ESSAY:
FISH HABITAT

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The Clear-water Paradox of Aquatic Ecosystem Restoration

INTRODUCTION

Several important resource policy questions involving trophic status, public perception, and fundamental approaches to aquatic ecosystem restoration were recently raised by Lackey (2003). Two of these questions are of particular relevance to the discussion of nutrients, water clarity, and aquatic ecosystem restoration: (1) is there an inherent policy conflict between adding nutrients to watersheds to restore salmon populations (and associated ecosystem function) and societal pressure to protect and enhance water quality, given that Western society typically desires both, and (2) is there a regulatory bias toward achieving "distilled water" in lakes, reservoirs, rivers, and streams such that the important beneficial role of waterborne nutrients is not given equivalent consideration and legislative weight? We believe the current answer to both of these questions to varying degrees is yes, and issues addressed by these questions form the basis for what we call the "clear-water paradox" of aquatic ecosystem restoration.

In this essay we: (1) review general roles, perceptions, and management of waterborne nutrients, (2) propose, define, and describe the nature and causes of the clear-water paradox of aquatic system restoration, and (3) discuss requirements for addressing and resolving this paradox.

BACKGROUND

Carbon (C), nitrogen (N), and phosphorus (P) are naturally occurring elements that are essential for growth and reproduction of all aquatic life forms. These nutrients drive primary and secondary productivity, and their concentration, ratio, and spatial/temporal availability dictate aquatic system metabolic rates and trophic status. Although excessive nitrogen and phosphorus are commonly recognized as pollutants in eutrophic waterways, societal awareness of the positive effects of these nutrients in oligotrophic ecosystems and their central role in regulating biological productivity is surprisingly limited. It is critical to recognize the importance of balance of C, N, and P, and how dysfunction occurs not only by too little or too much, but also by creating nutrient imbalances that can shift productive "classic" short-chain grazer communities into longer-chain ultra-oligotrophic microbial food webs that support minimal fish biomass and dissipate energy through picoplankton-dominated pathways with associated high respiratory costs (Weisse and Stockner 1992).

Eutrophication, the artificially elevated concentration of nutrients in natural waters, has occupied the center stage of applied limnology for nearly half the previous century (Vollenweider 1968; National Academy of Sciences 1969; Schindler 1974; Stockner 2003, and references therein). However, during the past 40 years, the opposite process, cultural oligotrophication, has become an important emerging problem in altered aquatic ecosystems in north temperate and boreal regions world-wide (Ney 1996; Stockner and Milbrink 1999; Stockner et al. 2000; Pieters et al. 2003; Stockner 2003; Hyatt et al. 2004). Cultural oligotrophication is the human-caused reduction of naturally occurring nutrients in aquatic systems. We recognize that natural ecosystems with high or low nutrient concentrations and ecosystem productivity do occur, and we are definitely not proposing that all aquatic ecosystems be "homogenized" to a middle ground of moderate productivity. Our intent is to raise scientific awareness of the magnitude and extent of culturally-induced oligotrophication such that these dysfunctional ecosystems (Ney 1996; Stockner et al. 2000) receive adequate restoration attention.

Water bodies located in formerly glaciated north and south temperate watersheds tend to be naturally oligotrophic (nutrient poor; Stockner and Milbrink 1999). Typically, these systems are characterized by low mean annual water temperature regimes, short growing seasons, underlying granitic geology, and relatively nutrient poor watersheds. Oligotrophication caused by dam and levee construction, habitat alteration, acidification, and declining returns of salmon derived nutrients at these latitudes worldwide has rendered many aquatic systems ultra-oligotrophic (Ney 1996; Stockner et al. 2000). Such systems now possess extremely clear, nutrient deficient water relative to their former naturally oligotrophic status and exhibit significantly reduced biological productivity. In their nutrient deprived states, these rivers, lakes, or reservoirs are incapable of supporting their historical pre-oligotrophication yields of fish. Kootenay Lake in British Columbia is a classic case of cultural oligotrophication in which pelagic kokanee (*Onchorhynchus nerka*) annual spawning escapement collapsed from 2–3 million to 250,000 following construction of two upstream hydroelectric impoundments and over 100 km of continuous levee construction, which sequestered inflowing nutrients and drastically reduced habitat diversity (Ashley et al. 1997,1999; Anders et al. 2002).

Limited societal awareness of cultural oligotrophication may be due in part to the fact that ultra-oligotrophic systems, although biologically constrained and ecologically dysfunctional at worst, often appear aesthetically pleasing. Eutrophic systems generate attention because they develop nuisance aquatic plant and algae growth that limit desired human activities and uses, and because they often look, taste, and smell bad. Alternatively, ultra-oligotrophic systems typically look pristine and don't violate clean water criteria. Hence they don't attract the equivalent attention because their productivity losses occur slowly over many decades. The causal mechanism (e.g., impoundment) is often associated with valuable societal benefits (i.e., hydroelectric power and flood control). Hence, oligotrophication is often quietly viewed "as the cost of doing business."

Local, regional, and national water quality policies and standards rightly exist to protect aquatic ecosystems from eutrophication and myriad organic and inorganic pollutants. These existing standards or policies could theoretically be used to protect natural water bodies from oligotrophication, but are rarely invoked, despite the fact that the magnitude of ecological damage and food web disruption associated with ultra-oligotrophy may rival that of eutrophication (Ashley et al. 1999; Stockner et al. 2000). For example, the U.S. Environmental Protection Agency (EPA) defines water quality standards as inclusive of beneficial uses, water quality criteria, and an anti-degradation policy. The beneficial uses (goals for the waterbody) often include "fish and aquatic life," whereas the water quality criteria are the minimum conditions that support the most sensitive beneficial use, and anti-degradation is designed to protect existing water quality from further degradation. Violations of water quality standards can and do occur even though the water quality criteria are achieved, e.g., the concentration of some contaminant in fish tissue might impair the "fishing" beneficial uses, but the water column concentrations are not above the water quality criteria. Since water quality standards include beneficial uses, the U.S. Clean Water Act is a policy tool that could be invoked to protect waters from cultural oligotrophication. In theory, anthropogenically-caused ultra-oligotrophic water quality should qualify as a violation of water quality standards when it results in impairment of the fish and aquatic life beneficial use. The EPA allows for the use of biocriteria, which should allow for consideration of ecosystem services. However, it is clear that the EPA's national nutrient criteria are focused primarily on addressing cultural eutrophication. The existing anti-degradation policy allows designation of waters as Outstanding (Natural) Resource Waters, which would prohibit any anthropogenic degradation of water quality. This policy would not address waters already naturally oligotrophic (e.g., Crater Lake, Oregon), but if used, could be invoked for naturally oligotrophic waters to prevent further depletion of nutrients.

THE CLEAR-WATER PARADOX

Clear water is the typically desired condition of public waterways. Entities as diverse as the Clean Water Act, and local or regional water clarity criteria support the notion that if clear is good, then crystal clear is even better. Understandably, the U.S. Clean Water Act was passed when increased turbidity of public waters was often associated with increased contamination, toxicity, and significant eutrophication problems. Of course such conditions still exist. However, natural biological turbidity is not automatically correlated with contamination, and biologically productive and ecologically functional aquatic systems are not always crystal clear. In fact, they often produce intermittent or seasonal conditions that may not be aesthetically pleasing to humans yet are necessary for the functioning of the ecosystem (Stockner et al. 2000). Herein lies the clear-water paradox of aquatic ecosystem restoration: Western society wants crystal clear public waters and ecosystem services or benefits like harvestable fish populations but simultaneously enforces water quality standards that limit or prohibit the biological productivity and ecological processes required to produce and maintain those benefits.

To understand the degree to which extreme water clarity is culturally engrained, one simply needs to envision initial responses by water resource and fisheries managers and the public to the two images presented in Figure 1. Initial responses by these groups tend to be positive to clean rock or substrate and more negative regarding the algae covered rock. Progress may be claimed when the same groups recognize clean substrate as an indicator of a potentially nutrient deficient system and the lower photo as an indicator of a more productive ecosystem that provides societally valued ecosystem services. To be emphatically clear: we are not promoting eutrophication or relaxation of legitimate water quality protection laws and enforceable standards that have protected countless water bodies from eutrophication and deleterious pollutants. Rather, we are promoting ecological education as a pathway toward protecting, restoring, and maintaining balanced aquatic ecosystems.

Due to this paradox, water resource agencies and restoration-oriented limnologists and fisheries biologists may find themselves caught between opposing management paradigms. Environmental quality monitoring and enforcement agencies are responsible for maintaining water quality standards in public waters. Some water quality standards are essentially managing for distilled water, in ecological terms. Alternatively, fishery researchers, restoration-oriented limnologists, and fisheries biologists are simultaneously designing and implementing fishery and aquatic ecosystem restoration programs that recognize the essential role of nutrient availability and its relationship with water clarity, including restorative nutrient addition prescriptions. Thus, the clear-water paradox involves conflicting "restoration" approaches among resource agencies despite their shared mission of environmental protection and some resemblance of a "normally functioning" ecosystem.

RESOLVING THE PARADOX

A fundamental change in the way aquatic resource managers and Western society view and understand aquatic resources is needed to resolve this paradox, including:

- Informative debate and accurate definition of the cultural oligotrophication problem within and among agency and public groups;

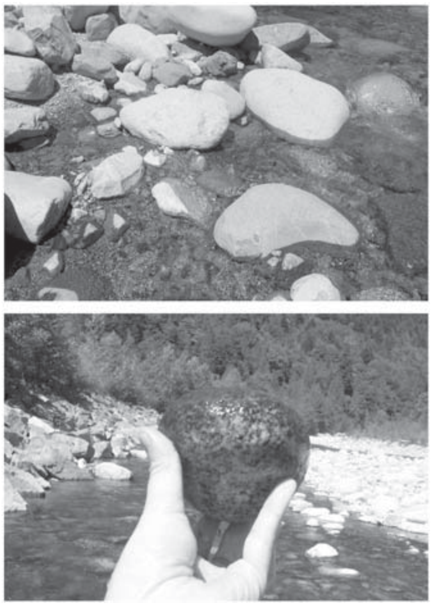

Figure 1. Differences in periphyton accrual or algal productivity on native substrates upstream (top) and downstream (bottom) from an experimental nutrient addition site in Norris Creek, British Columbia during 2005.

- Developing a better ecological, professional, and societal understanding of the cultural oligotrophication problem;
- Developing and adopting more consistent, ecologically relevant nutrient policy and standards among agencies; and
- Implementing successful aquatic ecosystem restoration projects that may not be associated with crystal clear water.

Although resolving the clear-water paradox involves formidable tasks such as changing a well-established societal paradigm, notable progress is being made in the field of restoration limnology. Unlike the aforementioned societal oversight, cultural oligotrophication and successful remedial measures are receiving increasing attention among the international ecological and limnological communities, and within local and regional water resources and fishery management agencies. For example, Washington and Oregon now have policies that attempt to address oligotrophication through the introduction of salmon carcasses (see http://wdfw.wa.gov/hab/ahg.shrg_t11.pdf) and British Columbia has been conducting stream and river enrichment experiments since the 1980s (Ashley and Slaney 1997).

A small meeting of ecologists and limnologists, held in Uppsala, Sweden in 1998, first focused scientific attention on the ecological effects and restoration options related to cultural oligotrophication (Stockner and Milbrink 1999). A second landmark international conference, on restoring nutrients in salmonid ecosystems sponsored by the American Fisheries Society was convened in Eugene, Oregon, in 2001, and included nearly 400 participants from Canada, Scandinavia, Japan, and the United States. This meeting produced a comprehensive peer-reviewed collection of nutrient addition studies designed to compensate for cultural oligotrophication of lakes, reservoirs, rivers, and streams (AFS Symposium 34: Stockner 2003). Contributors to this volume reported recent developments and challenges to the science of nutrient enrichment in various regions of the world. A subsequent review of 24 sockeye salmon nursery lake enrichment experiments in British Columbia concluded that lake fertilization was a successful technique for conserving and enhancing sockeye salmon populations (Hyatt et al. 2004). Most recently, a group of fishery consultants, researchers, and managers presented a symposium on nutrient enrichment as part of the Oregon Chapter of the American Fisheries Society meeting in Sunriver, Oregon (www.orafs.org/meeting2006/final_abstracts.pdf).

Advances in the emerging fields of nutrient enrichment and restoration limnology reveal the prevalence of cultural oligotrophication in north and south temperate regions of the world. Most of the hydroelectric reservoirs and downstream riverine ecosystems in British Columbia, Sweden, and Norway are culturally ultra-oligotrophic (Stockner and Milbrink 1999). Increased awareness of the cumulative effect and extent of ultra-oligotrophy and the important role of salmon-derived nutrients have contributed to an increasing number of nutrient restoration prescriptions and adaptive management experiments in streams, rivers, lakes, and reservoirs around the world, generally at or north of the 49th parallel (Ashley et al. 1997; Ashley et al. 1999; Murota 2003; Nakajima and Ito 2003; Stockner 2003; Ashley and Stockner 2003; Stockner and Ashley 2003; Thomas et al. 2003; Reimken et al. 2003; Anders 2006). Finally, ongoing interest in cultural oligotrophication among aquatic resource managers and researchers is reflected by a special session at the upcoming meeting of the International Limnological Society, in Montreal, Canada, in 2007, entitled "Cultural Oligotrophication: Causes, Consequences and Corrections" (www.sil2007.org).

CONCLUSIONS

Successful science-based restoration of culturally oligotrophic and eutrophic ecosystems will require improved understanding of these issues within the managing agencies and the general public. It will also require the development and implementation of appropriate fisheries and water resource management policies. This paradox is not unique. Similar conflicts exist where society's biases create ecological problems—for example, the conflict between fire suppression in forests and increasing concerns about catastrophic burns, or the removal of large woody debris from streams despite overwhelming evidence of its ecological importance. The move towards science based ecosystem management will no doubt uncover additional examples.

However, as the rigor, understanding, and predictability of limnological restoration improve, successful restoration programs will likely emerge, increasing the credibility and public support for science-based ecosystem restoration. This ecological or limnological restoration paradigm represents a significant change from past univariate, symptom-specific treatment approaches that often failed to restore fisheries and their supporting ecological processes. Rather than asking fishery and water resource managers and the public to choose between clear water or valued ecosystem services, education and effective ecological restoration involving the biologically productive middle ground, where appropriate, should provide a scientifically defensible strategy for restoring culturally oligotrophic ecosystems.

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