molecular phylogenetic tree (Yokoyama and Goto, 2002, Takahashi et al., 2001; Yamazaki et al., 2003; Yamamoto et al., 2004; Mukai et al., 2004; Watanabe and Uyeno, 1999). These research results have contributed greatly to understanding the derivation of Japanese fish fauna or the transition of the distribution pattern; however, the creation of a river environmental management or conservation plan was not conducted on a watershed scale based on the genetic information that resulted from these recent researches for the following reasons: 1) genetic information is difficult to use on a basinwide scale, which is the basic unit of river environmental conservation; 2) acquiring genetic information on each species is difficult from the perspective of cost and technical in-river surveys conducted by administrators; and 3) genetic information is difficult to understand and limited to fish ecologists and evolutionists.

On the other hand, the administrative agency or researchers have stored information on fish fauna, although the information is not centrally managed. In addition, information on fish fauna is expected to be added by environmental assessment or periodic environmental research; therefore, I attempted to delineate an ecological region based on the similarities among fish fauna by integrating the information on fish fauna that was collected by the researchers and the national government and local governments. In addition, as the influencing factors that contribute to fish distribution, geographic factors, such as distribution boundaries or the geological environment, were qualitatively discussed in previous research. In this study, quantitative analyses to investigate the relationship between fish fauna classification and meteorological and geographical factors were conducted to discuss the factors that influence fish fauna classifications. The results of this classification define the geographical unit in which ecological integrity is comparable, and will contribute to the management of the river environment and establishment of conservation plans.

2. Materials and methods

2.1. Study area

There is a logarithmic relationship between river size and number of fish species (Angermeier and Schlosser, 1989; Nakajima et al., 2006; Reyjol et al., 2007), and small rivers are not suitable for delineating an ecological region because fish fauna in them is poor compared with that in large rivers, regardless of geographical factors; therefore, this study focused on 181 rivers within the Japanese archipelago with a river basin area of $\geq 150\,km^2$ (except for the basin areas of the relatively small rivers of the Amami-Oshima and Okinawa Islands) encompassing the rivers where data on resident fish have been compiled and published. The targeted 181 rivers are located evenly within each region of Japan and the total value of the catchment area of these rivers accounts for 71% of total land area. Furthermore, primary freshwater fish confirmed in these rivers accounted for approximately 84% of that confirmed throughout Japan. Based on these facts, these rivers were sufficiently large and had enough fish fauna to enable ecoregion delineations within the Japanese aquatic areas.

2.2. Fish fauna data

I used fish fauna data on the presence–absence of fish species that were investigated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT; The National Census on River Environments from 1992 to 2015) and the Ministry of Environment (MOE; National Survey on the Natural Environment 1978 and 1994). In addition, I conducted a literature search to include any additional fish fauna information. 118 species of 84 rivers were added by the literature survey. The literatures used for addition were described in Supplementary data. Non-native species were excluded from the analysis based on the information from the invasive species database released by the National Institute for Environmental Studies (2015). I used the data on both freshwater and migratory fish. Migratory fish living in brackish water and freshwater have infiltrated into the Japanese archipelago using ocean currents (Aoyagi, 1957); therefore, I added these migratory fish species to the analysis because they appear to be an important factor in delineating the ecoregion. Presence–absence data on each species were used for analysis.

2.3. Environmental data

I conducted the statistical analysis to investigate the relationship between results of fish fauna classification and environmental factors. I adopted the meteorological factors (annual average of seawater temperature [ST], air temperature [AT], and average-rainfall over watershed [R]) and topographic factors (a reciprocal of the channel slope gradient [G] and form ratio [F]) as the environmental factors.

Annual average ST was calculated using the value of temperature data at definite points obtained from the Japan Oceanographic Data