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Differentiating the relative importance of land cover change and geomorphic processes on fine sediment sequestration in a logged watershed

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ABSTRACT

Timber harvest often results in accelerated soil erosion and subsequent elevated fine (<2 mm) sediment delivery to channels causing deleterious effects to numerous aquatic species, particularly salmonid fishes. Here we determine, through sediment physical analyses (pebble counts, embeddedness surveys, and interstitial shelter space counts) and geochemical analyses (^{7}Be and ^{210}Pb$_{ex}$ activities), the amount and timing of delivery of fine sediment currently found on streambeds of the Narraguagus River watershed in coastal Maine. The role of recent timber harvest, documented via aerial photo spatial analysis, on fine sediment delivery is contrasted with the ability of the glacially influenced topography and surficial geology to deliver fine sediment to streams and to influence channel substrate. Results show that of the land use and geomorphic variables examined, only ^{210}Pb$_{ex}$ activities were significantly correlated with the amount of upstream harvest ($r^2=0.49$). Concurrently, we find that unit stream power (particularly the slope component) explains much of the variability in channel substrate and that slope and stream power are largely influenced by the legacy of Pleistocene glaciation on channel form. Results suggest a conceptual model whereby fine sediment delivery as a result of late twentieth century timber harvest is likely dampened because of the low gradient landscape of coastal Maine. While geochemical tracers indicate recent fine sediment delivery in harvested areas, channels are likely capable of quickly winnowing these fines from the channel bed. These results further suggest that under contemporary land use conditions, the geomorphic and geologic setting represents a first-order control on channel substrate and habitat suitability for salmonid fishes, including federally endangered Atlantic salmon (*Salmo salar*), in coastal drainages of northeastern Maine.

1. Introduction

Considerable research has revealed the profound impacts of land use and land cover change on stream channel morphology, especially through changes in the hydrologic regime and the increased sediment yield associated with accelerated watershed-scale soil erosion (see reviews by Walling, 2004; Gregory, 2006; Wilkinson and McElroy, 2007). Increased sediment supply from these anthropogenic disturbances has led to accelerated rates of floodplain sedimentation, historical channel narrowing, and enhanced channel bed sedimentation (Costa, 1975; Knox, 1977; Magilligan, 1985; Jacobson and Coleman, 1986; Lowe and Bolger, 2002; Phillips and Gomez, 2007) often degrading channel habitat (Waters, 1995). Because of the tremendous concern for protecting aquatic habitat – particularly in the Pacific Northwest where logging impacts have led to increased flooding and intensified soil erosion, mass wasting, and channel sedimentation (Beschta, 1978; Jones and Grant, 1996; Wemple et al., 1996) – sustained geomorphic attention has been given to understanding the processes of sediment transport and storage along disturbed channel reaches. However, comparatively little research has been done on the potential for fine sediment generation and delivery resulting from timber harvest in lower-gradient watersheds of the northeastern United States, despite a disturbance history dating back several centuries.

In part because of the steep terrain of disturbed watersheds in the Pacific Northwest, much of this past work on channel bed impacts following logging has focused on coarse bedload. This research has led to important results concerning the primary mode of downstream transport, determining, for example, whether the sediment plug introduced by the disturbance moves downstream by dispersion or translation (Lisle et al., 2001; Cui et al., 2005; Madej et al., 2009), with the tracking relying primarily on channel bed surveys and pebble counts.

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Less attention, however, has been devoted to the sand component of bedload transport (0.0625–2 mm), in part because of the difficulty (and expense) in sampling and in tracing sediment sources. This transitional material interacts frequently with the bed and has significant ecological implications, as the high surface area of particles of this size may efficiently sorb pollutants (along with adsorbtion by finer clays, colloids, and iron oxide coatings), potentially controlling the transport and fate of particle-bound contaminants in riverine ecosystems (Axtmann and Luoma, 1991; Horowitz, 1991; Coulthard and Macklin, 2003). Fine sediment may also become embedded within the gravel matrix, ultimately reducing important oxygen exchanges necessary for salmonid egg survival (Greig et al., 2005).

With the advent of studies utilizing new geochemical tracers, particularly the fallout radionuclides ^{7}Be and ^{210}Pb, tracing the movement of fine material through watersheds is becoming progressively more possible (Bonniwell et al., 1999; Salant et al., 2007; Lauer and Willenbring, 2010), ultimately providing sediment transport rates and residence times of fine bed material. Using a watershed in coastal Maine heavily impacted by historical and recent logging, we use ^{7}Be and ^{210}Pb activity as proxies for sediment input from recently (post-1950) logged areas to (i) ascertain the flux of sediment from logging and (ii) trace the downstream movement of material associated with logging. Moreover, based on lidar-derived slope indices and channel morphological properties, we ascertain the inherent geomorphic (bedrock and surficial geology, channel slope, etc.) controls on sediment transport/storage relative to the role of sediment input from logging. In so doing, we have two major research questions: (i) what has been the late historical contribution of sediment input into the Narraguagus River of Maine associated with logging, and (ii) what is the relative role of geomorphic and watershed-scale controls on channel bed sedimentation relative to the sediment inputs associated with late twentieth century logging?

2. Study location

2.1. Geographic setting

The Narraguagus River flows generally southeast for 78 km through Washington and Hancock Counties of Maine. The river originates at the outlet of Eagle Lake and flows into the Atlantic Ocean at Milbridge (Fig. 1). The total watershed area is 588 km^2. A 2-m-high ice-control dam exists at Cherryfield, but its downstream location means it has negligible influence on sediment transport or storage over most of the basin. Historically, there have been numerous small dams along the stream associated with timber harvest (Harriman, 1977). These structures, colloquially referred to as 'splash dams,' were designed to assist in the storage and transport of felled timber downstream for milling and shipping. The last of these structures existed 41 km upstream from the Atlantic Ocean and was breached in 1951.

Coastal watersheds throughout Maine have been heavily affected by historic logging (Lorimer, 1977). Although the specific harvest chronology is not known for the Narraguagus watershed, historical reconstructions from adjacent watersheds indicate considerable logging activity throughout the nineteenth and twentieth centuries. For example, pre-settlement standing volume of eastern white pine (*Pinus strobus*) is estimated to have been ~14.1 million m^3 in the nearby Penobscot watershed, at least three times greater than contemporary volumes in Maine's eastern and northern region (Wilson, 2005). While historic logging was greatly aided by in-channel log drives, more recent (post-1950) harvest has relied on the construction of a network of gravel roads to transport felled trees for processing. In addition to fine sediments that may be generated by decreased soil cohesion following timber harvest, logging roads may accelerate the transport of fines to channels through hydrologic network extension (e.g., Wemple et al., 1996) or may themselves be sources of fine sediment from sheet erosion.

Current land use in the Narraguagus River basin consists primarily of timber harvest and blueberry farming. Roughly 60% of the watershed (and nearly the entire upper half of the basin) is under the ownership of forestry corporations (Arter, 2003) with significant historic and present logging potentially continuing to limit supplies of large woody debris to the stream channel (Magilligan et al., 2008; Kasprak et al., 2012). In the lower portion of the basin, blueberry farming is the dominant land use; but through examination of recent aerial photographs (USDA, 2007), we note that the spatial extent of blueberry farming in the lower basin is much smaller than that of timber harvest in the upper watershed.

2.2. Geologic/geomorphic setting

A large mainstem water body, Beddington Lake, is located 41 km upstream from the river's mouth and marks the marine transgressive limit during late Pleistocene deglaciation (Fig. 1; Thompson and Borns, 1985). Upstream of Beddington Lake, the watershed is primarily underlain by Paleozoic-age metamorphosed sediments from the Penobscot and Bucksport Formations (Osberg et al., 1985). The surficial landscape of this upstream segment is dominated by glacial till and coarse-grained glaciofluvial deposits (Thompson and Borns, 1985), and the channel is often bounded by eskers and exhibits low sinuosity. During field surveys upstream of Beddington Lake, bedrock outcrops and relict glacial knobs have been observed as controls on stream morphology and reach-scale slope (Snyder et al., 2012). Downstream of Beddington Lake, the bedrock consists primarily of Devonian-age alkali feldspar granites and gabbros (Osberg et al., 1985). The surficial geology of the lower basin is composed of generally fine-grained glaciomarine substrates (Thompson and Borns, 1985), and the stream exhibits numerous meanders and flows over a broad alluvial floodplain while some bedrock knobs and outcrops are still visible.

The contemporary longitudinal profile of coastal Maine streams still reflects the Pleistocene depositional history and associated drainage development (Snyder et al., 2009; Wilkins and Snyder, 2011; Snyder et al., 2012). In response to landscape scouring and drainage rearrangement, many coastal Maine streams (including the Narraguagus) possess structurally controlled irregular longitudinal profiles with long, continuous flat reaches alternating with steep gradient reaches. Moreover, for the Narraguagus River, the numerous mainstem ponds and lakes (such as Beddington Lake) serve as local sediment sinks along the longitudinal profile. The geologic and geomorphic legacy resulting from glaciation likely remains an important first-order control on contemporary processes, including sediment supply and delivery, and may establish a significant boundary condition in evaluating anthropogenic effects (such as logging) on sediment movement through the watershed.

3. Methods

In total, 42 study sites were initially selected throughout the Narraguagus River watershed (Fig. 1). These sites were located at tributary junctions, road crossings, and reaches adjacent to recently logged areas to document sedimentological inputs resulting from logging (Davies and Nelson, 1994; Forman and Alexander, 1998). Twenty-four study sites were located on the mainstem Narraguagus and 16 were located on tributary streams. Two sites were excluded from subsequent analyses because of (i) mass wasting of material directly into the channel and/or (ii) high uncertainty in radionuclide analysis, bringing the total number of sites used in the study to 40. At each site, numerous analyses (described below) were used to quantify the amount of fine sediment present in the channel substrate.