Estimation of nested spatial patterns and seasonal variation in the longitudinal distribution of *Sicyopterus japonicus* in the Datuan Stream, Taiwan by using geostatistical methods

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Abstract This study attempts to determine the scale-dependent hierarchical spatial variation and longitudinal distributions of *Sicyopterus japonicus* year round. The distribution of *S. japonicus* in the Datuan Stream in northern Taiwan was surveyed during the fall and winter 2007, as well as the spring and summer of 2008. The spatial structure of *S. japonicus* density was modeled using geostatistics. The longitudinal distributions of *S. japonicus* density were then estimated using kriging and hydrology distance with nested variogram models. Variography results indicate that nested variogram models could reflect the hierarchical structure in the spatial variation of seasonal *S. japonicus* density, with the small, median, and large ranges representing three nested scales. Models for the four seasons were consistent in that they shared the same shape of variogram models with various ranges and sill values. This model shape consistency implies stationary spatial correlations in the longitudinal fish distribution across the four seasons. The Kriging geostatistical method based on the multiple scales nested variogram models also provided robust estimates of *S. japonicus* densities at unsampled sections. We conclude that *S. japonicus* densities exhibit hierarchical patterns and variation in the four seasons along the study stream. Geostatistical methods with a nested variograms and hydrological distance are a highly effective means of delineating the hierarchical structure in longitudinal patterns of *S. japonicus* density in each season, providing estimates of the *S. japonicus* density for hierarchically structured spatial distributions and expanding knowledge of *S. japonicus* beyond the limits imposed by spatial and temporal scales.

Keywords Fish abundance monitoring · Kriging · Longitudinal pattern · Multiscale · Nested structure · Spatial variation assessment · Variogram

Introduction

Physical and biotic processes operate over a broad range of spatial and temporal scales (Menge and Olson 1990; Magalhães et al. 2002). The lack of spatial independence in ecological data has typically been viewed as obscuring an understanding the biology of organisms under study (Liebhold
and Gurevitch 2002). Stream systems can be described hierarchical subsystems and exhibit variation on multiple scales and can help to understand why fish are nested in space and time owing to their ability to respond to biological and physical patterns throughout their life cycles (Frisse1 et al. 1986; Schlosser 1991; Imhoff et al. 1996; Allan and Johnson 1997; Maddock 1999; Labbe and Fausch 2000; Li et al. 2001; Thompson et al. 2001; Fausch et al. 2002; Torgersen et al. 2004; Durance et al. 2006). Recent studies have demonstrated that stream fish respond to habitat features on a substantially larger scale than previously assumed, primarily owing to movements to various habitats to satisfy the requirements of different life history stages. Therefore, monitoring, managing, and restoring stream ecosystems largely depends on methods that effectively identify longitudinal variation in fish abundance and density.

Identifying the longitudinal patterns of stream fishes at a single spatial scale may be insufficient to understand the distribution of fish species because stream systems exhibit multiscale variation. Given the increased interest in the scale and the development of spatial analysis methods, the distribution of stream fish at multiple spatial scales is currently estimated using spatial statistical approaches (Thompson et al. 2001; Torgersen et al. 2004; Torgersen and Close 2004; Durance et al. 2006). Moreover, spatial autocorrelation in organism is the resultant of environmental or biotic factors acting at different scales (Wilkinson and Edds 2001; Grenouillet et al. 2004).

Geostatistics applies variograms to estimate or simulate the variables of interest (Lin et al. 2008). For instance, variograms provide an effective means of quantifying spatial variability and spatial autocorrelation of data by considering Euclidean spatial distance (Cressie 1993). By using sample data and geostatistical methods, biologists can estimate spatially dependent biological variables (e.g., species abundance) at potential sites where data have not been collected previously (Carroll and Pearson 2000).

As a geostatistical method, Kriging is a linear interpolation procedure that provides unbiased estimator for quantities that vary spatially (Cressie 1993). In terrestrial environments, Euclidean, or straight-line, distance is commonly used in the environmental models. In stream systems, however, Euclidean distances do not represent the transfer of organisms, material, and energy as accurately as functional distance measures (e.g., symmetric and asymmetric hydrologic or network distances) do. Therefore, a previous study suggested quantifying spatial patterns in the abundance of fish that inhabit a stream network by using geostatistical approaches and hydrologic distances (Peterson et al. 2007). Given the ability of the variogram to quantify the spatial variability in fish distribution, empirical models can be developed that incorporate spatial dependence and, in doing so, more accurately represent fish–habitat relationships (Hobert et al. 1997; Torgersen et al. 2004) or fish distributions. Among the notable studies that utilize geostatistical approaches in riverine fish and stream network studies include Torgersen et al. (2004), Ganio et al. (2005), Vilizzi et al. (2005), Cressie et al. (2006), Gresswell et al. (2006), Ver Hoef et al. (2006), Durance et al. (2006), Lloyd et al. (2006), and Peterson et al. (2006, 2007).

The objectives of this study are to: (1) monitor seasonal longitudinal patterns of *S. japonicus* densities in Datuan Stream in northern Taiwan, (2) analyze spatial variability of seasonal fish densities by using nested variogram models, (3) estimate longitudinal distributions of *S. japonicus* density based on the nested variogram models, and (4) compare and discuss suitability of the single variogram model and nested variogram models in modeling and estimating variation and distribution of *S. japonicus*.

**Materials and methods**

This study focused on estimating the scale-dependent hierarchical spatial variation of longitudinal distributions of stream fish hydrology distances. Specifically, the longitudinal patterns of *S. japonicus* in Datuan Stream in northern Taiwan were studied from September 2007 to July 2008. Spatial variation at multiple spatial scales during the summer, fall, and winter months was estimated by developing nested variogram models using asymmetric hydrologic distances and the densities of *S. japonicus*. Finally, the seasonal