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Effects of *in situ* phosphorus enrichment on the benthos in a subalpine karst stream and implications for bioassessment in nature reserves

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ABSTRACT

Park managers in nature reserves need scientifically defensible and operationally feasible ecological indicators to better manage protected areas for both nature conservation and tourism. Such needs are much more urgent in karst aquatic ecosystems where spectacular natural scenic wonders attract millions of visitors to natural areas with streams and lakes that are particularly vulnerable to nutrient pollution. To identify a set of biotic indicators of phosphorus (P) pollution in a karst stream, we conducted an *in situ* P enrichment experiment in a nearly pristine karst stream located at a UNESCO world heritage site in China. Our results show that both benthic algal assemblages and macroinvertebrates were sensitive to P enrichment. Changes in diatoms (e.g., *Achnanthidium minutissimum, Delicata delicatula*) and macroinvertebrates (e.g., collectors) were indicative of P enrichment. The color change of travertine bryophyte beds from creamy white to green was largely due to increase in filamentous green algae such as *Zygnema* sp., which may provide a visual cue for P enrichment and pollution. Our findings, in conjunction with further studies that directly link these indicators with human disturbance (e.g., tourist activities) throughout the park, could improve the operation of park managers in minimizing tourist-induced nutrient pollution and in operationalizing these indicators in the current environmental monitoring and assessment program.

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1. Introduction

Nature reserves are managed for both nature conservation (e.g., biodiversity) and human enjoyment (e.g., tourism) (Newsome et al., 2013). However, it has long been questioned if such dual mandates of conservation and tourism in the protected areas are in direct conflict (Budowski, 1976). This is particularly true in karst ecosystems, where the same processes that create the natural scenery also make them vulnerable to pollution. In karst systems, the dissolution limestone creates some of the most spectacular natural wonders in the world; however, thin limestone soils in watersheds and rapid surface-aquifer transmission of water and pollutants provide minimal filtration to remove the pollutants (Van Beynen and Townsend, 2005; Kresic, 2013).

Furthering compounding this problem is the fact that the impacts of tourist activities are often difficult to detect through traditional approaches of pollution monitoring. For example, anthropogenic impacts in upstream locations, such as increased organic debris and soil erosion due to trampling, may be unnoticeable because the rapid surface water to groundwater transmission may transport pollutants away from their source. Consequently, in karst systems, it is particularly difficult for park managers to directly link tourist activities to environmental degradation. In order to achieve the dual goals of managing tourism and conserving biodiversity in karst systems, park management would benefit from the use of ecological indicators that explicitly link tourism impacts with the ecological integrity of the protected ecosystems (Buckley, 2003).

Karst landscapes cover 12–25% of the earth's surface and have been subjected to increased human disturbance worldwide (Van Beynen and Townsend, 2005). However, there are very few ecological indicators of tourist impacts that have been developed and

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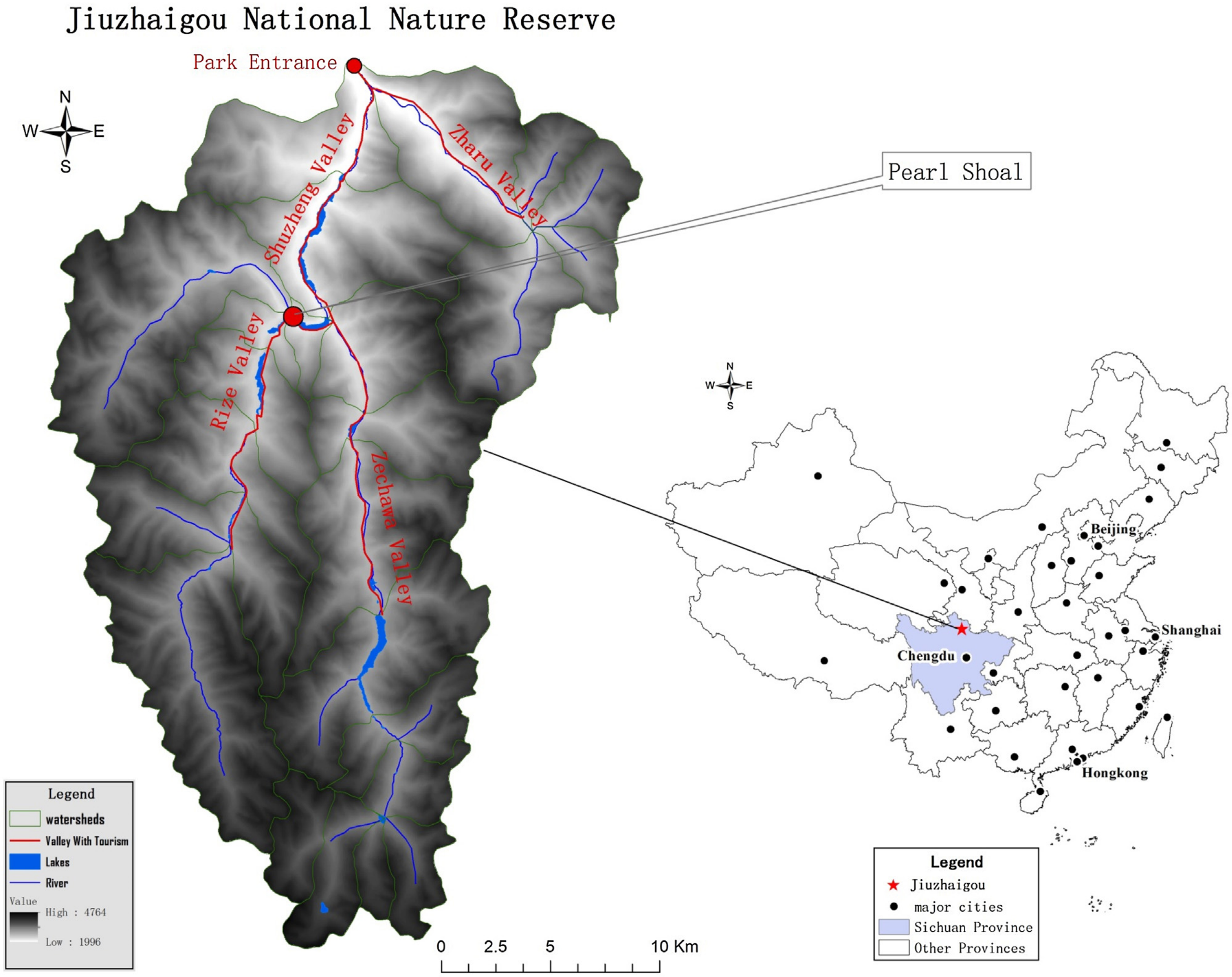

Fig. 1. A map of China showing the location of Jiuzhaigou Nature Reserve and the location of the Pearl Shoal study site.

tested for karst water that are scientifically defensible and can be practically applied by park managers (Buckley, 2003). Recognizing the unique nature of karst landscapes, Van Beynen and Townsend (2005) developed a holistic karst disturbance index for regional assessment. The index, tested in Florida (USA) and Mediterranean karst systems (Van Beynen et al., 2007; De Waele, 2009; North et al., 2009), was able to detect moderate to severe human impacts such as urbanization but “future application of the index requires potential retooling of the biota indicators” (Van Beynen et al., 2007). Such retooling is critically important in protected karst aquatic systems where human impacts are often minimal and thus require relatively more sensitive indicators that will provide an early detection of cumulative impacts (Pan et al., 2016). Currently, most researches on karst systems have focused on both hydrogeological and chemical processes underlying travertine formation (Pentecost, 2005). Less attention has been paid to the biota and ecology of karst lakes and rivers. For example, while it is well known that benthic algae and bryophytes play important roles in forming travertine and providing critical benthic habitat for macroinvertebrates, the research on benthic algal assemblages in karst systems has been largely limited to floristic investigations (Pentecost, 2005).

To evaluate potential biotic indicators for karst aquatic systems, we assessed effects of nutrient enrichment on both benthic algae and macroinvertebrates in Jiuzhaigou Nature Reserve, China, a nearly pristine karst ecosystem under the protection of the UNESCO World Heritage Convention (Fig. 1). The Reserve has experienced increased tourism pressure and some of the lakes are showing early indications of eutrophication (Cao et al., 2016; Pan et al., 2016). For our study site, we selected a travertine shoal called Pearl Shoal. Pearl Shoal is located downstream of the Rize Valley (Fig. 1), and thus likely integrates the overall effects of tourism-related disturbances in the valley. This is evident from photos taken downstream of an above-water wooden boardwalk that transverses the shoal one year after the park opened in 1984, which at that time had relatively few tourists (<30,000 annually). The 1985 photo shows the shoal was covered by a creamy-color calcified bryophyte bed. A recent photo from the same location in 2013, when annual tourist counts were more >4 million, shows benthic habitats that were largely green in color, indicating a proliferation of filamentous green algae (Fig. 2). The boardwalk is used by millions of tourists annually to walk across the shoal. This shifting from creamy calcified periphyton mats to floating filamentous green algae has been observed in other travertine aquatic systems, including a subtropical marsh on limestone bedrocks in USA, and through an *in situ* experiment that demonstrated the color changes associated with a shift in species from calcified periphyton dominated by cyanobacteria and diatoms to filamentous green algae caused by phosphorus (P) enrichment (McCormick and O’Dell, 1996; Pan et al., 2000).

We hypothesize that the color change of benthic habitats from historically creamy-white to green in the upstream section of the shoal below the boardwalk is caused by cumulative P enrichment associated with increasing tourism in the park. Since benthic