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FEATURED COLLECTION INTRODUCTION: RIPARIAN ECOSYSTEMS AND BUFFERS II[1]

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Riparian ecosystems, the interface of terrestrial and aquatic systems, are zones of high biodiversity (Naiman *et al.*, 1993), rapid biogeochemical activity (Vidon *et al.*, 2010), complex hydrologic activity (Mayer *et al.*, 2010a), and offer solace that can bestow significant mental health benefits (Alcock *et al.*, 2014). Yet, many riparian zones also represent intersections of policy disputes, economic tradeoffs, and environmental degradation. A clearer understanding of science is necessary to establish better resource policy, identify economic values, stave off environmental impacts to riparian ecosystems, and sustain valuable ecosystem services in the face of land-use change, ever-increasing resource consumption, pollution, and climate change. The value of assembling riparian scientists at a meeting every few years is to facilitate the exchange of information that will advance our knowledge to deal with the legacy of past impacts and to meet the challenges of the present and future.

The 11 papers in this collection were solicited from participants of the American Water Resources Association (AWRA) summer specialty conference "Riparian Ecosystems IV: Advancing Science, Economics, and Policy" held in Denver, Colorado, 27-29 June 2012. Over 100 conference attendees participated in an interdisciplinary forum with over 80 speakers in 19 technical sessions. Attendance, affected by government-wide budget cuts and a weak U.S. economy, was lower than in 2008 (Mayer *et al.*, 2010b). Nevertheless, enthusiasm and the quality of presentations remained high. The scheduling of the meeting was designed as a bridge from the AWRA specialty conference on "Contaminants of Emerging Concern in Water Resources." Two keynote speakers bridged the conferences with engaging talks, the first by Dr. Tyrone Hayes who spoke about "The Scarlet Letter: Much Ado About Nothing," an examination of the science and policy surrounding the pesticide Atrazine. The second keynote, kicking off the start of the riparian conference, was given by Dr. Sujay Kaushal who spoke about "Managing Contaminants along the Global Watershed Continuum: Riparian Zones to Rivers," a talk that featured data from a recent trip by Dr. Kaushal to the Himalayas where he documented severe pollution in the Ganges River. Plenary speaker, Dr. Jana Compton presented "Ecosystem Services: Science to Inform Policy and Management of Nutrients." Final plenary speaker, Ms. Jane Rowan provided a synthesis of information presented during the conference, "Riparian Ecosystem IV: Reflections and Advancement." Dr. Philippe Vidon led a special session on "Coupled Biogeochemical Cycles" and Dr. Kate Dwire led a field trip around the Denver

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metropolitan area showing how water issues have shaped the Front Range of Colorado, USA.

The papers herein are intended to advance our understanding of the science of riparian ecosystems. Paper topics fall within one of three broad categories: (1) Riparian Vegetation Management, (2) Restoration and Nutrient Management, and (3) Ecosystem Services and Modeling. Papers run a gamut from empirical and experimental studies to broad syntheses to modeling. Some papers represent complex corroborations of models and experiments. Several papers address the emerging issue of greenhouse gas production in riparian zones, emphasizing that riparian ecosystems are an interface among aquatic and terrestrial environments as well as the atmosphere.

RIPARIAN VEGETATION MANAGEMENT

Managing nonnative vegetation using herbicides in sensitive ecosystems presents a challenge to riparian managers. Hall *et al.* (2014) provided a methodology for managing one of the most aggressive plant species threatening riparian vegetative diversity, *Microstigeum vimineum*. This species is frequently found in new restoration sites and threatens the success of the restoration projects. Their research demonstrated that control performance of herbicides licensed for the use around aquatic systems and determined that herbicide application at pre- and post-emergent timing was acceptable for the control of *M. vimineum.* The findings of this study will be valuable to riparian ecosystem managers, particularly for those involved in stream and riparian restoration.

Pollock and Beechie (2014) conducted a massive review on large wood inputs to streams from riparian ecosystems. They first scoured the literature to identify patterns in usage of live trees and dead wood, standing and fallen, by various vertebrate species. Then, the authors employed a forest growth model to predict the sizes of live trees and deadwood that may result from various forest management practices designed to thin forest stands. Their analysis demonstrated that various management approaches will likely produce significantly different stand characteristics over the course of 200 years of growth and succession. Based on life-history traits, the resulting forests will vary in suitability among species dependent upon such forests, creating habitat tradeoffs among forest species.

Sweeney and Newbold (2014) conducted an extensive review of literature on riparian buffers to identify patterns in minimum widths necessary to protect water quality, habitat integrity, and population viability of organisms dependent upon streams and riparian zones. They focused on nitrate removal, sediment trapping, stream channel width and erosion, stream temperature regulation, instream large wood, macroinvertebrates, and fish. In addition to a thorough examination of existing literature, they went on to calculate nitrate removal efficiencies based on subsurface water flux, an approach that better explains the variability in efficiency calculated only based on buffer width. Successfully extracting useful patterns from numerous studies done at different scales and comparing among various parameters, the authors conclude that minimum buffer widths ≥30 m are necessary to effectively protect physical, chemical, and biological integrity of streams.

RESTORATION AND NUTRIENT MANAGEMENT

Kaushal *et al.* (2014) reviewed over 200 studies of hydrologic and gaseous fluxes to identify patterns in how land use and climate variability influence the flux and transformation of carbon, nutrients, and greenhouse gases in watersheds dominated by agriculture or urban development. Their synthesis illustrates the phenomenon of rapid movement of contaminants during extreme events, resulting in large pulses of organic matter and gases being transported and released through watersheds. Their review highlights the difficulty of adequately monitoring pulses. The authors identify emerging questions about the drivers that regulate contaminant and gaseous pulses and conclude with eight recommendations for managing pulses to ameliorate pollutant effects.

Lazar *et al.* (2014) conducted an ingenious comparative study of denitrification in two small streams, one a high N agricultural stream and the other a low N forested stream. Their experimental study focused on the influence of wood in streams and how biofilms growing on wood substrates support denitrification. Wood and stone substrates were placed in both streams and their field data were corroborated by laboratory mesocosms. Wood substrates at the forested site had higher denitrification than wood substrates at the agricultural site or from stone substrates located at either site. Nitrate removal rates were higher on wood substrates than on stone substrates at both the agricultural and forested sites. Their results demonstrate the value of wood additions to streams, a conclusion strongly supported by Pollock and Beechie (2014) in this issue.

Using a series of restored streams and associated riparian zones of various ages in Charlotte, North Carolina, USA, McMillan *et al.* (2014) investigated the impact of stream restoration age on N and P uptake,

and hypothesized that riparian vegetation and stream channel geomorphic complexity will play a critical role on N and P retention. They found that riparian vegetation age played a critical role at regulating stream temperature and carbon input to streams, but that sediment organic carbon content was inversely correlated with restoration age. P uptake was greater in newly restored sites owing to the presence of photosynthetic algae in the channel. As riparian vegetation developed over time and shading increased, P uptake decreased. Conversely, N uptake was highest at older sites owing to greater channel stability and well-established communities of denitrifying bacteria. This study stressed the complex interactions among stream channel morphology, riparian vegetation development, and nutrient uptake.

The success of riparian wetland restoration is frequently judged by the extent to which natural hydrology and vegetation have been restored. Vidon *et al.* (2014) extended this assessment of restoration success by comparing the biogeochemical function of a restored riparian wetland and a nonrestored, well-drained alluvial site in an agricultural watershed in Indiana, USA. The authors studied dynamics of N, P, S, and greenhouse gases at both sites, and found no significant differences between them. Ten years following restoration, the riparian wetland did not demonstrate the biogeochemical function expected in a natural wetland. These sobering results highlight the challenges of reconstructing hydric soils with adequate soil organic matter to support redox-sensitive biogeochemical reactions. The authors discuss implications of their findings for riparian zone management and restoration activities, especially in watersheds dominated by agricultural land use.

Wiseman *et al.* (2014) employed detailed studies of groundwater nitrate in a riparian buffer that was part of a conservation enhancement program in North Carolina, USA. Their study illustrated the challenges inherent in estimating the efficiency of riparian ecosystems in reducing nitrogen pollution including differentiating between denitrification, plant uptake, and dilution. In particular, their study demonstrated that simple dilution may account for reductions in nitrate concentration. This study demonstrates and quantifies the direct and ancillary benefits of managing lands under the guidance of specific agricultural policies.

ECOSYSTEM SERVICES AND MODELING

Tilak *et al.* (2014) provided a detailed evaluation of the commonly used Riparian Ecosystem Management Model (REMM) for a riparian zone in North Carolina, USA. After using daily water depth measurements and monthly nitrate concentration measurements to calibrate the model, the authors showed that REMM was successful in predicting plant N uptake and denitrification at the sites. Following calibration, the authors successfully used REMM to model the long-term performance of the buffer for a 33-year period from 1975 to 2007 using historical data. Long-term simulations confirmed the importance of riparian buffers for water quality, and further highlighted the suitability of REMM to simulate key hydrological and biogeochemical processes occurring in real-world buffers.

Warziniack (2014) utilized the concept of ecosystem services to frame a model that demonstrated how nonpoint source pollution from N fertilizer use for grain production in the Mississippi-Atchafalaya River Basin can influence the economics of fisheries in the Gulf of Mexico. The model followed the general equilibrium production economy model developed by Copeland and Taylor (2003) and was adapted to include payments for ecosystem services and the predicted economic losses incurred for damages to the ecosystem. The authors concluded that, based on their model, most of the damages to the environment are influenced by the economics of both agriculture and the fishing industry, emphasizing the importance of understanding the effect of competing resource use on the environment. This model has potential to inform agricultural land management practices and related regulatory policies for the protection of water quality and riparian ecosystems.

Using statistical models, Weller and Baker (2014) provide one of the first empirical estimates of riparian buffer effects on nitrate loads in streams of the Chesapeake Bay Watershed. The authors showed that across the entire watershed, 21.5% of nitrate released by croplands was intercepted by riparian buffers. Another 24% of the cropland load might be removed if riparian buffers were restored in croplands where there are currently no buffers. However, 42% of the cropland nitrate load cannot be reduced by riparian buffers and other management practices would have to implemented, including source control strategies. This manuscript supports previous research highlighting the need for healthy riparian zones to mitigate the impact of cropland nitrate on stream water quality, but also reveals the limits of riparian buffers as a nitrogen management strategy.

CONCLUSION

The research described herein represents a concerted, high-quality effort toward improving riparian

science. A consistent comment among the authors in this special issue was that we need further information on the complex interactions between riparian functions, climate, land use, management, and policy. That is, while our state of science is improving, our ability to apply our knowledge to mitigate stressors requires an ever more sophisticated understanding of riparian ecosystems. The topics of climate variability, green house gases, biogeochemical cycling, ecosystem services, nonnative vegetation, ecosystem restoration, and policy will be consistent themes of riparian research for the foreseeable future. Future research will need to focus on specific stressors of concern such as the effects of temperature increases from climate change. We will need to employ multidisciplinary research approaches derived from the laboratory, the landscape, and cyberspace. With declining budgets, combining talents and resources is the most effective and fiscally feasible approach to support sound science. However, mitigating stressor effects on riparian ecosystems will also require decision tools and policy approaches that implement science. We appeal to scientists to work toward filling gaps in our knowledge including (1) best management practices for urban riparian zones, (2) the impacts on riparian function of extreme events and pulses of contaminants released during floods or droughts, (3) effective methods to mitigate the effects of climate change and adaptation strategies to adjust to climate change, (4) scalable models that can be incorporated into existing policy infrastructure to inform regulatory action under future land use and climate scenarios, and (5) long-term, regional, and global monitoring networks, especially for groundwater, that employ real-time sensors and, where feasible, social networks. We look forward to exchanging information on these and other topics in a future Riparian Ecosystem AWRA meeting.

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