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Land use drives the physiological properties of a stream fish

Z.W. Blevins[a,b,*], E.L. Effert[a,b], D.H. Wahl[b], C.D. Suski[a]

[a] Department of Natural Resources and Environmental Science, University of Illinois, Turner Hall, 1102 South Goodwin Ave, Urbana, IL 61801, USA
[b] Illinois Natural History Survey, University of Illinois, 1816 S. Oak St., Champaign, IL 61820, USA

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ABSTRACT

Human activities within the riparian zone can alter abiotic properties of a watershed, potentially resulting in abiotic conditions that are stressful for resident fishes. The inability of fish to cope physiologically with stressful abiotic conditions can have deleterious effects on individuals, and could potentially lead to population declines or changes to community structure (biodiversity). Defining links between landscape-level processes and performance of individual stream fishes can therefore improve our ability to predict how land use changes can impact stream communities, which has relevance for management activities. This study tested the hypothesis that land use at the watershed scale influences the physiological stress response of resident fishes. For this, replicate streams in agricultural watersheds and forested watersheds were identified; sampling demonstrated that streams in agricultural watersheds were warmer and more thermally variable than streams from agricultural areas. Creek chub from each land use type were sampled for blood and muscle in the field, following exposure to thermal and oxygen stressors in the laboratory, and after prolonged holding at elevated temperatures that replicated field conditions. No differences in baseline physiological parameters were found in fish sampled directly from streams. However, when exposed to low oxygen and high temperature conditions in the laboratory, creek chub from streams within agricultural areas maintained physiological performance with a reduced stress response relative to creek chubs from streams within forested watersheds. In addition, prolonged holding at high temperature removed landscape-level differences in stress responses, resulting in improved physiological performance for all fishes after a heat challenge. Results indicate that creek chub have the ability to adjust physiological responses to improve performance in disturbed environments, and also provide a novel mechanism by which landscape-level processes can influence biodiversity.

1. Introduction

Changes in terrestrial land use and increasing human populations are two of the greatest threats to biodiversity in the United States (Czech et al., 2000). Land use changes, such as urbanization and agriculture, can negatively impact terrestrial biodiversity by consuming riparian habitat, altering riparian habitat properties, and increasing habitat fragmentation. Furthermore, recent research has demonstrated that alterations to terrestrial landscapes can exert pronounced negative effects on adjacent aquatic ecosystems (Allan, 2004). For example, destruction of riparian zones through urbanization and agriculture has been shown to impact watershed hydrology, sediment loads, inputs of nutrients, dissolved oxygen concentrations, and temperature regimes in adjacent aquatic ecosystems, which, in turn, can negatively impact biodiversity in aquatic ecosystems (Hayes et al., 1996; Jones et al., 1996; Stauffer et al., 2000; Meador and Goldstein, 2003). More importantly, research has demonstrated strong links between destruction of riparian habitat, increased stream temperatures, and concomitant reductions in dissolved oxygen, all of which can impact community structure and biodiversity (Schlosser, 1991; Gergel et al., 2002; Allan, 2004).

Currently, the mechanisms that translate habitat alterations into changes in biodiversity have not been well defined. Through a cascade of biotic and abiotic interactions, alterations to terrestrial and aquatic habitat can negatively impact fish communities by modifying environmental parameters that can change predation risk, predator abundance, growth patterns, reproductive characteristics, and possibly mortality rates of fish (Hayes et al., 1996; Jones et al., 1996; Stauffer et al., 2000; Meador and Goldstein, 2003; Albanese et al., 2004). In addition, anthropogenic changes in land cover that alter the thermal, oxygen, and habitat properties in many aquatic systems have caused, or are suspected to cause, the declines of numerous North American inland fish taxa. One of the major contributing factors in the decline of brook trout (*Salvelinus fontinalis* Mitchill, 1814) in aquatic ecosystems, for example, is human landscape alterations that lead to warming

* Corresponding author. Present address: 4235 N. Winchester, Chicago, IL 60613, USA. Tel.: +1 773 414 5456; fax: +1 773 687 8371.
E-mail address: zblevs@gmail.com (Z.W. Blevins).

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past the fish's physiological ability to cope, causing direct mortality and reproductive failure (Robinson et al., 2010). Furthermore, fish such as rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792), bull trout (*Salvelinus confluentus* Suckley, 1859), and endangered topeka shiner (*Notropis Topeka* Gilbert, 1884) are all suspected to be experiencing declines in abundance through part of their range partially due to increases in temperatures and decreases in dissolved oxygen levels in streams brought about by land use alterations (Menzel et al., 1984; Matthews and Berg, 1997; Selong et al., 2001). Therefore, it is of critical importance to define the mechanism(s) that influence the ability of individual fish to cope with human alterations of aquatic systems (thermal and oxygen stressors in particular) that can translate to changes at the population level and impact biodiversity.

Physiological indicators have been identified as a useful tool in providing a mechanistic understanding of how human disturbances influence individual animals. Physiological indicators such as blood-based stress metrics are sensitive to varying levels of stressors associated with anthropogenic activity, and respond quickly (hours to days) to environmental change (Barton, 2002; Cooke and Suski, 2008). Glucocorticoids, for example, are stress hormones that have been used in management to mitigate the impacts of human activity in Rocky Mountain elk (*Cervus Canadensis* Linnaeus, 1758), grey wolves (*Canis lupis* Linnaeus, 1758), and black howler monkeys (*Alouatta* spp. Lacapede, 1799) (Millspaugh and Washburn, 2004; Creel et al., 2002; Homan et al., 2003; Martinez-Mota et al., 2007). Similarly, metabolic rate (i.e., oxygen consumption) represents a quantitative measure of the total activity of all physiological mechanisms and, for fish, includes processes such as ion regulation, maintenance costs (e.g., heart rate, opercular beats, etc.), and waste generation (Hill et al., 2008). In aquatic systems, riparian forest destruction can alter the thermal properties of streams from the range of temperatures to which aquatic organisms are accustomed and may be perceived by the organism as a stressor, resulting in physiological and/or metabolic consequences. Organisms that can successfully preserve homeostasis (physiological performance) of secondary stress indicators, such as hydromineral (Na^+, K^+, Water Content) and circulatory systems (Hematocrit), in a challenging environment are able to maintain normal physiological function, and likely growth and reproduction (Barton, 2002). Together, the sum of these individual physiological responses can change population growth rates, birth rates, and death rates and determine whether certain fish species persist or decline in the face of human alterations.

The goal of this study is to quantify the relationship between riparian land use at the watershed scale and the capacity of resident fishes to respond physiologically to environmental challenges. To achieve this goal we conducted a complimentary set of field and laboratory studies to ascertain differences in baseline and stress-induced physiological parameters of creek chub (*Semotilus atromaculatus* Mitchill, 1818) from streams within replicate disturbed (agricultural riparian zone) and undisturbed (forested riparian zone) watersheds following acute thermal and hypoxia challenges. Additionally, creek chub from replicate disturbed (agricultural riparian zone) and undisturbed (forested riparian zone) watersheds were acclimated to two different thermal conditions and given a thermal challenge to test how acclimation to different thermal regimes can impact the magnitude and scope of physiological responses. The hypothesis being tested with these experiments is that within-stream environmental variation (i.e., water temperature and dissolved oxygen concentration) caused by differences in riparian land use at the watershed scale will alter physiological properties of creek chub and permit improved performance during environmental challenges. Together, these experiments establish mechanistic links between altered terrestrial landscapes and their potential impacts on aquatic ecosystems.

2. Material and methods

To obtain fish from both disturbed (agricultural riparian zone) and undisturbed (forested riparian zone) streams, it was necessary to use a candidate fish species that could be found in adequate numbers across a range of habitat conditions. Creek chub were selected because they are one of the most common and abundant stream fishes in the eastern United States, are relatively easy to collect, and can tolerate a wide range of oxygen concentrations and thermal regimes (Pflieger, 1997; Fitzgerald et al., 1999). Creek chub living in streams within agricultural and urban areas (i.e., disturbed habitats) display reduced longevity, lower growth rate, and increased levels of reproductive anomalies compared to creek chub living in less-disturbed habitats (Fitzgerald et al., 1999). Creek chub also display high site fidelity, typically moving < 400 m in a year, providing opportunity for acclimatization to local habitat conditions (Fitzgerald et al., 1999; Belica and Rahel, 2008).

2.1. Site selection

To quantify how forest and agricultural land use affects the physiological properties of resident fish, replicate watersheds with similar proportions of forest and agriculture were identified. Both replicate watersheds, as well as individual study sites within each watershed, were selected using ArcView GIS 9.1 (ESRI, 2005) based on the Land Cover of Illinois 1999–2000 Classification on-line database compiled by the Illinois Department of Natural Resources and the Illinois State Geological Survey (IDOA, 2001). Using this database, a total of 4 headwater (2nd order) streams were chosen. Two were located within watersheds with forested riparian areas; Big (N39°4′, W87°49′) and Brushy Creeks (N38°52′, W87°39′) in Crawford County, IL. Two streams were located within watersheds with agricultural riparian areas: Bear (N39°18′, W88°17′) and Cottonwood Creeks (N39°19′, W88°13′) in Cumberland County, IL. Land cover proportions for each stream were calculated for the riparian zone scale (land cover within 30 m of the stream bank) and the watershed level scale (the entire area upstream of each site). The riparian zone scale was selected based on the resolution of available land cover data (30 m pixels) and because a riparian width of 30 m is the minimum size recommended by the United States Department of Agriculture (USDA) for maintenance of water quality (Welch, 1991). Land cover categories were created based on the overall proportion of agriculture (row crop + non-row crops), forest (upland + lowland wooded forest), and urban development (residential + commercial). Agricultural streams had >65% agriculture and <26% forest in the riparian area of the watershed above sampling locations. Forested streams had >70% forest and <23% agriculture in the riparian area in the watershed above the sampling sites. All watersheds had very little (<1%) urban development upstream of sampling sites, so urban land use was not included as a category. Agricultural and forested classifications are consentient with land cover categories developed through the Land Use Land Cover classification system (Anderson et al., 1975).

2.2. Habitat characteristics

Water temperatures were collected for the 4 streams using a temperature logging device (DS1921G Thermochron iButton, Maxim Integrated Products, Sunnyvale, CA, USA) over a period of 57 days during the months of July and August, 2009. Two temperature loggers were placed at a depth of 1 m in the middle of the stream at each site and programmed to record temperature every 30 min (minutes). Dissolved oxygen concentrations were also collected using oxygen probes (YSI Model 600XL, Yellow Springs, Ohio, USA) for two separate 48 h (hour) time periods on two consecutive days during the months of June and July 2009. Additional