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Predicting strontium isotope variation and fish location with bedrock geology: Understanding the effects of geologic heterogeneity

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ABSTRACT

Recent advances in using naturally occurring isotopes to reconstruct movement patterns have revolutionized the study of migration and spatial patterns across taxa. Isoscape approaches utilize isotopic variation in the underlying geology to quantify migration pathways. Spatial patterns in the geology can be used to predict isotopic variation, such as $^{87}Sr/^{86}Sr$; however, previous attempts to create predictive models have had mixed results. Our primary objective was to investigate the relationship between bedrock lithology and $^{87}Sr/^{86}Sr$ ratio as a tool to extend the spatial resolution of animal migration studies. Secondly, we investigated the ability to use geologic prediction as an *a priori* tool for determining chemically distinct watersheds. We first developed a regression model to relate known stream water $^{87}Sr/^{86}Sr$ to rock information from geologic maps, then used model outputs to classify adult fall Chinook salmon to their juvenile rearing location from $^{87}Sr/^{86}Sr$ signatures recorded in their otoliths (ear bones). We discuss the effect of scale and geologic heterogeneity on our ability to determine $^{87}Sr/^{86}Sr$ ratios within the study area. Our results indicate that the relationship between $^{87}Sr/^{86}Sr$ values and bedrock lithology can be used to accurately determine the rearing location of fish using otolith $^{87}Sr/^{86}Sr$ signatures. The scale at which geology can be used as a predictor of $^{87}Sr/^{86}Sr$ values is constrained by geologic heterogeneity and inherent variability in $^{87}Sr/^{86}Sr$ ratios within major rock categories. Further, our results indicate that geological data alone can be used to quantitatively investigate which watersheds are likely to be distinguishable using this method within a basin. Geologic prediction also has the potential to improve the scale and resolution of isotopic studies and the development of isoscapes. By applying measures of spatial heterogeneity we will be better able to quantitatively place limits on the accuracy of geologic predictions of $^{87}Sr/^{86}Sr$ ratios.

1. Introduction

Recent advances in reconstructing location and movement patterns using naturally occurring isotopes have revolutionized the study of migration and spatial patterns of habitat use across taxa (Hobson et al., 2010). Isotopic methods have allowed researchers to link breeding and overwintering grounds of butterflies (Wassenaar and Hobson, 1998) and birds (Marra et al., 1998; Wassenaar and Hobson, 2000; Hobson et al., 2012), to quantify the natal origins and movement patterns of fish (Harrington et al., 1998; Thorrold et al., 1998; Kennedy et al., 2002; Hogan et al., 2007), whales and bats (Hobson, 1999), and to identify the forensic location of marijuana origin and growing conditions (Hurley et al., 2010). Recent investigations have reconstructed movement patterns in unprecedented temporal and spatial detail (1–10 km) (Hamann and Kennedy, 2012) and at larger regional scales (Barnett-Johnson et al., 2010) that would be impossible using traditional tagging techniques.

The precision and power of landscape isotope, or isoscape, approaches rely on the underlying isotopic variation in the landscape (West et al., 2010). The ratio of strontium isotopes ($^{87}Sr/^{86}Sr$) can exhibit fine scale environmental variation in river systems, making it useful in studying, origin, migration and species distribution at both large and small scales (Kennedy et al., 1997; West et al., 2009; Barnett-Johnson et al., 2010; Hamann and Kennedy, 2012; Muhlfeld et al., 2012). Also, in contrast to most other isotope systems, $^{87}Sr/^{86}Sr$ values are tightly linked to the underlying geology (Faure, 1977; Bain and Bacon, 1994; Stewart et al., 1998). This significant relationship between bedrock geology and watershed chemistry may allow stream water $^{87}Sr/^{86}Sr$ ratios to be directly predicted from geology, potentially leading to more accurate $^{87}Sr/^{86}Sr$ isoscapes and increasing the resolution and extent of research with less sampling effort. Lastly, because biological fractionation of Sr isotopes does not occur, a precise signature of provenance of organisms or habitat use is possible if water chemistry can be characterized or predicted (Graustein, 1989; Kennedy et al., 1997, 2000).

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Previous attempts to predict $^{87}Sr/^{86}Sr$ using geologic variation, both across the landscape and in surface water, have been met with varying degrees of success (Chesson et al., 2012). Humston et al. (2006) introduced a qualitative, *a priori* tool for researchers to determine the feasibility of isotopic and elemental studies within a study reach. Barnett-Johnson et al. (2008) reported that the majority of $^{87}Sr/^{86}Sr$ variation in the California Central Valley could be explained using felsic and old sedimentary rock within the basin but did not extend this predictive relationship to predict $^{87}Sr/^{86}Sr$ values within the basin or determine the location of salmon in the study. Bataille and Bowen (2012) created large scale isoscapes of $^{87}Sr/^{86}Sr$ values with landscape geology, age, and weathering rates which explained 70% of the variation in surface water $^{87}Sr/^{86}Sr$ across the United States. They then applied this model to Caribbean watersheds and extended it to include additional sources of $^{87}Sr/^{86}Sr$ (Bataille et al., 2012). While contributing to our understanding of spatial variation in Sr isotope signature, prior studies have been hampered by an inability to generalize predictions and difficulty in predicting across large differences in geologic makeup or spatial scale.

We hypothesize that understanding how geology varies across the landscape using metrics of landscape scale and heterogeneity will improve our ability to generalize isotopic predictions from bedrock geology in the future. We further hypothesize that geologic predictions can be used to increase the resolution and extent of migration studies, and that watershed geologic makeup alone can be used as an *a priori* tool to isolate landscapes that are conducive to such studies.

The objective of this paper is to investigate the feasibility of $^{87}Sr/^{86}Sr$ prediction from bedrock as a tool to extend the spatial resolution of animal migration studies. We first present a regression-based approach that relates surface water $^{87}Sr/^{86}Sr$ measurements to bedrock lithology in the Snake River basin of Idaho and Washington. We then demonstrate that outputs from this model can be used to correctly classify the location of juvenile salmon. Next, we apply our regression model to unsampled watersheds within the basin and discuss the effect of watershed scale and geologic heterogeneity in creating generalized predictions of $^{87}Sr/^{86}Sr$ prediction in the future. Finally, we analyze the geologic differences needed to distinguish watersheds isotopically and use geologic data alone as an *a priori* tool to determine the whether watersheds are likely to be isotopically distinct.

2. Methods

Our primary goal was to develop a statistical relationship between $^{87}Sr/^{86}Sr$ values within the Snake River basin and the associated bedrock geology to test whether it could be applied to answer ecological questions. Secondly, we examined this geologic relationship to determine under what geologic conditions and watershed scales this type of geologic modeling could be used to improve isoscape modeling of $^{87}Sr/^{86}Sr$ ratios.

To develop our geologic relationship we used water samples collected seasonally to measure dissolved $^{87}Sr/^{86}Sr$ isotope ratios from 13 sites throughout the Snake River basin by Hegg et al. (2013) as the dependent variable to create a multiple linear regression. All samples were analyzed using Thermal Ionization Mass Spectrometry and the seasonal values for each site were averaged. Refer to Hegg et al. (2013) for specific analysis methods. The primary rock types in the watershed upstream of each sample point were quantified and used as the independent variable (Table 1 in the Online Appendix).

This regression relationship was then applied to a recent dataset of fish otolith $^{87}Sr/^{86}Sr$ values to test whether it could be used to extend the resolution or scale of migration studies. To do this, a linear discriminate function was developed using the predicted outputs of our regression equation with the geology of watersheds within the Snake River basin as inputs. We used $^{87}Sr/^{86}Sr$ signatures of the rearing stage for 127 adult and juvenile salmon from Hegg et al. (2013) to test the performance of our regression relationship as a method for determining the rearing location of fish of fish. We used this fish dataset because the original classification had been completed using the same water samples as we used to create our regression relationship. Therefore, by comparing these two approaches, we can attribute any differences in classification accuracy to the effects of geologic prediction.

Understanding the scale at which geologic predictions can be made is important for developing future isoscape models. Therefore, we analyzed the ability of our regression model to determine $^{87}Sr/^{86}Sr$ ratios from geology at various scales. First we applied our original regression model to three additional, small watersheds within the basin to determine if the relationship can be generalized to smaller watershed scales. Next, we created a second regression model that includes $^{87}Sr/^{86}Sr$ values for these three additional watersheds to determine if prediction accuracy can be improved. We then quantified the effects of watershed scale and heterogeneity on the accuracy of regression outputs using the percentage area of rock types within basin watersheds and the Shannon index of diversity and evenness.

Finally, the relationship between geology and $^{87}Sr/^{86}Sr$ chemistry offers the possibility that researchers could quantify whether a study area is amendable to isotopic research before valuable time and resources are expended in sample analysis. We tested our ability to use geologic maps directly, without water sampling, to determine whether watersheds are distinguishable, and thus amendable to isotopic study. We used watershed geologic data as the independent variable in a linear discriminate function with major watersheds as the dependent variable. Our ability to distinguish watersheds using this method was then compared with the results based on water sampling. Finally, we analyzed the geologic differences required for two watersheds to be distinguishable using logistic regression on the pairwise comparisons of the major Snake River watersheds.

All statistical analyses were conducted in R statistical package (versions 2.10.1 and 2.15.1, http://www.r-project.org/).

2.1. Study site

The Snake River, the largest tributary to the Columbia River, drains an area of 280,000 km^2 encompassing six states (Fig. 1). Fall Chinook salmon, which spawn in the lower reaches of the major tributaries in the basin, are listed as endangered under the Endangered Species Act (April 22 1992, Federal Register, Vol 57, No 78, p 14653). Fall Chinook salmon in the Snake River inhabit a river system that has been significantly altered by hydropower construction, blocking upstream access to the majority of fall Chinook salmon spawning grounds and impounding a large portion of the downstream habitat behind eight hydropower dams.

The Snake River tributaries can be grouped broadly by geology (Fig. 1). The Clearwater and Salmon Rivers flow over felsic rocks of the Idaho batholith, with the Clearwater being influenced most heavily by the older metamorphic rock (Foster and Fanning, 1997). The Tucannon, Grande Ronde and Imnaha Rivers flow primarily over the Columbia River Basalts (Hooper et al., 2007), with the Grande Ronde and Imnaha Rivers being influenced in their headwaters by the more diverse Wallowa terrane (Hales et al., 2005). The upper Snake River begins in the geologically more diverse and older Teton Range (Love et al., 1978), and the basalt and rhyolites of the Snake River Plain (Leeman, 1982). The unique geologic conditions through which each group of rivers flows lead to detectable differences in geochemical fingerprints between rivers in the Columbia River Basin.

Geochemical variation among basin tributaries has allowed previous classification of salmon spawning and rearing areas based upon geochemical signature (Hegg et al., 2013). Hegg et al. (2013) classified the main tributaries and Upper and Lower Snake River into four groups based upon $^{87}Sr/^{86}Sr$ ratio in stream water using a linear discriminate function. Otoliths from returning adult fall Chinook salmon were then analyzed and the $^{87}Sr/^{86}Sr$ signatures from their natal, rearing and overwintering stages were recovered using laser ablation inductively