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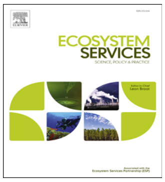

A synoptic survey of ecosystem services from headwater catchments in the United States

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ABSTRACT

Ecosystem production functions for water supply, climate regulation, and water purification were estimated for 568 headwater streams and their catchments. Results are reported for nine USA ecoregions. Headwater streams represented 74–80% of total catchment stream length. Water supply per unit catchment area was highest in the Northern Appalachian Mountains ecoregion and lowest in the Northern Plains. C, N, and P sequestered in trees were highest in Northern and Southern Appalachian and Western Mountain catchments, but C, N, and P sequestered in soils were highest in the Upper Midwest ecoregion. Catchment denitrification was highest in the Western Mountains. In-stream denitrification was highest in the Temperate Plains. Ecological production functions paired with published economic values for theses services revealed the importance of mountain catchments for water supply, climate regulation, and water purification per unit catchment area. The larger catchment sizes of the plains ecoregions resulted in their higher economic value compared to the other ecoregions. The combined potential economic value across headwater catchments was INT $14,000 ha^{-1} yr^{-1}, or INT $30 million yr^{-1} per catchment. The economic importance of headwater catchments is even greater considering that our study catchments statistically represent more than 2 million headwater catchments in the continental United States.

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1. Introduction

Headwater streams and their catchments have received much attention in recent years, with issues ranging from their contribution to, and connection with, larger downstream ecosystems (Nadeau and Rains, 2007), to the loss of headwater streams to burial and routing through underground pipes (Roy et al., 2009; Kaushal and Belt, 2012). An emerging concern is the underestimation of the extent of headwater stream channels, even when mapped at scales finer than 1:100,000 scale (Roy et al., 2009). Headwater streams are defined as the terminal branchings of a stream drainage network, the point where water flowing in a catchment first coalesces into defined stream channels (Gomi et al., 2002). Nadeau and Rains (2007) extend the definition of headwater streams to first- and second-order streams (Strahler, 1957) on 1:100,000 scale maps, even though researchers have demonstrated the underestimation of headwater streams at this larger (coarser) map scale (Meyer and Wallace, 2001; Roy et al., 2009). Because of stream network scaling properties (Dodds and Rothman, 2004), the proportion of total basin-wide headwater stream length is approximately 70% of total stream length on both 1:100,000 and 1:24,000 scale maps (Leopold et al., 1964; Nadeau and Rains, 2007; Lassaletta et al., 2010).

In addition to their dominance in terms of numbers and cumulative length, headwater streams also exert controls on stream runoff and downstream fluxes of dissolved and particulate matter organic matter and nutrients (Alexander et al., 2007; Dodds and Oakes, 2008; Lassaletta et al., 2010). Using spatial regression models, Alexander et al. (2007) estimated that headwater streams deliver 60% of the runoff and 45% of the nitrogen load in downstream reaches in northeastern US streams and rivers. They attribute this result to the high density of headwater streams and the frequency of their connections to higher-order stream channels. In a review of the influence of headwater streams on downstream reaches, MacDonald and Coe (2007) reported an even greater proportion of runoff and nutrient loading is directly attributable to headwater streams. Similarly, Dodds and Oakes (2008) reported that nutrient chemistry in fourth-order Kansas streams was best predicted by riparian land cover adjacent to

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upstream first-order streams. These results are similar to those reported for European streams (Lassaletta et al., 2010).

This downstream influence by headwater streams indicates a hydrologic connectivity that links headwater catchments, their soil, and groundwater resources, with larger-order streams (Gomi et al., 2002; Wipfli et al., 2007; Freeman et al., 2007). Headwater streams are not specifically protected by the Clean Water Act (CWA), but until recently they were included as necessary for the maintenance of healthy, productive, and navigable streams and rivers. Their protection under the CWA has recently been limited by the Supreme Court (Rapanos v. United States 547 US 715, 2006) to only those headwater streams that are directly connected to, or have demonstrated a significant influence on, navigable waters (Nadeau and Rains, 2007). Even with CWA protections, headwater streams have been lost from the landscape, primarily by human-driven changes in catchment land use including agriculture, urbanization, and mining (Meyer and Wallace, 2001; Roy et al., 2009; Kaushal and Belt, 2012). An analysis of 106 catchments from around the world revealed that nearly one-third of them experienced extensive conversions ($>50\%$ of the catchment) of forests to agriculture or urban development (Postel and Thompson, 2005).

Ecosystem services are the result of direct and indirect contributions of ecosystems to human well-being (Burkhard et al., 2012). The Millennium Ecosystem Assessment (2003) classified ecosystem services into four categories: provisioning services which provide goods for direct human use (food, freshwater, timber); regulating services to maintain biophysical properties for living beings (climate stability, water purification); cultural services including aesthetic and spiritual benefits; and supporting services which are necessary for the maintenance of functioning ecosystems (nutrient cycling, primary production, soil formation). Catchments represent a discrete unit for accounting for the delivery of ecosystem goods and services to society (Postel and Thompson, 2005). Catchment ecosystem services are many, including biodiversity, climate regulation, recreation, timber and crop production, and water supply and purification. Timber markets are globally well established, carbon exchange markets are developing (Intercontinental Exchange, 2012), and water supply is easily valued as a commodity (Krieger, 2001; Postel and Thompson, 2005; Nunez et al., 2006; de Groot et al., 2012; Townsend et al., 2012); but the value of water purification via nitrogen and phosphorus sequestration in biomass and soils, and through denitrification, are only beginning to receive economic consideration (Dodds et al., 2009; Turpie et al., 2010, Compton et al., 2011). Some of these catchment ecosystem services co-vary while others compete, and understanding the interplay and relationships among ecosystem services under varied management of these resources is critical to the sustainable delivery of catchment ecosystem goods and services (Bennett et al., 2009; de Groot et al., 2010; Deal et al., 2012; Townsend et al., 2012).

Our objectives in this paper are to highlight the importance of headwater catchments by focusing on the quantity and value of a few ecosystem services derived from them, and to extrapolate that importance from regional to national scales within the continental United States. We focus on headwaters because that is a particular category of streams that is of interest in the US regulatory community. As an under-protected resource, we wanted to highlight their particular value. We combine data collected from headwater streams as a part of the US Environmental Protection Agency's (USEPA) National Rivers and Streams Assessment (NRSA) with catchment attributes related to water supply, the sequestration of C, N, and P, and the removal of N via denitrification. We use these data to develop ecological production functions related to the delivery of ecosystem services from headwater catchments, and combine these services with published valuations to estimate potential cumulative benefits derived from headwater catchments in the United States.

2. Materials and methods

2.1. Study sites

Catchments included in this study were those drained by the 568 first- and second-order (Strahler, 1957) streams that were sampled during the NRSA (Fig. 1). The sampling design was spatially-balanced and employed an unequal probability survey with the unequal selection based on stream order. The design selected a single point along the center line of each stream as depicted by the National Hydrography Dataset (NHDPlus, Version 1; http://horizon-systems.com/nhdplus; based on 1:100,000 scale maps). All sample sites were selected using NHDPlus as the sample frame. Each site included in the survey represented a known stream or river length based on the population of streams included in the survey design, the probability of that site being selected for sampling, and the number of sites actually sampled. These stream and river lengths were summed to estimate the cumulative extent of streams sampled (Olsen and Peck, 2008).

The NRSA design allows the assessment of ecological conditions of streams at three hierarchical spatial scales: national, regional, and ecoregional (Olsen and Peck, 2008). Here we report results nationally and for nine ecoregions: Northern Appalachian Mountains, Southern Appalachian Mountains, Coastal Plains, Northern Plains, Southern Plains, Temperate Plains, Upper Midwest, Western Mountains, and Xeric ecoregions (Fig. 1).

2.2. Catchment attributes

Total catchment area (*A*, ha) for each site was calculated by summing the areas of all NHDPlus catchments intersected while navigating upstream from each sampling site. Cumulative catchment area (Cum *A*, ha) within an ecoregion was calculated as the product of mean *A* and the total number of catchments (*n*) in that ecoregion (Table 1; Fig. 2). Percent of the catchment in forests (% forest), grasslands (% grassland), row crops (% agriculture), and wetlands (% wetland) were extracted from the National Land Cover Database (NLCD, USGS, 2006; Fig. 2). The NLCD, derived from multi-temporal and terrain-corrected satellite imagery, provides consistent land cover estimates for the United States. Targeted assessments found accuracy of land cover estimates ranged from 78 to 89% (Xian et al., 2009).

Catchment stream lengths (*L*, km) were estimated using NHDPlus flow line and stream order data layers (Fig. 2). NHDPlus codes flow lines as connectors, canals and ditches, underground pipes, intermittent and perennial streams, artificial paths, and coastlines. We excluded underground pipes and coastlines from our analyses, and the remaining types of water conveyances are collectively treated as streams. Each stream segment of a given order was included in the estimate of *L* by stream order, and cumulative catchment stream length (Cum *L*, km) was calculated as the product of *L* and *n*.

Catchment-scale estimates of soil organic carbon (SOC) and % sand were derived from US Department of Agriculture soil survey data (SSURGO and STATSGO2; http://soildatamart.nrcs.usda.gov/; Fig. 2) and associated with each headwater catchment as the mean of the 30-m pixels included in each catchment. Soil drainage index (DI), previously called the natural soil wetness index, is a measure of the long-term wetness of a soil (Schaetzl et al., 2009). Catchment-scale estimates of DI were estimated from area-weighted STATSGO2 map units (http://www.drainageindex.msu.edu; Fig. 2) that intersected our study catchments.

Data on the wet deposition of atmospheric N were available from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu). We used annual (2005–2009) precipitation-weighted mean TN concentrations in precipitation. Estimates of